The Role of Limb Movements in Maintaining Upright Stance: The "Change-in-Support" Strategy

Change-in-support strategies, involving stepping or grasping movements of the limbs, are prevalent reactions to instability and appear to play a more important functional role in maintaining upright stance than has generally been appreciated. Contrary to traditional views, change-in-support reactions are not just strategies of last resort, but are often initiated well before the center of mass is near the stability limits of the base of support. Furthermore, it appears that subjects, when given the option, will select these reactions in preference to the fixed-support "hip strategy" that has been purported to be of functional importance. The rapid speed of compensatory change-in-support reactions distinguishes them from "volitional" arm and leg movements. In addition, compensatory stepping reactions often lack the anticipatory control elements that are invariably present in non-compensatory stepping, such as gait initiation. Even when present, these anticipatory adjustments appear to have little functional value during rapid compensatory movements. Lateral destabilization complicates the control of compensatory stepping, a finding that may be particularly relevant to the problem of falls and hip fractures in elderly people. Older adults appear to have problems in controlling lateral stability when stepping to recover balance, even when responding to anteroposterior perturbation. Increased understanding and awareness of change-in-support reactions should lead to development of new diagnostic and therapeutic approaches for detecting and treating specific causes of imbalance and falling in elderly people and in patients with balance impairments. [Maki BE, McIlroy WE. The role of limb movements in maintaining upright stance: the "change-in-support" strategy. Phys Ther. 1997;77:488–507.]

**Key Words:** Balance, Grasping, Postural control, Stepping.

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The age-related or pathologic changes within the neuromusculoskeletal system can lead to balance impairments that can have a tremendous impact on health care costs and quality of life. Hip fractures and other acute injuries that result from falls in elderly people, as well as the fear of falling, loss of independence, and other psychosocial consequences of falls, constitute a major health care problem. Similarly, difficulty in controlling balance and movement can be a consequence of vestibular disorders or neurologic lesions due, for example, to Parkinson's disease or stroke.

Identifying causes of instability and developing improved methods for diagnosing and treating individuals with compromised balance can provide an important opportunity to reduce health care costs and improve independence and quality of life.

Maintenance of upright stance requires the center of mass (COM) of the body to be positioned over the base of support (BOS). The body is inherently unstable, however, due to the force of gravity, and additional destabilizing forces arise due to movement of the body and interaction with the environment. The ability to regulate the relationship between the COM and BOS during activities of daily life results from a combination of reactive (compensatory) and predictive (anticipatory) balance control strategies. Whereas predictive control can serve to minimize the destabilizing effect of predictable disturbances due, for example, to volitional movement, reactive control is the only recourse in the event of unexpected perturbation; hence, reactive control is likely to be of paramount importance in allowing stability to be maintained in the unpredictable circumstances of daily life.

There appear to be two distinct classes of strategies for reactive balance recovery, which we refer to as (1) "fixed-support" strategies and (2) "change-in-support" strategies. These two classes of strategies are distinguished by the absence or presence of limb movement to alter the BOS. The vast majority of studies have focused on the fixed-support strategies, which reflect the ability to control the movement of the COM over an unchanging BOS defined by the feet (and, in some instances, by the hands). In these studies, movement of the arms or legs has usually been restrained either explicitly (eg, by instruction) or implicitly (eg, by lack of space to step or handholds to grasp). In contrast, the more recent work that is the subject of this article has featured the change-in-support strategy, highlighted by movements of the lower or upper limbs to make new contact with support surfaces. Figure 1 presents examples of fixed-support and change-in-support balance recovery strategies.

Until recently, it was widely believed that the change-in-support strategies were only mechanisms of last resort (eg, reports that stepping occurs when fixed-support strategies have failed). Change-in-support strategies actually appear to be very prevalent and can occur very rapidly after the onset of postural disturbances. Experimentally, these compensatory limb movements have been shown to be common reactions to externally applied postural perturbation, even when the distur-
Although with very common reactions without loss of stability can be increased dramatically. Maki and
Second, in increasing the "moment arm" between the balance
abilities are small and stability could have been main-
tained without moving the arms or legs. Furthermore, outside of the laboratory, video surveillance
studies of falling incidents in geriatric health care facil-
ities have shown that compensatory limb movements are
very common reactions to loss of balance in daily life,
with compensatory stepping evident in 32% to 45% of
falls or near-falls and arm movements evident in 65% to
72% of these incidents.14,15

