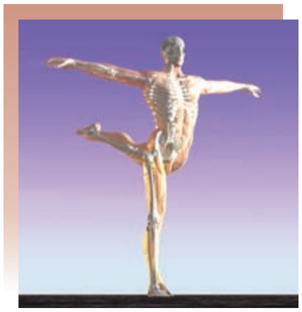

©DIGITAL STOCK

Change-in-Support Reactions for Balance Recovery

Control Mechanisms, Age-Related Changes, and Implications for Fall Prevention

BRIAN E. MAKI,
WILLIAM E. MCILROY,
AND GEOFF R. FERNIE

Falling is one of the most common and most serious problems associated with aging. Falls are the leading cause of accidental death and the leading cause of injury admission to acute-care hospitals in seniors. In the United States alone, falls result in nearly 300,000 hip fractures per year, with associated health care costs of US$10 billion [1]. In addition to the injuries and other serious medical sequelae, psychosocial problems such as fear of falling lead to social withdrawal, inactivity, and immobility. Falling is cited as a major reason for 40% of nursing-home admissions [2]. With the "graying" of the baby-boom generation, projections indicate that fall-related problems such as hip fractures will quadruple over the next 40 years. These problems will heavily burden our healthcare systems unless more effective approaches to prevent falls and promote safe mobility and independence can be developed.

There is little doubt that difficulty in controlling balance is a major contributor to an increased risk of experiencing falls and sustaining fall-related injuries in older adults. Numerous studies have demonstrated associations between falling risk and measures pertaining to the control of balance during stance, both unperturbed (spontaneous postural sway) and perturbed (reactions to support-surface motion or forces applied to the body) [3]. Because subjects are instructed not to move the feet, such balance tests reflect the capacity to regulate the position and movement of the body's center of mass (COM) with respect to a fixed, or unchanging, base of support (BOS). While such "fixed support" (FS) balancing reactions are important in providing an early defense against loss of balance, it has become clear, in recent years, that the capacity to avoid falling is likely to be highly dependent on a second, fundamentally distinct type of balance control, which involves rapidly moving the limbs so as to alter the BOS, either by taking a step or by reaching and grasping an object for support (Figure 1).

Biomechanically, these "change-in-support" (CS) reactions have the potential to provide a much greater degree of stabilization than FS reactions [4], [5]. However, the control of CS reactions is likely to be more demanding, because of the need to initiate and execute, at rapid speed, a complex limb movement that is appropriate to the characteristics of the balance disturbance and the constraints of the surrounding environment (location of unobstructed space to step and handholds to grasp). The demands of controlling these complex reactions may create difficulties for older adults, due to age-related impairments in the neural and musculoskeletal systems, leading to an increased risk of falling. In this article, we provide an overview of our own recent research in this area (see [4]-[6] for comprehensive literature reviews).

Methodological Approach

Traditionally, CS reactions have received relatively little attention in the balance-and-falls literature, in comparison to FS reactions. One likely reason is that many of the approaches used to study balancing reactions have tended to constrain the use of CS reactions. Implicit constraints commonly occur due to a lack of space to step or an absence of handholds to grasp. Explicit instructional constraints to avoid moving the limbs are also common practice. Under such conditions, subjects may well be able to inhibit the natural tendency to move the limbs. It is also important to note that traditional approaches to studying balancing reactions have typically allowed the subject to stand quietly, in an unchanging environment, and to focus attention on the balance task, prior to perturbation. In contrast, balance control during daily life is often complicated by ongoing activity (physical and cognitive) and by variation in environmental constraints and affordances (e.g., space to step, objects to grasp for support). We believe that these heightened task demands, in daily life, are critical factors that may contribute to an increased risk of falling in older adults; hence, it is very important to study the effects of these heightened task demands on balance control.

Our approach to testing balance and studying the control has been developed with the express aim of better understanding how falls are prevented in daily life. In daily life, there is seldom opportunity to practice the response to a given perturbation. In the laboratory, we minimize opportunity for learning and adaptation by testing naive subjects, by focusing on early trials where the perturbations are most unfamiliar and responses are unpracticed, and by making the characteristics of the postural perturbations (direction, amplitude, timing, waveform) as unpredictable as possible. To study natural behavior, instructional and physical constraints are relaxed: subjects are simply told to do whatever comes naturally to recover balance, sufficient space is provided to allow the option of stepping, and handholds are provided to allow the op-

 0739-5175/03/$17.00©2003IEEE

tion of grasping. Heightened demands of controlling balance in daily life are simulated by perturbing balance while subjects engage in ongoing movement and/or cognitive tasks and by modifying the testing environment to impose a variety of constraints on limb movement (e.g., obstacles to interfere with stepping or grasping). To circumvent the limitations of commercial perturbation systems, we developed our own moving-platform system (Figure 2) [7]. Moving platforms use horizontal acceleration of the support surface as a convenient means of inducing relative motion between the body's COM and BOS. Our system differs from conventional platforms in terms of the large surface area (2 m × 2 m) and the capacity to administer a wide range of perturbations (acceleration up to 5 m/s^2, velocity 1.5 m/s, displacement 0.6 m) along any horizontal axis. This latter feature allows the perturbation characteristics to be varied in a highly unpredictable manner.

