

# Control of rapid limb movements for balance recovery: age-related changes and implications for fall prevention\*

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## Abstract

**Background:** balancing reactions that involve rapid stepping or reaching movements are critical for preventing falls. These compensatory reactions are much more rapid than volitional limb movements and can be very effective in decelerating the centre-of-mass motion induced by sudden unpredictable balance perturbation; however, age-related deterioration in the neural, sensory and/or musculoskeletal systems may impede the ability to execute these reactions effectively.

**Objective:** this paper summarises recent research regarding age-related changes in compensatory stepping and reaching reactions and the practical implications of these findings for fall prevention programmes.

**Results:** even healthy older adults experience pronounced difficulties. For stepping reactions, the main problems pertain to control of lateral stability—arresting the lateral body motion that occurs during forward and backward steps, and controlling lateral foot movement so as to avoid collision with the stance limb during lateral steps. Older adults appear to be more reliant on arm reactions than young adults but are less able to execute reach-to-grasp reactions rapidly.

**Conclusions:** it is important for clinicians to assess compensatory stepping and reaching, in order to identify individuals who are at risk of falling and to pinpoint specific control problems to target for balance or strength training or other intervention. More effective use of stepping and reaching reactions can be promoted through improved design and appropriate use of sensory aids, mobility aids, footwear, handrails and grab-bars. It is particularly important to address the problems associated with the control of lateral stability because it is the lateral falls that are most likely to result in hip fracture.

**Keywords:** ageing, falls, postural balance, reachings, tepping

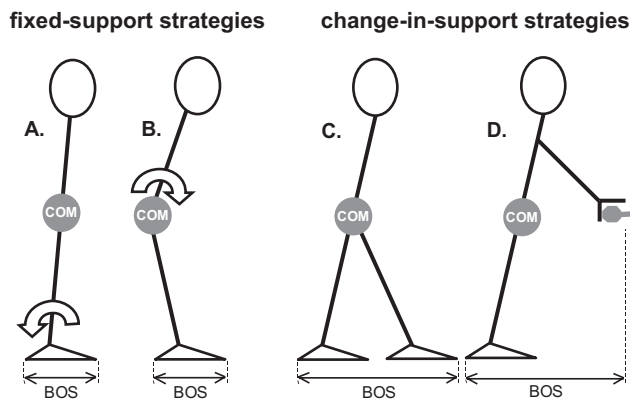
## Introduction

Although the causes of falling are varied and complex, a critical factor is the ability to respond effectively to ‘loss of balance’, i.e. balance perturbation [1]. In the course of our daily activities, we all experience countless perturbations, e.g. we slip, we trip and we bump into things. In fact, every time we move volitionally, we perturb our balance. The key factor that ultimately determines whether or not a balance perturbation leads to a fall is our ability, or inability, to recover balance. In the simplest terms, recovering balance means keeping the centre of mass of the body over the base of support (Figure 1). We can slow down the centre-of-mass

motion, to some extent, by rapidly generating muscle torque at the ankles, hips or other joints. However, if we are on the verge of falling, then it may become necessary to actually change our base of support, either by rapidly taking a step or by rapidly reaching and grasping or touching an object for support. Biomechanically, these ‘change-in-support’ reactions can provide a much larger degree of stabilisation, compared with ‘fixed-support’ reactions where the base of support does not change [2, 3]. Because of these biomechanical advantages, compensatory stepping and reaching play a vital functional role in preventing falls. They are the only recourse in responding to large perturbations, but they are also prevalent even when the perturbation is small [2, 4].

Change-in-support reactions are initiated and executed very rapidly, much more so than even our fastest efforts to move the feet or arms volitionally [2, 5, 6], yet the control is remarkably sophisticated.

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**Figure 1.** Balance-recovery reactions: fixed support (**A** and **B**) versus change in support (**C** and **D**). Static equilibrium requires the body centre of mass (COM) to be positioned over the base of support (BOS). In fixed-support reactions, perturbation-induced COM motion is arrested by muscle torques. For anteroposterior perturbations, the stabilising torque is generated predominantly via an ‘ankle strategy’ (**A**), although generation of hip torque (**B**) may also be involved. For mediolateral perturbations (not shown), hip torque predominates. In change-in-support reactions, the dramatic increase in the BOS due to stepping (**C**) or reaching and touching/grasping an object for support (**D**) allows a much larger range of COM motion to be accommodated and arrested, as illustrated here for forward falling motion (the same principles apply for falling motion in other directions). If the supporting object can be grasped with sufficient grip strength, then the reaching reaction has the additional advantage of anchoring the body with respect to the environment.