Although change-in-support reactions can, and do,
occurs even when disturbances are small, they are the
only reactions that can successfully be used to maintain
balance in the face of large perturbations. Fixed-support
reactions may be important in providing an early
defense against loss of balance; however, change-in-
support reactions ultimately have, in at least two ways,
the potential to make a much larger contribution to
stabilization. First, in increasing the size of the BOS, the
range of COM displacement that can be accommodated
without loss of stability can be increased dramatically.
Second, in increasing the "moment arm" between the
point of action of the foot- or hand-contact force and the
COM, the stabilizing moments induced by the contact
force, which act to decelerate the COM, can be greatly
amplified. Ability to decelerate the COM may be further
enhanced by the fact that grasping reactions can serve to
"anchor" the body relative to the location of the
handhold.

If, as it appears, change-in-support reactions are funda-
mental to the control of balance and prevention of falls,
then it is imperative to understand how the central
nerveous system (CNS) controls these reac-
tions. Critical aspects include the spatial char-
acteristics of the response (limb trajectory) and the
timing of response initiation and execution (latency and speed), both of which
must be matched to the ongoing motion of the
COM and the active attempts to control
this motion. Inaccurate or inappropriately
timed limb movements may fail to "capture" and
decelerate the COM and may even act to
induce destabilizing forces and moments. In
view of the potential implications for func-
tional stability and risk of falling, it is impor-
tant to understand the mechanisms by which
the CNS is able to rapidly transform sensed
instability into limb movements that are
appropriately patterned and timed and to
determine the effects of pathology, injury,
and aging on the control of this process.
We anticipate that such understanding will
lead to the development of new diagnostic
and therapeutic approaches for detecting and
addressing specific causes of imbalance and
falling.

In the remainder of this article, we summarize the
current state of knowledge with regard to the change-in-
support strategies. We focus first on compensatory stepping
reactions, highlighting the key characteristics: prevalence, early initiation and rapid execution, absence of
functional anticipatory control, adaptive changes that
can occur, and effects of lateral destabilization. This
section concludes with a discussion of control mecha-
nisms. The second section, which deals with grasping
reactions, describes the similarities and differences that
arise when the upper limb rather than the lower limb is
used to change the base of support and examines the
influence of specific task conditions (ie, sitting versus
standing, light cue versus perturbation). In the third
section, we examine the interactions between fixed-
support and change-in-support reactions, highlighting
the evidence for parallel, rather than sequential, control
of the two types of reactions, the persistence of the early
fixed-support "ankle strategy," and the predominance of
the change-in-support reaction with respect to the fixed-
support "hip strategy." In the final section, we summa-
rize existing knowledge concerning the effects of aging
and pathology on the change-in-support reactions.
evoked by postural perturbation (see “Speed of Response” and “Anticipatory Control” sections for details).

Studies of compensatory stepping reactions are now becoming increasingly common, although almost all of these studies have examined only forward or backward responses. In several studies,28–32 forward stepping has been evoked by suddenly releasing a cable that was supporting the subject in a forward-lean position. Forward or backward stepping has also been evoked by pulling on a cable attached to the subject’s waist, by means of a motor-driven device,33 or by dropping weights attached to the cable via pulleys.34–37 Another approach, one that we have adopted, is to perturb balance by horizontally accelerating a platform on which the subject stands (McIlroy and Maki, unpublished research).10–13,38–46 This latter approach has the advantage of allowing the direction of perturbation to be varied in an unpredictable manner (including, in the case of multiaxis platforms, multiple planes of motion), while avoiding potential constraints on movement due to attachments to the subject. The main disadvantage of the moving-platform approach is the cost and complexity of the equipment. Some authors have also questioned the “ecologic validity” of support-surface perturbations, suggesting that the perturbations are relatively uncommon in daily life; however, the extent to which any perturbation method generalizes to control of functional stability in daily life has yet to be well established. In comparing results from different studies, readers should note that the different methods of perturbation may well evoke different patterns of joint motion and sensory drive. Results may be further affected by differences in the unpredictability of the task conditions (ie, perturbation waveform, magnitude, direction, timing) and the specific instructions given to the subject (ie, whether the subject is instructed to step, to try not to step, or is “unconstrained” by any specific instructions).