Control Characteristics

Basic Principles

Essentially, maintaining balance involves regulating the static and dynamic relationships between the COM of the body and the BOS. Reactions to balance perturbations must therefore involve deceleration of the COM motion (as in FS reactions) and/or change in the BOS (CS reactions). A traditional view has been that CS reactions only emerge as a last resort when earlier FS reactions (e.g., torque generation at the ankle and/or hip) fail to keep the COM within the stability limits of the BOS. However, we have found that compensatory stepping and grasping are commonly initiated very early, with the COM well within the stability limits, and in fact appear to be the preferred response in many situations [4]. For example, subjects almost always take a step and begin to move the arms (toward the nearest available handhold) when the perturbation is unexpected or novel, even if the perturbation is relatively small.

Distinctions Between Compensatory and Volitional Movement

CS reactions appear to differ in some fundamental ways from volitional limb movement. One key difference pertains to the quicker initiation and more rapid speed of execution of the compensatory movements [4]. For example, a compensatory step is completed in about half the time that it takes to complete the most rapid volitional step. Compensatory arm reactions are initiated even more rapidly and coincide with the earliest FS reaction (80 ms after perturbation onset). Despite the rapid speed of the compensatory reactions, the control is remarkably sophisticated. Whereas volitional limb movements can be preplanned, the direction, amplitude, and speed of compensatory limb reactions must be modulated, in "real time," to account for the unpredictable body motion unexpectedly induced by the perturbation, as well as environmental constraints on limb movement (e.g., location of handholds or obstacles). Another key difference in comparing compensatory and volitional stepping pertains to the mechanism by which lateral stability is controlled. Invariably, when stepping volitionally, an anticipatory postural adjustment (APA) acts to propel the COM toward the stance leg prior to lifting the swing foot. These APAs are typically absent or severely truncated during compensatory stepping reactions [8]. As a result, the tendency of the COM to fall toward the unsupported side, during the swing phase, must be countered after landing the swing foot.

Control Mechanisms

There is, at present, limited understanding of the control of CS reactions. It does, however, seem clear that the control is more complex than the simple "release" of an immutable, reflex-like reaction. We recently used a dual-perturbation method to reveal evidence for online modulation of the step trajectory. In this study, a second lateral perturbation was delivered during specific phases of a forward stepping reaction evoked by an initial forward perturbation [9]. By analyzing muscle activation and comparing the measured swing-foot displacement to that predicted by a passive mechanical model, we found evidence that "reprogramming" of step direction can, in fact, occur during early stages of the reaction; i.e., prior to foot-off.

Another key question pertains to control objectives. For a given perturbation, there exist numerous combinations of step parameters (swing leg; step distance; timing) that could reestablish equilibrium, but it is not clear how the central nervous system (CNS) selects the specific response characteristics. The control is further complicated by the fact that the stepping reaction is typically initiated well before the full influence of the perturbation on the COM motion has taken effect [4], [10]. One possible control strategy is to maximize the speed of completing the step. This would facilitate execution of multi-

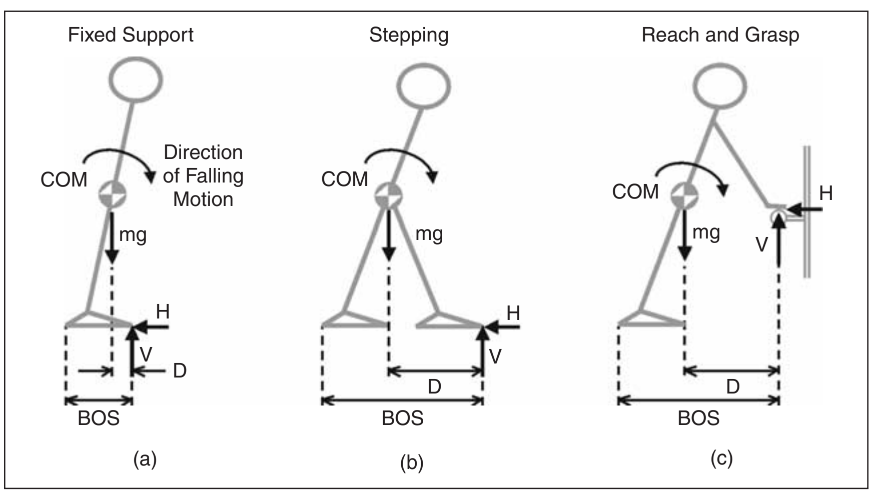

Fig. 1. Balance-recovery reactions: fixed-support (a) versus change-in-support [(b) and (c)]. The postural reaction must generate a horizontal ground-reaction shear force (H) in order to decelerate the horizontal motion of the center of mass (COM). Note that the stepping (b) and grasping (c) reactions can greatly amplify the moment arm (D) between the COM and the contact force (V), which allows greater shear force to be generated (H is approximately proportional to D). In addition, the increase in base-of-support (BOS) allows a larger range of COM motion to be accommodated without loss of stability. Adapted from [6].