In contrast to volitional movement, where there is the opportunity to pre-plan the movement, successful execution of these compensatory reactions must take into account the unpredictable body motion suddenly induced by the perturbation, as well as the constraints on limb movement imposed by the environment, e.g. the location of handrails or other objects to grasp and the location of obstacles [7–10]. The capacity, in daily life, to detect onset of instability and to rapidly plan and execute an effective stepping or reaching reaction may be further complicated by effects of ongoing physical or cognitive activity [11–15].

Older adults may be at increased risk of falling if they are unable to meet these various demands for executing effective change-in-support reactions, as a consequence of age-related deterioration in the neural, sensory and/or musculoskeletal systems [1–3].

## Effects of ageing

### Age-related changes in stepping reactions

Studies of responses evoked by anteroposterior perturbation have shown that older adults tend to initiate stepping at lower levels of instability than young adults [16, 17] but often appear to experience difficulty in executing an effective

stepping reaction, as evidenced by a much greater tendency to take multiple steps [18–20], initiate arm reactions [20] or fail to recover equilibrium [21]. The difficulties appear to be even more pronounced in individuals having a history of falling [18, 22]. Although the use of multiple steps can be a pre-planned strategy in some situations [19], it appears that the later steps often emerge as a consequence of instability arising after the initiation of the first step [20]. Findings that the timing and scaling of the initial step are often very similar in young and older adults [20, 23, 24] support the view that the difficulties are primarily associated with control of the swing phase and/or landing, rather than step initiation.

Impaired ability to control the tendency of the centre of mass to fall laterally towards the unsupported side during step execution appears to be a particular problem. In one study [20], over 30% of the initial forward or backward stepping reactions in older adults were followed by steps that were directed so as to recover lateral stability, a tendency that was rarely seen in young adults (Table 1). Findings that older subjects with a history of falling tended to include lateral foot movement in the initial step of the reaction, when responding to forward instability [25], would also appear to indicate difficulty in controlling lateral stability during anteroposterior step execution. A prospective study found that the tendency to take multiple steps to recover balance was predictive of increased risk of experiencing forward or backward falls in daily life and that the tendency to follow an initial forward or backward step with a lateral step predicted an increased risk of falling laterally [26].

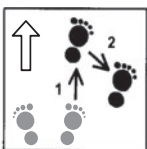
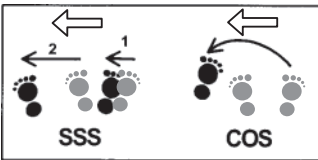
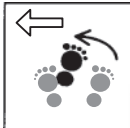
For responses to lateral perturbation, similar trends occur: older adults are more likely than the young to step and are also more likely to take multiple steps or use arm reactions to regain equilibrium [27].

In addition, there are age-related differences in the pattern of stepping. One common pattern in young adults involves a single large ‘crossover’ step with the leg that is unloaded by the lateral perturbation-induced centre-of-mass motion (see Table 1). This requires accurate control of the foot trajectory (i.e. to move the foot across the body while avoiding contact with the stance limb) and an ability to sustain a prolonged interval of single-leg support. Older persons often select a less demanding pattern of response comprising a small medial step with the unloaded leg followed by a large lateral step with the other leg [27]. Regardless of the stepping pattern, older adults are much more likely than the young to experience collisions between the swing foot and stance limb (particularly when walking ‘in place’ prior to perturbation) [27, 28], and increased tendency to sustain limb collisions is predictive of an increased risk of falling in daily life [26].