The measurement approaches that are typically used to study compensatory stepping involve perturbation of static stance. We propose that these “static” tests are relevant to functional stability in daily life for two reasons. First, a sizable proportion of falls (40%–50%) actually occur during quasi-static movements and activities.47, 48 Second, the “static” test results may also provide information that is relevant to the many falls that occur during gait,47, 49–53 because step adjustments during gait and step initiation from stance share a number of fundamental control subtasks (eg, appropriate placement of the swing foot, stabilization of the COM during swing). The multiaxis moving platform allows the control of these motor subtasks to be assessed safely, under perturbation conditions that are tightly controlled yet unpredictable to the subject, while avoiding many of the methodological difficulties of gait-perturbation studies.

**Speed of Response**

One of the key features that appears to distinguish compensatory stepping from noncompensatory behavior is the rapid speed of the response to instability. This difference occurs when behavior is unconstrained, but it is also evident when the perturbation-evoked response is clearly volitional.12, 39, 44 In one of our studies,39 subjects were given prior instructions to step as rapidly as possible in response to either visual cueing (as in gait initiation studies) or onset of platform motion. The results showed, for both forward and backward stepping, that instability, due to platform motion, elicits a much more rapid response, marked by a twofold (450-millisecond) reduction in the duration, as well as a 100-millisecond reduction in latency. In a similar study, Burleigh et al44 also found very rapid response initiation (150 milliseconds from perturbation onset to start of lateral “weight shift”), with a 50-millisecond delay occurring when a proprioceptive cue was used, instead of platform motion, to elicit a rapid forward step. Although the perturbations used in these studies may passively induce a more rapid motion of the body in the anteroposterior direction, it is important to recognize that the more rapid initiation and execution of swing-leg unloading, which involves lateral weight transfer, must be the result of a more rapid active response.

The timing of the perturbation-evoked stepping response appears to be equally, if not more, rapid in early trials, in which subjects are free to respond “naturally” (no specific instructions), as compared with trials in which subjects are instructed to step as quickly as possible.12, 13 Response initiation is also very rapid, in most subjects, even when they are instructed to try not to step, although some subjects are able to delay the onset of swing-leg unloading under this task condition.15 Delay of response initiation tends to occur more commonly during forward, rather than backward, stepping and appears to be associated with the ability to balance “on the toes.” Even when response onset is delayed, however, the speed at which the swing leg is unloaded and moved tends to be extremely fast during compensatory stepping.41 Data illustrating the effects of the different task conditions on the speed of the stepping response are summarized in the Table, and representative responses are shown in Figure 2.

**Anticipatory Control**

A second, fundamental way in which compensatory and noncompensatory stepping behaviors differ pertains to the presence or absence of an “anticipatory postural adjustment” (APA) prior to the lifting of the swing leg. For unperturbed stance, movements that involve raising
Postural adjustment (APA) present if the ML AF'A is most likely to be absent in early trials, when the preparatory behavior is often absent during compensatory stepping (ie, the ML APA). This anticipatory postural behavior has been shown to occur, without exception, in studies involving leg abduction,54 leg flexion,55-57 and gait initiation.18-20,25-27 Importantly, such anticipatory postural behavior is often absent during compensatory stepping in response to perturbation.13,38 The absence of the anticipatory phase appears to be related to the absence of preplanning for compensatory stepping (ie, the ML APA is most likely to be absent in early trials, when the perturbation is unfamiliar, or in trials in which subjects are not given specific instructions to step).13,33,38,42 Conversely, ML APAs occur most consistently when subjects are given prior instructions to step (Table).36,39,44,45 Inclusion of an anticipatory phase delays the lifting and placement of the swing foot by about 100 milliseconds during rapid compensatory stepping.53 Such a delay could seriously jeopardize stability, which may explain why the ML APA tends to be absent when the perturbation is unfamiliar. Curiously, however, in view of this apparent “cost,” the inclusion of the ML APA during rapid compensatory responses seems to provide little functional benefit. The ML APAs that occur appear to be either too small or too brief to have any impact on the COM dynamics, as evidenced by the lack of any measurable effect on the lateral displacement, velocity, or acceleration of the COM, either at foot-off or at contact (Fig. 2B). McIlroy and Maki, unpublished research). In this respect, it appears that the ML APA may be a “vestigial” feature of attempts to utilize the same motor programs associated with volitional stepping. Possibly, the anticipatory phase is truncated, and consequently rendered nonfunctional, as a result of the anteroposterior instability induced by the perturbation, which must drive a more rapid initiation of the unloading and swing phases of the step in order to safeguard stability. The idea that the time course of the reaction to instability defines the extent to which the anticipatory