ple steps and thereby allow "more adjustments to be made to correct for ill-chosen early responses" [11]. Another possibility is that the CNS attempts to maximize the stability of the initial step. Biomechanical modeling indicates that there is a trade-off between the speed of compensatory step execution and the stability of the resulting step, and that maximizing dynamic stability normally takes precedence [12]. Further modeling has demonstrated that the static stability margin (horizontal distance between COM and BOS perimeter) does not predict the need to initiate stepping and has confirmed the importance of addressing dynamic stability; i.e., taking into account the influence of the COM momentum [13].

Control of impact force at landing may also be an important control objective, serving not only to avoid musculoskeletal injury but also to aid in controlling the stability of the landing. The latter is supported, indirectly, by apparent associations between high rates of contact loading and the need to take additional steps to recover equilibrium [14]. Modeling work by Hsiao et al. [15] has demonstrated that step length can be controlled to minimize impact force; however, more research is needed to determine the relative importance, in comparison to the other control objectives described above. We have recently performed simulations to examine the role of the stance-leg hip abductors: activation of these muscles during swing phase retards downward COM acceleration and hence reduces impact force; however, there is a trade-off. Activation of the hip abductors also causes the COM to be accelerated laterally toward the unsupported side, which exacerbates the problem of controlling lateral stability.

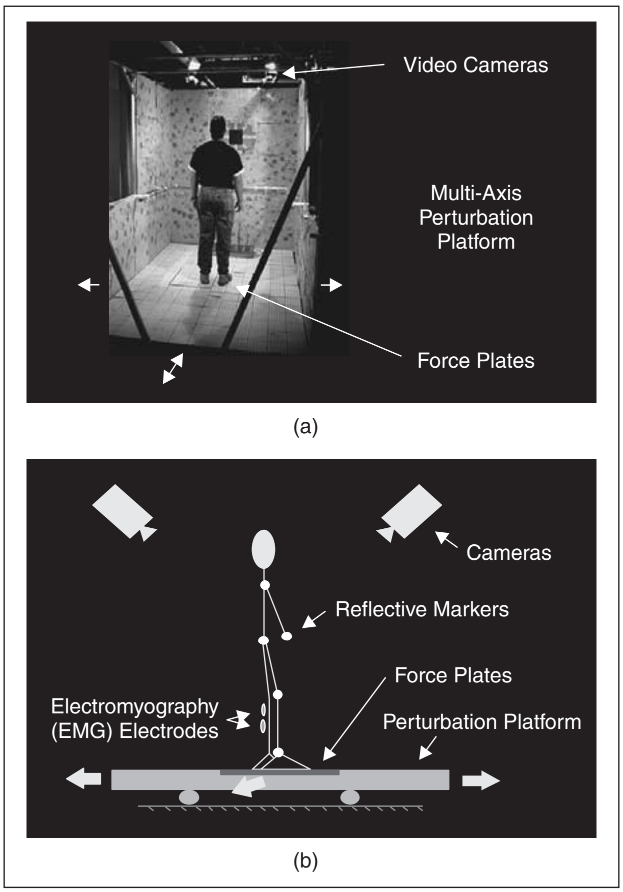

Fig. 2. The multi-axis moving-platform perturbation system. The platform floor surface and walled enclosure seen in the photograph are supported by an undercarriage (which slides on two orthogonal pairs of ball-bushing rails) as well as castors mounted under each corner of the floor surface. The platform undercarriage is driven by a dc motor and ball screw under computer control (a D/A signal is inputted to an analog proportional+derivative control circuit). The drive train is mounted on a motor-driven turntable, underneath the undercarriage, which is rotated to set the direction of the platform motion prior to perturbation onset. Three force plates, embedded in the surface of the moving-platform floor, measure the ground-reaction forces and are used to characterize the reactions that are evoked by the platform motion, along with motion-analysis systems (video-based and/or electromagnetic) and surface electromyographic recordings.

Effects of Environmental Constraints

We have recently begun to investigate the effect of obstacles to foot movement on the control of compensatory stepping. Remarkably, young adults were well able to step forward over a high obstacle placed in front of the feet and recover equilibrium, in response to an unpredictable perturbation, even in the very first trial. Clearance of the obstacle required a doubling of the swing duration and therein presented significant challenge to lateral stability. Surprisingly, in view of previous findings that the APA is normally absent or truncated during compensatory stepping, a large APA was used to counter lateral instability when stepping over the obstacle [16]. A more lateral foot placement was also used to provide lateral stabilization; however, it was found that the APA could be further up-regulated to maintain lateral stability, without need for lateral stepping, when barriers were used to prevent lateral placement of the swing foot [17]. The above findings suggest a hybrid control combining both predictive (APA) and reactive (foot placement) elements. Ongoing work is directed at determining how the CNS deals with unpredictable variation in obstacle location.