### Age-related changes in reaching reactions

To date, only a small number of studies have examined age-related changes in postural arm reactions. In one series of platform-perturbation studies, older adults were found to be more likely than the young to initiate arm movement and to grasp safety rails for support [20, 27], yet the speed at which they could initiate and execute reach-to-grasp movements was slower [26]. Increased dependence on arm

**Table I.** Features of compensatory stepping and reaching reactions related to ageing and increased falling risk (summary of results from [20,26,27])

Feature of the reaction	Significant association with	
	Ageing <sup>a</sup>	Falling risk <sup>b</sup>
Stepping reactions		
Takes one or more additional steps after the initial stepping reaction	Yes	Yes (a-p falls)
Follows a forward or backward stepping reaction with one or more lateral steps	Yes	Yes (m-l falls)
		
Tends to use a side-step sequence (SSS), rather than a crossover step (COS) during lateral stepping reactions	Yes	No
		
Sustains limb collisions during lateral stepping reactions (during stance but particularly when walking in-place)	Yes	Yes (a-p falls)
		
Reaching reactions		
Initiates arm movements despite instructions not to move the arms	Yes	Yes (a-p falls)
Slowed initiation and execution of reach-to-grasp movements <sup>c</sup>	Yes	Yes (all falls)

<sup>a</sup>Age-related association: significant difference ( $P < 0.05$ ) between cohorts of healthy young adults (aged 20–30 years) and healthy community-dwelling older adults (aged 65–75 years) [20,26,27].

<sup>b</sup>Association with falling risk: significant association ( $P < 0.05$ ) with risk of experiencing one or more falls (during a 1-year prospective follow-up) in the anteroposterior (a-p) direction, mediolateral (m-l) direction or in any direction, within a cohort of healthy community-dwelling older adults (aged 65–75 years) [26].

<sup>c</sup>All measures other than reach-to-grasp reaction speed can be assessed by direct observation or video recording, i.e. no instrumentation is required.

reactions and slowing of these reactions were both found to predict an increased risk of experiencing falls in daily life [26]. In another study, which involved lateral platform-tilt perturbations, arm reactions in older adults were delayed, reduced in amplitude and opposite in direction, in comparison with younger subjects [29]. The older subjects moved the arms in the direction of the fall, which the authors interpreted as a protective response serving either to cushion the impact of the fall or to reach towards a safety handrail.