<table>
<thead>
<tr>
<th>Measurea</th>
<th>Task Conditionb</th>
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<tr>
<td></td>
<td>Light-Cued (Instructed to Step as Rapidly as Possible)</td>
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<td>Instructed to Step as Rapidly as Possible</td>
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<td>[n=26]</td>
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<tr>
<td>Forward steps</td>
<td>Percentage of trials with APA</td>
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<tr>
<td>Step onset (ms)</td>
<td>360 ± 106 (250-625)</td>
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<tr>
<td>Foot-off (ms)</td>
<td>778 ± 121 (580-1,160)</td>
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<tr>
<td>Preparatory duration (ms)</td>
<td>994 ± 138 (720-1,475)</td>
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<td>Swing duration (ms)</td>
<td>418 ± 89 (250-645)</td>
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<tr>
<td>Backward steps</td>
<td>Percentage of trials with APA</td>
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<tr>
<td>Step onset (ms)</td>
<td>359 ± 118 (215-725)</td>
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<tr>
<td>Foot-off (ms)</td>
<td>714 ± 140 (515-1,110)</td>
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<tr>
<td>Preparatory duration (ms)</td>
<td>931 ± 172 (705-1,460)</td>
</tr>
<tr>
<td>Swing duration (ms)</td>
<td>356 ± 74 (250-555)</td>
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*a Onset of stepping response defined by onset of mediolateral center-of-pressure (COP) excursion (>4 mm, or approximately 1% of stance width); anticipatory postural adjustment (APA) present if the initial COP excursion was toward the swing leg; foot-off and foot-contact defined by vertical load <1% of body weight (in eight trials in which the foot did not land on the force plates, the foot-contact time was estimated from the onset of the sudden decrease in loading of the stance leg); preparatory duration = time from response onset to foot-off, swing duration = time from foot-off to foot-contact; response onset, foot-off, and foot-contact defined with respect to onset of platform acceleration (0.1 m/s²) or light cue.

*b The “try not to step” data were collected from 10 young adults in a study involving multiaxis platform perturbations. All other data were collected from 5 young adults in protocols that were restricted to forward and backward platform translation (McIlroy and Maki, unpublished research). In tasks involving instructions to step, subjects were asked to step to markings placed on the floor to ensure that the anteroposterior step length was similar to that observed, on average, in the other tasks (ie, 30-40 cm for forward steps, 20-30 cm for backward steps). In all perturbation tasks, perturbation direction was varied unpredictably (step direction was also varied unpredictably, in the light-cued trials). Perturbation magnitude was also varied unpredictably, except in the unconstrained task. The tabulated data correspond to perturbations of moderate magnitude (duration=0.6 s, acceleration=1.5 and 2.0 m/s², velocity=0.45 and 0.6 m/s, and displacement=0.14 m and 0.18 m for forward and backward translations, respectively).