Effects of Ongoing Activity

Although balancing reactions are often considered to be "automatic," there is growing evidence that high-level attentional and cognitive processing may be involved in controlling specific aspects of these reactions [18] and that the CNS can quickly switch attention from an ongoing activity to the balancing task when necessary. To study attention switching, we have developed a dual-task paradigm where a balance perturbation is delivered while the subject performs a secondary cognitive task that involves continuous visuomotor pursuit tracking (Figure 3). Switching of attention to the balancing reaction is inferred to occur at the onset of pauses or other large errors in tracking. This apparent shift of attention invariably occurs after the earliest phase of the FS reaction, suggesting that it is the later phases of the reaction that require cognitive resources [19]. Moreover, it appears that compensatory stepping can be initiated with minimal attentional involvement; however, attention switching invariably occurs prior to lifting the swing foot, suggesting that control of foot lift and/or foot trajectory requires significant cognitive involvement [20].

Ongoing physical activity could potentially affect ability to execute CS reactions through a number of mechanisms. One possibility is that it becomes more difficult for the CNS to detect onset of instability amidst the ongoing movement-related sensory discharge. Our results suggest that sensory dis-

charge arising from rhythmic ongoing movement does cause delays in initiating compensatory grasping reactions [21]. The specific effects of the sensory discharge were isolated from other effects of ongoing movement by using a seated lower-limb movement task (pedaling) while restricting the balancing reactions to the upper limbs (evoked via rapid tilts of the chair). Compared to no-pedaling trials, both active and passive (motor driven) pedaling resulted in similar delays in the initiation and execution of grasping reactions. These results indicate that the sensory discharge associated with the lower-limb movement was the primary mediating factor. Ongoing studies are investigating effects of competing demands for muscle activation; e.g., to determine if initiation of compensatory grasping is delayed when the ongoing movement involves activation of agonistic or antagonistic arm muscles (e.g., due to swinging the arms or holding a cane).

Age-Related Changes and Falling Risk

Age-Related Changes

Even healthy and relatively young seniors (ages 65-75) exhibit marked differences in the control of CS reactions when compared to young adults (ages 20-30). One of the most consistent findings is that older adults are much more likely to take multiple steps to recover balance or to reach to grasp objects for support [11], [22], [23]. When stepping in response to forward or backward perturbation, the average temporal and spatial characteristics of the initial step and COM motion, up to time of foot-contact, are remarkably similar in young and older subjects [22], suggesting that the need to take additional steps arises from difficulty in controlling the landing phase rather than the earlier phases of the response. There appears to be a particular problem in dealing with the tendency of the COM to fall toward the unsupported side during forward or backward step execution, as evidenced by the tendency to take additional steps in the lateral direction [22]. When stepping laterally in response to lateral perturbation, the main problem appears to be avoiding collisions between the swing foot and stance limb, particularly when the perturbation occurs during ongoing motion (e.g., walking in place on the moving platform) [23]. When using grasping reactions to regain balance, older adults exhibit a delay in onset of muscle activation and slowing of arm movement [24].

Do the Age-Related Changes Predict Increased Risk of Falling?

To address this question, we monitored falling in 64 older adults prospectively for one year after balance testing [24]. Half of the subjects experienced one or more falls: 24 subjects had one or more falls in the antero-posterior (a-p) direction and eight subjects had one or more lateral falls. Most of the measures described above that showed age-related differences were also associated with risk of falling in the a-p direction. One of the best predictors of a-p falling was the tendency to rely on using the arms to recover balance. The a-p fallers moved the arms in twice as many trials as the nonfallers, yet their arm movements were significantly slower. In fact, slowing of arm reactions was the one measure that predicted falling risk regardless of fall direction. Only one measure predicted lateral falls: the tendency to take a lateral step after taking an initial forward or backward step. However, finding this predictor is important, given that it is primarily the lateral falls that result in debilitating, and life-threatening, hip-fracture injuries [1].

What Are the Causes of the Age-Related Changes?

The control of CS reactions is dependent on a number of factors: the CNS has to be able to use sensory information from an array of receptors (vestibular, visual, somatosensory) to detect instability and to monitor the motion of the body; neural processing is also required to process and integrate the sensory data and to select appropriate responses; and the musculoskeletal system must have sufficient strength and range of motion to generate the required movements. All of