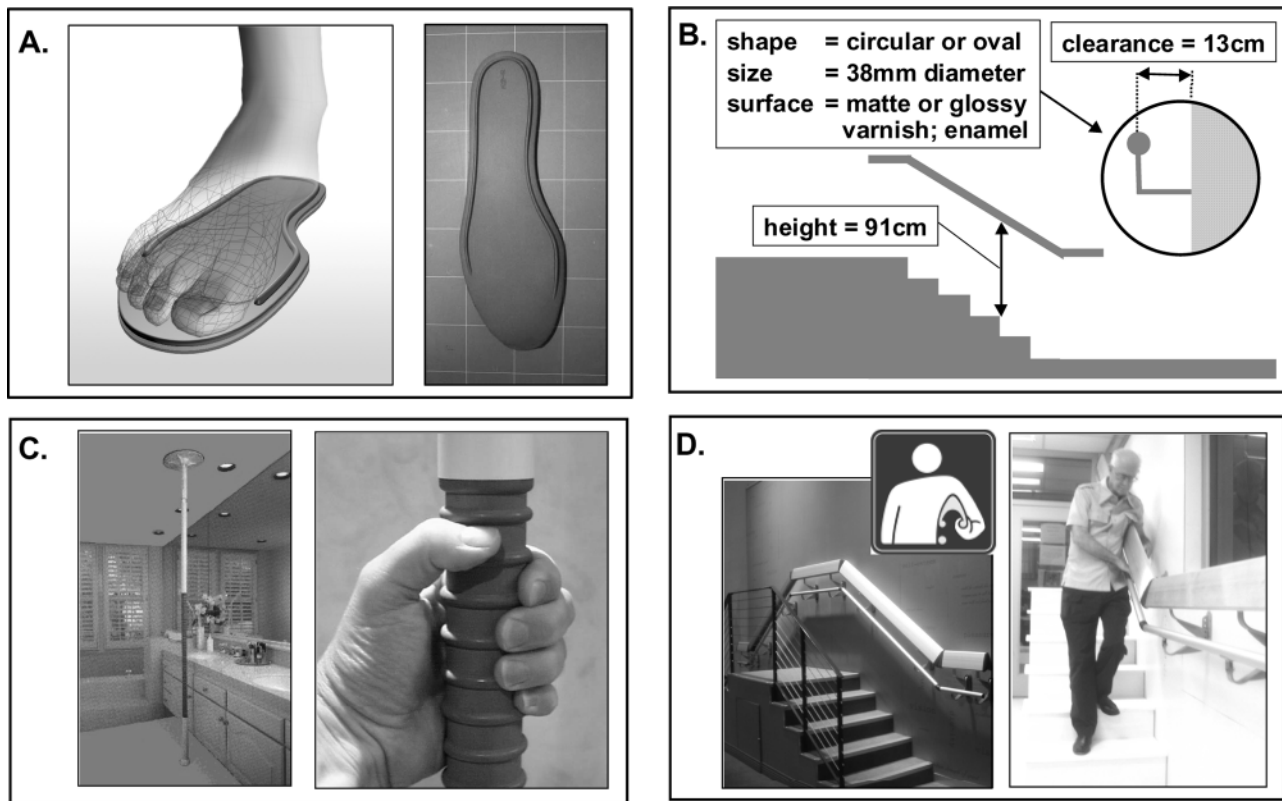
**Mechanisms**

The age-related changes in stepping and reaching reactions described above could potentially be a consequence of decrements in musculoskeletal capacity, sensory function and/or neural processing. To date, supporting evidence has been limited to stepping reactions. With regard to musculoskeletal function, one study showed that the flexion–extension joint torques (as well as range of joint motion) required to initiate rapid compensatory steps were well within the capabilities of healthy older adults [19]. However, decreased strength has been shown to be associated with the tendency to take multiple steps to recover balance [1], and it appears that the torque demands in certain muscles (e.g. hip abductors, hip flexors and knee extensors) during later phases of the step can actually exceed the strength limits measured in older adults [3]. These findings raise the possibility that age-

related strength loss in certain muscles may, in some older individuals, contribute to difficulty in controlling stability during the swing phase and landing. Particularly important is the profound weakening of the hip abductors and adductors that has been observed in older adults, which is likely to compromise the capacity to maintain lateral stability during stepping [28].

Rate of muscle-force production may also be an important limiting factor. Although it appears that healthy older adults are well able to generate rapid anteroposterior stepping movements in responding to moderate levels of perturbation [20, 23], they seem to be unable to generate the faster movements that are required to deal with very severe postural challenge [23]. Age-related slowing of neural processing could also limit the capacity to generate rapid and effective change-in-support responses, as could age-related changes in ‘attentional dynamics’ (i.e. delays in switching of attention and reallocation of cognitive resources from an ongoing motor or cognitive task to the task of controlling the balancing reaction) [30].

With regard to sensory function, it appears quite likely that loss of cutaneous sensation from the foot sole, a very common occurrence in older adults, is an important factor contributing to impaired control of compensatory stepping [31]. In support of this, mechanical facilitation of sensation from the boundaries of the plantar foot surface (Figure 2a)



**Figure 2.** Examples of new interventions and information for fall prevention, arising from research by Fernie, Maki, McIlroy, Perry and colleagues [8, 32, 33, 35]: **(A)** SoleSensor footwear insole (note the compliant elastomeric ridge located around the perimeter of the insole which provides increased cutaneous stimulation when loss of balance is imminent, i.e. as the body centre of mass approaches the limits of the base of support); **(B)** summary of recommendations for handrail design (to optimise the ability of a wide range of users to generate stabilising force and to reach and grasp the rail effectively); **(C)** SturdyGrip™ safety pole (note the contoured surface to prevent hand slippage; an internal spring holds the pole in place, allowing it to be easily installed or removed without the need to drill holes in the ceiling and floor) and **(D)** LifeRail handrail system (the rail is hugged under the arm in the manner of a crutch, which allows large reaction forces to be generated even if the user has poor hand strength; the higher height, in comparison with a conventional rail, enhances the ability to generate larger moments to help stabilise the body and to aid in stair climbing; note that a conventional rail is also provided, for users who prefer to grasp the rail with the hand). SoleSensor and SturdyGrip have both been patented, and a patent is pending for LifeRail. SturdyGrip is commercially available and SoleSensor is scheduled for commercial release in 2007. LifeRail is not yet ready for commercial release. A clinical trial of SoleSensor has recently been completed.