Table.
Temporal Characteristics of Compensatory and Noncompensatory Stepping Responses: Mean±Standard Deviation (Range)
Figure 2.
Effect of task conditions on stepping. Representative backward-step responses of young adults without balance impairments are shown for (A) light-cued "volitional" stepping, (B) perturbation-cued volitional stepping, (C) unconstrained perturbation-evoked compensatory stepping, and (D) constrained perturbation-evoked compensatory stepping. In Figs. 2A and 2B, subjects were instructed to step as rapidly as possible in response to the cue (activation of a light or onset of platform motion) (McIlroy and Maki, unpublished research). Fig. 2C represents an early trial in which the subject was given no specific instructions. In Fig. 2D, the subject was instructed to try not to step. For each trial, the vertical ground reaction forces \(F_z\) and the mediolateral (ML) and anteroposterior (AP) center of mass (COM) and center of pressure (COP) are shown up to the point of foot-contact (forward AP and rightward ML displacements are positive; subjects stepped with the right lower extremity in each trial shown). Symbols P, A, FO, and FC indicate onset of perturbation (or cue), initiation of the stepping response (onset of asymmetry in \(F_z\)), foot-off, and foot-contact, respectively (in Fig. 2A, foot-contact occurred at 1,050 ms, beyond the range of the time axis). Similar moderately large platform motion was used in all perturbation trials (acceleration=1.5 m/s\(^2\), velocity=0.5 m/s, displacement=0.14 m, duration=0.6 s). Perturbation leads to a much more rapid response, regardless of the instruction, when compared with light-cued stepping. Note the large anticipatory postural adjustment (APA) (initial increase in swing-limb \(F_z\), initial COP displacement toward the swing limb) and the associated ML movement of the COM toward the stance limb in the light-cued task, and the absence of these features in the perturbation responses (Fig. 2B shows a very small APA but no concomitant effect on the ML COM displacement).

Phase can be expressed is consistent with observations that the duration of the ML APA increases with decreasing magnitude of perturbation (McIlroy and Maki, unpublished research) and that large ML APAs are seen during stepping responses to very small perturbations. Small perturbations would require less rapid stepping behavior, thereby allowing an ML APA to be expressed more fully. The ML APA is more likely to be important during slower movements because the COM has greater opportunity to fall laterally as the duration of the swing phase increases.

Adaptive Changes
It appears, from our studies of unconstrained compensatory stepping reactions, that the ML APA is almost always absent when the perturbation is first presented (ie, when the perturbation is novel), but tends to appear more frequently as the subject is given an opportunity to
practice the response and to gain familiarity with the characteristics of the perturbation. In addition, over repeated perturbation trials, subjects tend to step less frequently, and to take fewer and smaller steps when they do step, even when perturbation direction is unpredictable. Furthermore, in a study involving multiaxis perturbations, subjects who were instructed to avoid stepping were able to reduce their frequency of stepping by 50% when perturbation direction was unpredicted. Unpracticed responses to unpredictable disturbances are likely to be most relevant to the prevention of falls because daily life rarely presents an opportunity to become familiar with the characteristics of a specific perturbation or to adapt one's response. Attempts to use clinical or experimental assessments of compensatory stepping to draw inferences about the ability of the individual to respond to unexpected perturbations in daily life could well be confounded by the adaptive changes that occur during repeated testing, and intersubject differences recorded under such conditions.

Figure 3.
Effect of lateral destabilization on compensatory stepping. In this study, anterior-posterior (AP), mediolateral (ML), and "oblique" perturbations of varying magnitude were presented in random order, and subjects were instructed to try not to step. Example responses from one subject are shown, illustrating the interactions between perturbation-induced loading, swing-limb selection, and swing-foot trajectory. Vertical ground reaction forces and swing-foot trajectory are shown for responses where the swing limb was (A) the perturbation-unloaded (right) leg ("cross-over step") and (B) the perturbation-loaded (left) leg ("side step"). In both trials, the platform moved forward and to the right, as indicated in the figure (acceleration = 2.6 m/s², velocity = 0.78 m/s, displacement = 0.23 m, duration = 0.6 s). Symbols P, U, FO, and FC indicate onset of platform acceleration, unloading of the swing limb, foot-off, and foot-contact, respectively. Note the earlier onset of swing-limb unloading and foot-off in Fig. 3A. In Fig. 3B, unloading and foot-off are delayed until the perturbation-induced loading can be countered and reversed. The longer swing duration (FO to FC) in Fig. 3A is associated with a longer and more complex swing trajectory (the foot must cross behind the stance limb).
could well be due, in whole or in part, to differences in predictive, rather than reactive, capabilities. To minimize the potential for adaptation, we believe that test conditions should be as unpredictable as possible.

**Influence of Lateral Destabilization**

Almost all studies of compensatory step initiation have been limited to the forward and backward stepping that occurs in response to anteroposterior perturbation. In everyday life, perturbations can occur in an unlimited number of directions; therefore, it becomes important to characterize stepping responses that are not limited to the sagittal plane. Although relatively little attention has been given to lateral stability, the ability to compensate for lateral destabilization is particularly relevant to the problem of falling because a large proportion of falls involve lateral motion and debilitating hip fractures are most likely to occur as a result of lateral falls. Observations from a video surveillance study of naturally occurring falls in elderly people showed problems in the control of laterally directed steps in a number of lateral falls.