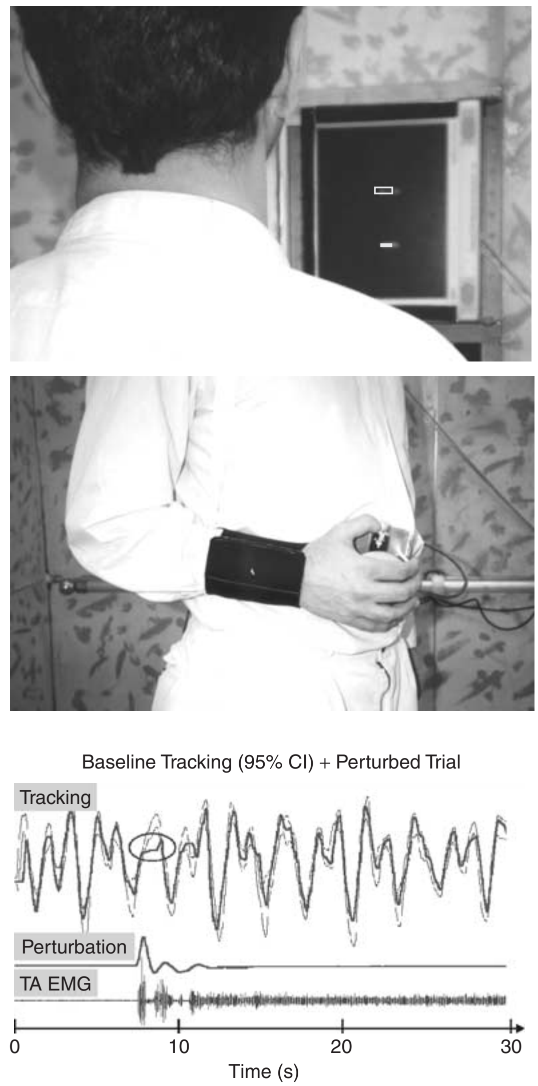

Fig. 3. Dual-task paradigm involving visuomotor pursuit tracking. The subject uses the thumb to control movement of a cursor to track the target, which moves continuously and unpredictably up and down on the computer screen. Tracking during a postural-perturbation trial (thick line) is superimposed on the confidence interval (CI) for unperturbed baseline tracking (thin lines). Note the pause in tracking (circled), which occurred approximately 300 ms after perturbation onset (200 ms after the onset of the postural reaction in tibialis anterior, TA). This pause is inferred to reflect switching of attention to balance recovery.

these factors are affected adversely by aging. Although the causes underlying age-related slowing of grasping reactions remain to be determined, we have begun to explore a number of factors that may contribute to impaired control of compensatory stepping.

One way to delineate the importance of age-related change in the different sensory systems is to study the effect of either attenuating or facilitating a particular sensory input. We have, in our initial studies, focused on sensory contributions from the cutaneous mechanoreceptors on the soles of the feet. These receptors are quite likely to play an important role in controlling stepping, by providing information about foot contact and limb loading. Another compelling reason for studying these receptors is that age-related loss of cutaneous sensation is very prevalent. To study the effects of loss of cutaneous sensation, we attenuated the sensation, in young adults, by cooling the soles of the feet in ice water [25]. In a separate experiment, involving older adults, we facilitated cutaneous sensation from the foot sole by adhering plastic tubing (3 mm diameter) to the perimeter of the sole [14]. The idea was to selectively promote sensation from the stability boundaries of the foot. The results of the two experimental approaches, attenuation and facilitation, tended to provide complementary information. For example, during forward stepping, attenuation caused younger adults to take multiple steps more frequently, while facilitation reduced the frequency of multiple-step reactions in older adults. Overall, the results suggested that cutaneous sensation from the heel plays an important role in controlling: 1) the landing during forward stepping, 2) step initiation during backward stepping, and 3) stability during the prolonged swing phase of lateral "crossover" steps.

Does age-related loss of strength compromise the ability to execute compensatory stepping reactions? In a pilot study, we used an inverse dynamics approach to estimate the net joint torques during compensatory stepping and found that older adults often exhibited lower stance-leg hip-abductor torques during swing phase, in comparison to young adults [5]. As noted earlier, this reduction in hip-abductor torque is likely to lead to higher impact forces at landing, which could require increases in the knee-extensor and hip-flexor torques in the contacting leg; such increases often did appear in the older subjects. Furthermore, these age-related differences in torque production appeared to be associated with the tendency to take multiple steps. In view of these findings, and the fact that the required torques were often close to the strength limits that were measured in these subjects, it is possible that problems in generating and controlling such large torques may lead to difficulty in controlling the landing. The importance of leg strength also appears to be supported by a study in which we used cluster analysis and multiple regression to identify whether age-related changes in sensory, neural, or musculoskeletal function could predict stepping performance [26]. Reduced strength and slowing of reaction time were found to be the strongest predictors of the tendency to take multiple steps to recover balance.

Fig. 4. Examples of new balance-enhancing products developed as a consequence of our research into stepping and grasping reactions: (a) SoleSensor footwear insole, (b) SturdyGrip™ safety pole, and (c) LifeRail handrail system. SturdyGrip is commercially available; we are currently seeking industrial partners for the other two products. Patents are issued on SoleSensor and SturdyGrip and are pending for LifeRail.