was found to decrease the frequency of multiple-step reactions, during forward ‘falls’, in older adults having moderate levels of cutaneous insensitivity [32]. Conversely, in young adults, attenuation of plantar sensation (via hypothermic anaesthesia) led to an increased frequency of multiple-step reactions [33]. The observed effects of cutaneous facilitation/attenuation on control of forward stepping appear to be related to the ability to sense and control heel contact and subsequent weight transfer during step termination [3]. Other apparent contributions of the cutaneous receptors, in sensing the posterior stability limits and in maintaining stability during the prolonged swing phase of lateral crossover steps [32, 33], may tie in with other age-related changes in stepping, i.e. loss of sensation may contribute to the increased tendency to step in response to backward instability and to avoid the use of crossover steps.

## Clinical implications

### Clinical assessment of stepping and reaching reactions

Evidence of differences in the neural control of volitional and compensatory limb movement would imply that it is necessary to apply controlled postural perturbations during clinical assessment of change-in-support reactions. Testing of volitional stepping may, for example, give misleading information by indicating that older adults initiate stepping more slowly than the young, whereas perturbation tests indicate that the young and old are equally fast [24]. Conversely, a volitional test may fail to reveal the problems that older adults experience in controlling lateral stability during anteroposterior compensatory stepping, because the large

anticipatory postural adjustments that preserve lateral stability during volitional stepping are typically absent or severely truncated when stepping to recover balance [34]. Nonetheless, testing of volitional movement may have some value. For example, a reduced speed of initiating and executing reach-to-grasp movements was found to be predictive of falling risk regardless of whether the arm movement was volitional or evoked by perturbation [26].

The most widely used perturbation method involves platform motion. Unfortunately, the platforms that have been available commercially tend to be expensive. Moreover, they typically have insufficient surface area to permit assessment of stepping or reaching reactions. It is possible to apply perturbations using other methods; however, there are potential problems. Manual perturbation (e.g. sternal nudge or shoulder pull) would, of course, be the simplest approach but can be difficult to administer in a repeatable fashion or in such a way as to evoke an interpretable stepping or reaching reaction. More controlled approaches involve sudden release of a cable supporting the subject in a leaning posture [23, 31], or using weights and pulleys or an electric motor to pull on a cable attached to the subject's pelvis [18, 19, 22, 28].

Potential concerns with these approaches include the predictability of the perturbation direction and the potential constraints on movement due to the attachments to the subject, although it is possible to design the systems to avoid these problems [24]. Unpredictability of the perturbation is a critical requirement that is necessary to simulate the unpredictable nature of the events that commonly precipitate loss of balance in daily life and to prevent the central nervous system (CNS) from learning to respond in a predictive manner. Other key requirements for developing a clinical testing protocol are listed in Table 2. Fortunately, it appears that expensive instrumentation is not required to assess performance. Table 1 lists a number of simple behavioural measures (which could be derived from video recordings, or even direct observation) that may be useful in identifying individuals who are at increased risk of falling

and in detecting specific control problems that can be targeted for intervention.

**Interventions to improve control of stepping and reaching reactions**

Potential interventions to counter age-related impairment of change-in-support reactions include sensory and mobility aids, footwear, handrails and grab-bars, and strength and balance training. In addition, there is the potential to reduce possible problems due to side-effects of medications, through the adjustment of dosages, elimination of unnecessary drugs and substitution of drugs that have fewer CNS side-effects.

Sensory aids that help to compensate for age-related sensory loss could potentially improve ability to recover balance by stepping or reaching by providing enhanced: (i) detection of instability, (ii) feedback about the limb and body movement and/or (iii) information about the location of obstacles and potential handholds in the surrounding environment. The latter factor can potentially be addressed through correction of undetected or poorly corrected visual impairment (via refractive lenses, medication or surgery), avoidance of multifocal lenses, and increase in lighting level or reduction of glare. One possible way to enhance instability detection and movement feedback is to use footwear as a sensory aid, so as to provide heightened stimulation of cutaneous receptors in the foot sole (Figure 2a) [32]. Conversely, although effects on stepping reactions have not yet been studied directly, it seems likely that overly cushioned shoes can adversely affect balance control by masking accurate pressure sensation.