The introduction of a lateral component to the destabilization complicates the control of stepping, due to anatomical restrictions on ML foot movement and the effects of perturbation-induced COM displacement on the unloading of the swing leg. When subjects were discouraged from preplanning to step, the predominant strategy, seen in 87% of lateral stepping responses, was to "cross over" with the foot that was unloaded by the perturbation. This strategy allowed a much more rapid foot-lift in comparison with responses where the perturbation-loaded leg was swung but required a longer and more complex swing trajectory to move the foot across (either in front of or behind) the body while circumventing the stance leg (Fig. 3). In 10% of the lateral stepping responses, the need for a long trajectory was avoided by taking multiple steps, moving the perturbation-unloaded foot medially prior to a second laterally directed step with the contralateral foot. A third strategy involved "side-stepping" with the perturbation-loaded leg. Although it took much longer (200 milliseconds, on average) to unload this leg, the swing trajectory was simpler and shorter; that is, the foot was simply moved laterally (swing duration was reduced by 240 milliseconds, and step length was reduced by 9 cm). The "side-step" strategy may be dependent on preplanning. Although this strategy occurred in only 3% of constrained ("try not to step") lateral-step responses, the prevalence increased to 43% when subjects performed repeated trials in the absence of instructional constraints (Maki et al, unpublished research).

**Control Mechanisms**

Very little is known about how compensatory stepping reactions are controlled by the CNS. It may be that the underlying sequences of muscle activation are established by the same central pattern generators that are thought to be involved in the control of gait, whereas the initiation and amplitude scaling of the response may involve transcortical or subcortical pathways similar to those that are thought to be involved in the control of the early fixed-support postural responses. Although some authors have suggested that elements of the stepping response are "released" as predefined motor programs (based on studies of gait initiation and "stumbling"), sensory feedback would be expected to play a more critical role in controlling compensatory stepping, particularly when unpredictable task conditions preclude effective preplanning of an "open-loop" response. Observations that subjects are able to abort a stepping response prior to foot-lift clearly indicate that sensory information can be used to modify the response "on-line."

One sensory source that has the potential to provide critical information for the control of stepping is the input from the soles of the feet regarding pressure. This afferent information may be particularly relevant to the control of swing-limb unloading, foot-lift, foot-contact, and weight transfer. Do and colleagues reported that plantar pressure feedback plays an important role in controlling "volitional" stepping responses to forward perturbation (subjects instructed to step), based on the effects of variation in plantar support surface and anesthesi of the sole. Conversely, because there was negligible muscle stretch prior to response onset, Do et al concluded that the early muscle activation associated with the step initiation was not triggered by muscle spindles. Do et al also concluded that the response was not initiated by vestibular cues, based on testing of three patients with "vestibular syndrome"; however, observed effects of optokinetic stimulation would suggest that the interaction between the vestibular and visual systems can play an important role in initiating this type of stepping response.

We have recently begun to examine the contribution of plantar pressure feedback to the control of unplanned compensatory stepping (subjects forced to step, in a proportion of trials, despite instructions to try not to step) using hypothermic anesthesia (cooling the feet in ice water) to attenuate plantar sensation in blindfolded subjects. In the six subjects tested, cooling increased the incidence of stepping, as well as the incidence of multiple-step responses, in response to unpredictable multiaxis platform perturbation. Moreover, there appears to be a profound effect on control of lateral stepping. When the feet were cooled, the subjects...
The process by which the CNS determines the spatial and temporal step parameters is unclear, particularly because it appears that, for a given perturbation, many different combinations of step length and swing duration can achieve a stable response. We have tentatively proposed a model in which step parameters are selected to maximize the "stability margin" (i.e., the distance between the COM and the boundary of the BOS), thereby maximizing the ability to decelerate the COM (Fig. 5) (Maki and Sinha, unpublished research). Studies are under way to test this model and to evaluate other possible control criteria (e.g., optimizing the transfer of weight to the swing limb to facilitate subsequent stepping).