Another way that aging could affect control of CS reactions is through changes in cognitive function. Several studies have demonstrated that concurrent cognitive demands affect postural reactions to a greater extent in older adults, in comparison to young adults [18]. One possible explanation is impaired attentional dynamics; i.e., impaired capacity to reallocate attention (or other cognitive resources) to the balancing task when required. We studied this using the dual-task visuomotor-tracking paradigm described earlier and discovered that older adults are, indeed, slower than the young in switching attention to the balance-recovery task [27]. Moreover, delay in attention switching correlated with subsequent delay in generating

the peak FS response, suggesting an adverse effect on postural stabilization.

Implications for Fall Prevention

Clearly, clinicians need to be able to assess compensatory stepping and grasping. In view of the evidence that the control of volitional and compensatory limb movements differs in some fundamental ways, it appears that it is necessary to apply controlled perturbations during testing. Furthermore, to extrapolate the assessment findings to the natural behavior that occurs in potential falling situations in daily life, the perturbation should be as unpredictable as possible, subjects should be allowed to respond in a natural manner, and ongoing physical or cognitive tasks should be included. In terms of performance measures, expensive instrumentation (electromyography, force plates, motion-analysis systems) may not be necessary. Rather, it appears that simple, observable behavioral measures (e.g., number of steps taken, pattern of foot placement, frequency of collisions between swing foot and stance limb, frequency of arm movements) may be useful predictors of impaired control and falling risk.

What interventions are available to improve the effectiveness of stepping and grasping reactions in recovering balance and thereby reduce falling risk? Ongoing studies in our laboratory are investigating different balance-training approaches, as well as effects of visual factors and side effects of antidepressant medications. From an engineering perspective, we have focused on the design of footwear, handrails, and mobility aids. The cutaneous-sensation studies described earlier, for example, have led to the design of a footwear insole (SoleSensor) that is intended to facilitate sensation when loss of balance is imminent, and thereby help to compensate for effects due to age-related loss of cutaneous sensation [Figure 4(a)]. A clinical trial is currently underway to determine whether the balance-enhancing benefits of wearing such footwear, as demonstrated in our laboratory experiments, will persist over a longer term (i.e., three months of daily use).

Handrails and grab-bars need to be designed so that they can be grasped effectively. Our early studies looked at the effect of the handrail design (height, shape, size, etc.) on ability to generate stabilizing forces and moments when pushing and pulling on the rail. More recently, we have begun to use our moving-platform system to investigate the effect of the design on the ability to reach and grasp the rail during a simulated stairway loss of balance [28]. Based on these studies, we recommend a handrail that is considerably higher than many existing building codes (to increase the moment arm of the rail reaction force relative to the feet) and also mounted farther from the wall (to allow the hand to attack the rail with fingers fully extended). Spinoffs of our handrail research include the development of a graspable vertical-pole system (SturdyGrip™) that can be easily installed (without tools) wherever needed [Figure 4(b)] and a novel stairway handrail (LifeRail), which is positioned and shaped so it can be "grasped" in the manner of an underarm crutch [Figure 4(c)]. The latter may be particularly useful for persons with poor hand strength.

Although canes and walkers are generally thought to increase stability, it is also possible that they may interfere with the ability to recovery balance via lateral stepping reactions in situations where the user is unable to stabilize the body by pushing on the device. In an initial study involving healthy young adults, we found that collisions between the swing foot and walker occurred frequently during trials in which the subject attempted to recover lateral stability by stepping [29]. An ongoing study is examining the possibility that holding a cane may inhibit or impair ability to grab a more stable handhold when loss of balance occurs. These studies may ultimately lead to safer designs for mobility devices.

Conclusion

Compensatory stepping and grasping are critical reactions for preventing falls. These reactions are much more rapid than volitional limb movements and can be very effective in decelerating the COM motion induced by sudden unpredictable perturbation, despite environmental constraints on limb trajectory and additional demands imposed by ongoing physical or cognitive activity. However, even healthy older adults experience difficulty in controlling these reactions, and they appear to have particular problems in controlling lateral stability and lateral leg movement. These problems may be particularly relevant to the problem of hip fractures, which are most likely to occur as a result of a lateral fall. Older adults also appear to be more reliant on grasping reactions than young adults, but they are less able to execute these reactions rapidly. From a clinical perspective, it is important to assess compensatory stepping and grasping. Such tests could be used as a screening tool to identify high-risk individuals and could also serve to pinpoint specific control problems to target for balance training or other intervention. More effective use of stepping and grasping reactions can be promoted through improved design of footwear, mobility aids, handrails, and grab-bars.

Acknowledgments

Supported by grants from the Canadian Institutes of Health Research (CIHR), the Natural Sciences and Engineering Research Council, the Ontario Rehabilitation Technology Consortium, the Physician Services Foundation, and the National Institute on Aging (U.S.). B.E. Maki is a CIHR Senior Scientist, and W.E. McIlroy holds a Canada Research Chair in Neurorehabilitation. The authors gratefully acknowledge the following persons who have contributed to the studies described: H. Bateni, A. Cillis, Y-Y Chung, S. Colangelo, M.A. Edmondstone, M. Ghafouri, G. Griggs, E. Heung, P. Holliday, N. Kirshenbaum, J. Ma, A. Mihailidis, R. Norrie, M. Pacitto, S. Perry, S. Quant, R. Safaei, G. Shoham, B. Tripp, P. Wilcox, A. Zecevic, and J. Zettel.