Although mobility aids, such as walkers and canes, are widely used to improve ability to move about safely, it appears that these devices may actually increase risk of falling in certain situations. Recent studies have shown that walkers can impede the ability to recover balance by stepping laterally [9] and that holding a cane (or any object) may inhibit the natural tendency to grasp more stable objects (such as handrails) for support [15]. We are currently performing studies aimed at developing safer and more effective walker designs. Improved guidelines for the prescription

**Table 2.** Recommendations (by the authors) for clinical assessment of compensatory stepping and reaching reactions

Test feature	Recommendation
1. Postural perturbation	Safe and well-controlled (repeatable) perturbation method (e.g. motion platform, tethered lean + cable release, cable pull) Perturbations must be unpredictable in timing, duration, direction and/or magnitude Not sufficient to assess volitional limb movement alone
2. Task conditions	Include trials involving Ongoing movement (e.g. walking in place, turning, bending) Ongoing cognitive activity (e.g. count backward by 3 s) Vary environmental constraints Location of potential handholds to touch or grasp Location of obstacles that impede foot or hand movement
3. Instructional set	Include trials (particularly at the start of the session) to assess natural behaviour (subjects instructed to 'do whatever comes naturally to prevent falling') Include trials where subject is instructed to try not to move the arms (to assess dependence on arm reactions) Include trials where subject is instructed to grasp a handhold as quickly as possible (to assess speed of arm reactions)
4. Measurements	Simple behavioural measures can be determined from video recordings or direct observation (see Table 1) Measurement of speed of reach-to-grasp reactions requires instrumentation to determine timing relative to perturbation onset (e.g. arm-motion sensor, contact switches on handrail)

and safe use of mobility aids may be another practical outcome of this line of research.

More effective use of reach-to-grasp reactions can be promoted by improved design of handrails and grab-bars. We have performed a series of studies to examine the effect of the handrail design (height, shape, size, etc.) on the ability to: (i) generate stabilising forces and moments (when pushing and pulling on the rail) and (ii) reach and grasp the rail (to recover balance) [35]. On the basis of these studies, we recommend a handrail that is considerably higher than many previously existing building standards (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) (Figure 2b). Spin-offs of this research include the development of a graspable vertical-pole system that can be easily installed (without tools) wherever needed (Figure 2c) and a novel stairway handrail that is positioned and shaped so it can be ‘grasped’ in the manner of an underarm crutch (Figure 2d). The latter may be particularly useful for persons with poor hand strength.

Finally, there is the possibility of using strength or balance training to improve control of stepping and reaching reactions. The findings, described earlier, that substantial levels of force, or rate of force generation, may be required in certain muscle groups (e.g. hip abductors) would suggest that strength training could be of benefit in weaker individuals, whereas balance training could potentially help to overcome effects of sensorimotor deficits. In view of evidence that some of the neural substrates associated with compensatory and volitional limb movements may differ [2, 3, 6, 24, 34], it is likely that effective training of the balancing reactions will require use of perturbations. We are currently performing a study to examine this issue, by comparing training of volitional stepping and reaching movements versus use of platform perturbations to evoke the limb movements. Rogers *et al.* [36] performed a similar study but focused on a volitional-stepping outcome measure and did not attempt to train upper-limb reactions. Other studies that have attempted to train stepping or reaching have focused entirely on volitional movement. Findings described earlier suggest that the aspects of stepping reactions that are most likely to require training include control of lateral stability (during forward and backward stepping) and control of lateral limb movement (during lateral stepping). These aspects of stepping appear to create the greatest difficulty for many older adults and are particularly relevant to the problem of hip fractures, which are most likely to occur during lateral falls. Results to date from upper-limb studies suggest that the speed of the reaching reaction may need to be targeted.

### Key points

- Balancing reactions that involve rapid stepping or reaching movements are critical for preventing falls, yet even healthy older adults experience difficulties in executing these reactions effectively.