Figure 4.
Effects of attenuation of plantar sensation (due to cooling of the feet) on the placement of the initial step in response to mediolateral (ML) platform translation (acceleration = 3 m/s², velocity = 0.9 m/s, displacement = 0.27 m, duration = 0.6 s). In this study, anteroposterior (AP) and ML perturbations of varying magnitude were presented in random order; subjects were blindfolded and instructed to try not to step. Initial step locations (marker on fifth metatarsal) are shown for the responses of one subject to four leftward platform translations (top panel) and four rightward translations (bottom panel). Trials where the feet were cooled are indicated by thick lines, and trials where the feet were not cooled are indicated by thin lines. Multiple small steps were taken in each cooled trial (only the first step is shown), whereas a single large "cross-over" step was used in each uncooled trial. The duration of single-limb stance was reduced by a factor of 2 in the small steps (220 ms versus 390 ms).

Avoided taking large "cross-over" steps that would require a long duration of one-limb stance (Fig. 4). The implication that sensory information from the sole of the foot is critical in controlling stability during single-leg support is supported by observations that subjects are unable to balance on one leg after anesthesia of the sole (due to local injection of Xylocaine®) (McIlroy et al, unpublished research).

Change-in-Support Movements of the Upper Limb: Grasping
Although increasing numbers of studies are examining compensatory stepping, very few studies have addressed arm reactions resulting from instability. Arm movements can serve a protective role, to absorb impact and shield the head in the event of a fall, and can also help to stabilize the COM over a fixed BOS, through inertial effects. The focus here, however, is on grasping reactions that serve to increase external support. Control of the grasping reaction is likely to be one of the most challenging aspects of balance control, particularly when graspable surfaces are restricted in size or location. One important distinction between compensatory upper- and lower-limb reactions is the fact that the location of potential handholds can vary widely, whereas the ground (the "target" for stepping) is usually likely to remain relatively level and predictable. Because of such challenges, these arm reactions may well be more sensitive to subtle CNS changes that define an individual's ability to maintain balance.

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Figure 5.
Schematic representation of an optimal control model of compensatory stepping (Maki and Sinha, unpublished research). The solid line shows the anteroposterior (AP) center-of-mass (COM) displacement that would result from a large backward platform acceleration at time 0, assuming a maximal fixed-support ("ankle strategy") stabilizing response. The dashed line represents the position of the great toe of the swing foot during the forward-step response; at time of foot-contact, this point defines the anterior-most limit of the base of support (BOS). The distance between the COM and swing-foot trajectories at any given point in time (following the start of the swing phase) defines the "stability margin" that would be achieved if foot-contact occurred at that point in time. There is a finite range of foot-contact times that would allow the BOS to "capture" the COM (BOS > COM). There is also an optimal foot-contact time that maximizes the stability margin and, in doing so, allows for maximal COM deceleration.
Figure 6. Modulation of the compensatory grasping response according to (A) proximity of handrails and (B) direction of perturbation (platform translation). In this study,\textsuperscript{14,15} anteroposterior and mediolateral perturbations of varying magnitude were presented in random order; subjects were not constrained by any specific instructions. In both panels, the first 400 ms of the wrist trajectory, relative to the shoulder, is shown in the frontal plane. Fig. 6A shows two trials where the subject grasped the rails, in response to leftward platform translation (acceleration=2.6 m/s\textsuperscript{2}, velocity=0.78 m/s, displacement=0.23 m, duration=0.6 s). Solid line=handrails distant (2 m apart), dashed line=handrails close (1 m apart). Fig. 6B shows four close-rail trials, for a single subject, where the platform moved in each of the four directions indicated (perturbation characteristics similar to those noted in Fig. 6A). The circular symbol on each trajectory indicates the point in time 150 ms after onset of perturbation. The difference in trajectory, due to change in environment or perturbation, is evident even in the earliest part of the response.