Brian E. Maki received a B.A.Sc. in mechanical engineering from the University of British Columbia in 1979, an S.M.M.E. from the Massachusetts Institute of Technology in 1982, and a doctoral degree in bioengineering from the University of Strathclyde in 1987. He has worked at the Centre for Studies in Aging, Sunnybrook and Women's College Health Sciences Centre, in Toronto since 1982. He is currently a professor at the University of Toronto and a senior scientist at Sunnybrook and Women's and holds a senior scientist career award from the Canadian Institutes of Health Research. His primary research interests involve the biomechanics and neural control of human posture and movement, and his research has focused on the problem

of falling in older adults: understanding age-related deterioration in postural control, developing improved methods for assessing balance and predicting falling risk, and developing novel interventions to prevent falls and related injuries.

William E. McIlroy received a doctorate, with specialization in neurophysiology, from the University of Guelph in 1991. He is currently an associate professor in the Graduate Department of Rehabilitation Science and the Department of Physical Therapy, University of Toronto, and holds a Canada Research Chair in Neurorehabilitation. The focus of his work is directed toward developing innovative rehabilitative techniques to improve the mobility and upper limb function of persons who have suffered a stroke. An important objective of Dr. McIlroy's research is to translate basic science and clinical knowledge into post-stroke interventions that provide the best possible functional recovery. To meet this objective, his work ranges from basic fundamental research to clinical trials.

Geoff R. Fernie is a mechanical engineer with a doctorate in bioengineering from the University of Strathclyde. He is director of the Centre for Studies in Aging (CSiA) at Sunnybrook and Women's College Health Sciences Centre in Toronto and professor in the Department of Surgery at the University of Toronto with cross-appointments that include the Institute of Biomedical Engineering and the Departments of Mechanical Engineering, Physical Therapy, Occupational Therapy, Exercise Science, and Geriatric Medicine. Dr. Fernie's multidisciplinary CSiA team researches common problems of aging including mobility, falling, dementia, and environmental design. He also devotes much time to developing ways of transferring inventions efficiently from his research lab to the marketplace.

Address for Correspondence: B.E. Maki, Ph.D., P.Eng., Centre for Studies in Aging, Sunnybrook and Women's College Health Sciences Centre, 2075 Bayview Avenue, Toronto, Ontario, M4N 3M5 Canada. Tel: +1 416 480 6100, ext. 3513. Fax: +1 416 480 5856. E-mail: brian.maki@swchsc.on.ca.

References

[1] W.C. Hayes, E.R. Myers, S.N. Robinovitch, A. Van Den Kroonenberg, A.C. Courtney, and T.A. McMahon, "Etiology and prevention of age-related hip fractures," *Bone*, vol. 18, pp. 77S-86S, 1996.

[2] M.E. Tinetti and C.S. Williams, "Falls, injuries due to falls, and the risk of admission to a nursing home," *New Engl. J. Med.*, vol. 337, pp. 1279-1284, 1997.

[3] B.E. Maki and W.E. McIlroy, "Postural control in the older adult," *Clin. Geriatr. Med.*, vol. 12, pp. 635-658, 1996.

[4] B.E. Maki and W.E. McIlroy, "The role of limb movements in maintaining upright stance: the 'change-in-support' strategy," *Phys. Ther.*, vol. 77, pp. 488-507, 1997.

[5] B.E. Maki and W.E. McIlroy, "Control of compensatory stepping reactions: age-related impairment and the potential for remedial intervention," *Physiotherapy Theory and Practice*, vol. 15, pp. 69-90, 1999.

[6] B.E. Maki and W.E. McIlroy, "Effects of aging on control of stability," in *A Textbook of Audiological Medicine: Clinical Aspects of Hearing and Balance*, L. Luxon, A. Martini, J. Furman, and D. Stephens, Eds. London: Martin Dunitz Publishers, 2003, pp. 671-690.

[7] B.E. Maki, W.E. McIlroy, and S.D. Perry, "Influence of lateral destabilization on compensatory stepping responses," *J. Biomech.*, vol. 29, pp. 343-353, 1996.

[8] W.E. McIlroy and B.E. Maki, "The control of lateral stability during rapid stepping reactions evoked by antero-posterior perturbation: does anticipatory control play a role?," *Gait & Posture*, vol. 9, pp. 190-198, 1999.

[9] B. Tripp, W.E. McIlroy, and B.E. Maki, "On-line mutability of step direction during rapid stepping reactions evoked by postural perturbation," submitted for publication.

[10] A.L. Burleigh, F.B. Horak, and F. Malouin, "Modification of postural responses and step initiation: evidence for goal-directed postural interactions," *J. Neurophysiol.*, vol. 72, pp. 2892-2902, 1994.