- Older adults often have difficulty in controlling lateral stability during stepping reactions, which may increase the risk of falling laterally and sustaining a hip fracture.
- Older adults appear to be more reliant on arm reactions than young adults but are less able to execute reach-to-grasp reactions rapidly.
- Clinicians need to assess compensatory stepping and reaching reactions in order to identify high-risk individuals and to pinpoint specific control problems to target for intervention.
- Potential approaches to promote more effective use of stepping and reaching reactions include balance and strength training, and more effective design and appropriate use of sensory aids, mobility aids, footwear, handrails and grab-bars.

### Conflicts of interest declaration

Royalties or licensing fees associated with the three products mentioned in this article (SoleSensor, LifeRail and SturdyGrip) may be used to support the authors’ research.

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### References

1. Maki BE, McIlroy WE. Effects of aging on control of stability. In: Luxon L, Martini A, Furman J, Stephens D, eds. *A Textbook of Audiological Medicine: Clinical Aspects of Hearing and Balance*. London: Martin Dunitz Publishers, 2003; 671–90.
2. Maki BE, McIlroy WE. The role of limb movements in maintaining upright stance: the “change-in-support” strategy. *Phys Ther* 1997; 77: 488–507.
3. Maki BE, McIlroy WE. Control of compensatory stepping reactions: age-related impairment and the potential for remedial intervention. *Physiotherapy Theory Pract* 1999; 15: 69–90.
4. Rogers MW, Hain TC, Hanke TA, Janssen I. Stimulus parameters and inertial load: effects on the incidence of protective stepping responses in healthy human subjects. *Arch Phys Med Rehabil* 1996; 77: 363–8.
5. Burleigh AL, Horak FB, Malouin F. Modification of postural responses and step initiation: evidence for goal-directed postural interactions. *J Neurophysiol* 1994; 72: 2892–902.
6. McIlroy WE, Maki BE. Influence of destabilization on the temporal characteristics of ‘volitional’ stepping. *J Motor Behav* 1996; 28: 28–34.
7. Zettel JL, McIlroy WE, Maki BE. Environmental constraints on foot trajectory reveal the capacity for modulation of anticipatory postural adjustments during rapid triggered stepping reactions. *Exp Brain Res* 2002; 146: 38–47.
8. Maki BE, McIlroy WE, Fernie GR. Change-in-support reactions for balance recovery: control mechanisms, age-related changes and implications for fall prevention. *IEEE Eng Med Biol Mag* 2003; 22: 20–6.
9. Bateni H, Heung E, Zettel JL, McIlroy WE, Maki BE. Can use of walking frames or canes impede lateral compensatory stepping movements? *Gait Posture* 2004; 20: 74–83.

10. Ghafouri M, McIlroy WE, Maki BE. Initiation of rapid reach-and-grasp balance reactions: is a pre-formed visuospatial map used in controlling the initial arm trajectory? *Exp Brain Res* 2004; 155: 532–6.
11. Brown LA, Shumway-Cook A, Woollacott MH. Attentional demands and postural recovery. the effects of aging. *J Gerontol* 1999; 54A: M165–71.
12. Maki BE, Norrie RG, Zecevic A *et al.* Initiation and execution of rapid postural reactions and stepping movements: which phases require visuospatial attention? In: Duysens J, Smits-Engelsman BCM, Kingma H, eds. *Control of Posture and Gait*. Maastricht, Netherlands: International Society for Postural and Gait Research, 2001; 573–6.
13. Quant S, Maki BE, Verrier MC, McIlroy WE. Passive and active lower-limb movements delay upper-limb balance reactions. *NeuroReport* 2001; 12: 2821–5.
14. Brauer SG, Woollacott M, Shumway-Cook A. The influence of a concurrent cognitive task on the compensatory stepping response to a perturbation in balance-impaired and healthy elders. *Gait Posture* 2002; 15: 83–93.
15. Bateni H, Zecevic A, McIlroy WE, Maki BE. Resolving conflicts in task demands during balance recovery: does holding an object inhibit compensatory grasping? *Exp Brain Res* 2004; 157: 49–58.
16. Jensen JL, Brown LA, Woollacott MH. Compensatory stepping: the biomechanics of a preferred response among older adults. *Exp Ageing Res* 2001; 27: 361–76.
17. Mille ML, Rogers MW, Martinez K *et al.* Thresholds for inducing protective stepping responses to external perturbations of human standing. *J Neurophysiol* 2003; 90: 666–74.
18. Wolfson LI, Whipple R, Amerman P, Kleinberg A. Stressing the postural response: a quantitative method for testing balance. *J Am Geriatr Soc* 1986; 34: 845–50.
19. Luchies CW, Alexander NB, Schultz AB, Ashton-Miller J. Stepping responses of young and old adults to postural disturbances: kinematics. *J Am Geriatr Soc* 1994; 42: 506–12.
20. McIlroy WE, Maki BE. Age-related changes in compensatory stepping in response to unpredictable perturbations. *J Gerontol* 1996; 51A: M289–96.
21. Pavol MJ, Runtz EF, Edwards BJ, Pai YC. Age influences the outcome of a slipping perturbation during initial but not repeated exposures. *J Gerontol* 2002; 57: M496–503.
22. Chandler JM, Duncan PW, Studenski SA. Balance performance on the postural stress test: comparison of young adults, healthy elderly, and fallers. *Phys Ther* 1990; 70: 410–5.
23. Thelen DG, Wojcik LA, Schultz AB, Ashton-Miller JA, Alexander NB. Age differences in using a rapid step to regain balance during a forward fall. *J Gerontol* 1997; 52A: M8–13.
24. Luchies CW, Wallace D, Pazdur R, Young S, DeYoung AJ. Effects of age on balance assessment using voluntary and involuntary step tasks. *J Gerontol* 1999; 54: M140–4.
25. Rogers MW, Hedman LD, Johnson ME, Cain TD, Hanke TA. Lateral stability during forward-induced stepping for dynamic balance recovery in young and older adults. *J Gerontol* 2001; 56: M589–94.
26. Maki BE, Edmondstone MA, Perry SD, Heung E, Quant S, McIlroy WE. Control of rapid limb movements for balance recovery: do age-related changes predict falling risk? In: Duysens J, Smits-Engelsman BCM, Kingma H, eds. *Control of Posture and Gait*. Maastricht, Netherlands: International Society for Postural and Gait Research, 2001; 126–9.
27. Maki BE, Edmondstone MA, McIlroy WE. Age-related differences in laterally directed compensatory stepping behavior. *J Gerontol* 2000; 55A: M270–77.
28. Rogers MW, Mille ML. Lateral stability and falls in older people. *Exerc Sport Sci Rev* 2003; 31: 182–7.
29. Allum JHJ, Carpenter MG, Honegger F, Adkin AL, Bloem BR. Age-dependent variations in the directional sensitivity of balance corrections and compensatory arm movements in man. *J Physiol London* 2002; 542: 643–63.
30. Maki BE, Zecevic A, Bateni H, Kirshenbaum N, McIlroy WE. Cognitive demands of executing rapid postural reactions: does aging impede attentional switching? *NeuroReport* 2001; 12: 3583–7.
31. Do MC, Bussel B, Breniere Y. Influence of plantar cutaneous afferents on early compensatory reactions to forward fall. *Exp Brain Res* 1990; 79: 319–24.
32. Maki BE, Perry SD, Norrie RG, McIlroy WE. Effect of facilitation of sensation from plantar foot-surface boundaries on postural stabilisation in young and older adults. *J Gerontol* 1999; 54A: M281–7.
33. Perry SD, McIlroy WE, Maki BE. The role of cutaneous mechanoreceptors in the control of compensatory stepping reactions evoked by unpredictable, multi-directional perturbation. *Brain Res* 2000; 877: 401–6.
34. McIlroy WE, Maki BE. The control of lateral stability during rapid stepping reactions evoked by anteroposterior perturbation: does anticipatory control play a role? *Gait Posture* 1999; 9: 190–8.
35. Maki BE, Perry SD, McIlroy WE. Efficacy of handrails in preventing stairway falls: a new experimental approach. *Safety Sci* 1998; 28: 189–206.
36. Rogers MW, Johnson ME, Martinez KM, Mille ML, Hedman LD. Step training improves the speed of voluntary step initiation in aging. *J Gerontol* 2003; 58A: M46–51.