[11] C.W. Luchies, N.B. Alexander, A.B. Schultz, and J. Ashton-Miller, "Stepping responses of young and old adults to postural disturbances: kinematics," *J. Amer. Geriatr. Soc.*, vol. 42, pp. 506-512, 1994.

[12] B.E. Maki and W.E. McIlroy, "The control of foot placement during compensatory stepping reactions: does speed of response take precedence over stability?," *IEEE Trans. Rehabil. Eng.*, vol. 7, pp. 80-90, 1999.

[13] Y.C. Pai, B.E. Maki, K. Iqbal, W.E. McIlroy, and S.D. Perry, "Thresholds for step initiation induced by support-surface translation: a dynamic center-of-mass model provides much better prediction than a static model," *J. Biomech.*, vol. 33, pp. 387-392, 2000.

[14] B.E. Maki, S.D. Perry, R.G. Norrie, and W.E. McIlroy, "Effect of facilitation of sensation from plantar foot-surface boundaries on postural stabilization in young and older adults," *J. Gerontol.*, vol. 54A, pp. M281-M287, 1999.

[15] E.T. Hsiao and S.N. Robinovitch, "Biomechanical influences on balance recovery by stepping," *J. Biomech.*, vol. 32, pp. 1099-1106, 1999.

[16] J.L. Zettel, W.E. McIlroy, and B.E. Maki, "Can stabilizing features of rapid triggered stepping reactions be modulated to meet environmental constraints?," *Exp. Brain Res.*, vol. 145, pp. 297-308, 2002.

[17] J.L. Zettel, W.E. McIlroy, and B.E. Maki, "Environmental constraints on foot trajectory reveal the capacity for modulation of anticipatory postural adjustments during rapid triggered stepping reactions," *Exp. Brain Res.*, vol. 146, pp. 38-47, 2002.

[18] M. Woollacott and A. Shumway-Cook, "Attention and the control of posture and gait: a review of an emerging area of research," *Gait & Posture*, vol. 16, pp. 1-14, 2002.

[19] R.G. Norrie, B.E. Maki, W.R. Staines, and W.E. McIlroy, "The time course of attention shifts following perturbation of upright stance," *Exp. Brain Res.*, vol. 146, pp. 315-321, 2002.

[20] B.E. Maki, R.G. Norrie, A. Zecevic, S. Quant, N. Kirshenbaum, H. Bateni, and W.E. McIlroy, "Initiation and execution of rapid postural reactions and stepping movements: which phases require visuospatial attention?," in *Control of Posture and Gait*, J. Duysens, B.C.M. Smits-Engelsman, and H. Kingma, Eds. Maastricht, The Netherlands: International Society for Postural and Gait Research, 2001, pp. 573-576.

[21] S. Quant, B.E. Maki, M.C. Verrier, and W.E. McIlroy, "Passive and active lower-limb movements delay upper-limb balance reactions," *NeuroReport*, vol. 12, pp. 2821-2825, 2001.

[22] W.E. McIlroy and B.E. Maki, "Age-related changes in compensatory stepping in response to unpredictable perturbations," *J. Gerontol.*, vol. 51A, pp. M289-M296, 1996.

[23] B.E. Maki, M.A. Edmondstone, and W.E. McIlroy, "Age-related differences in laterally directed compensatory stepping behavior," *J. Gerontol.*, vol. 55A, pp. M270-M277, 2000.

[24] B.E. Maki, M.A. Edmondstone, S.D. Perry, E. Heung, S. Quant, and W.E. McIlroy, "Control of rapid limb movements for balance recovery: do age-related changes predict falling risk?," in *Control of Posture and Gait*, J. Duysens, B.C.M. Smits-Engelsman, and H. Kingma, Eds. Maastricht, Netherlands: International Society for Postural and Gait Research, 2001, pp. 126-129.

[25] S.D. Perry, W.E. McIlroy, and B.E. Maki, "The role of cutaneous mechanoreceptors in the control of compensatory stepping reactions evoked by unpredictable, multi-directional perturbation," *Brain Research*, vol. 877, pp. 401-406, 2000.

[26] S.D. Perry, W.E. McIlroy, and B.E. Maki, "Does neural, musculoskeletal or sensory impairment predict compensatory stepping behavior in the older adult?," submitted for publication.

[27] B.E. Maki, A. Zecevic, H. Bateni, N. Kirshenbaum, and W.E. McIlroy, "Cognitive demands of executing rapid postural reactions: does aging impede attentional switching?," *NeuroReport*, vol. 12, pp. 3583-3587, 2001.

[28] B.E. Maki, S.D. Perry, and W.E. McIlroy, "Efficacy of handrails in preventing stairway falls: a new experimental approach.," *Safety Science*, vol. 28, pp. 189-206, 1998.

[29] H. Bateni, E. Heung, J.L. Zettel, W.E. McIlroy, and B.E. Maki, "Can use of walking frames or canes impede lateral compensatory stepping movements?," submitted for publication.