Many researchers have explored reactions of arm muscles to external loads applied to the limb itself; however, such a focus is distinctly different from balance-related arm reactions because perturbation of whole-body stability (with arms relaxed by the sides) results in complex arm responses without any prior stretch or loading of the muscles of the arms.\textsuperscript{14,15} In addition, many investigators have studied the control of noncompensatory reaching and pointing movements of the arms, as well as the APAs associated with the execution of rapid noncompensatory arm movements. To our knowledge, we have conducted the only inquiries to date into compensatory grasping responses evoked by external perturbation of upright stance (Mcllroy et al, unpublished research).\textsuperscript{14,15}

**Characteristics of Compensatory Grasping**

Our initial studies\textsuperscript{14,15} focused on arm responses to whole-body instability evoked by platform translation, both anteroposterior and ML. Handrails were located on each side of the platform, either in close proximity (1 m apart) or distant (2 m apart). Even though subjects were given no specific instructions, arm reactions were very prevalent, with activation of the shoulder muscles occurring in over 85% of trials. (Stepping occurred frequently, as well.) The prevalence of arm reactions was similarly high regardless of whether handrails were close or distant, even though subjects actually touched the rails in only 3% of distant-rail trials, in comparison with 78% of close-rail trials. Activity in the shoulder muscles began very early, 90 to 140 milliseconds after onset of perturbation, which is very similar in timing to the “automatic” (fixed-support) postural responses in the ankle muscles. Unlike the ankle muscles, however, the arm and shoulder muscles were not activated or involved in balancing prior to the perturbation nor was there any measurable motion that would have stretched or loaded the muscles prior to the onset of activation. These findings indicate that a remote sensory source was responsible for driving these responses.

The arm reaction was clearly modulated according to the characteristics of the perturbation (which were varied unpre-
dictably), as well as of the environment. The timing and magnitude of the shoulder-muscle activation were adjusted to the perturbation magnitude, and even the earliest trajectory of the arm motion varied according to the direction of the perturbation and the location of the handrails (regardless of whether the rails were actually grasped) (Fig. 6). Furthermore, this tuning of the response was evident in the subjects’ very first trial. These findings provide evidence that these reactions were not simply a generic “startle” response or the release of a stereotypical ballistic, inertial, or protective reaction. The ability of the CNS to rapidly and accurately control the trajectory of the hand to a fixed target, despite unpredictable movement of the frame of reference (ie, the shoulder), reveals the remarkable sophistication of this arm control.

Influence of Task Demands: Sitting Versus Standing

One of the potential advantages of studying arm reactions is the possibility of assessing CNS control of balance in seated subjects, which may open a number of important clinical and experimental opportunities. For example, it would be possible to test or train patients who are unable to stand (eg, patients at an early stage of recovery following a stroke) to control confounding factors such as anxiety related to fear of falling and to perform measurements (eg, mapping of cortical activity) that are not as feasible in freestanding subjects. Although certain aspects of postural control are specific to whether the individual is seated or standing, we propose that the ability, or inability, of the CNS to perform the required sensorimotor transformations may well generalize across the different task conditions.

In a recent study, we compared standing and seated grasping reactions (McIlroy et al, unpublished research). Subjects either stood on a moving platform or were seated in an unstable chair that tilted slightly when the platform moved. Handrails were mounted in the same position, relative to the subjects, for each of the two tasks, and subjects were instructed to grasp the rails as rapidly as possible in response to onset of platform motion. In all trials, the arm muscles were activated very early, similar to the timing observed in our studies of unconstrained arm reactions. Moreover, the timing, pattern of muscle activity, and trajectory of these rapid grasping reactions were remarkably similar, regardless of whether subjects were standing or seated (Figs. 7A and 7B). Interestingly, the responses were also similar when the chair was translated but not allowed to tilt, suggesting that the sensation of whole-body movement is sufficient to evoke this pattern of very rapid muscle activation, regardless of the specific nature of the body motion. These findings could indicate an important role of the vestibular system in triggering the response, although we cannot rule out a possible contribution from visual or somatosensory receptors (eg, trunk pressoreceptors).

Compensatory Versus Noncompensatory Grasping

Preliminary tests have been performed to determine the differences between perturbation-cued and light-cued grasping reactions (McIlroy et al, unpublished research). In these trials, seated subjects were instructed to grasp handrails as fast as possible in response to the cue (light or platform motion). In all subjects, the timing of response to the perturbation cue was more rapid (by 130 milliseconds, on average) and less variable (mean within-subject coefficient of variation of 18% versus 32%). Furthermore, the timing and magnitude of the shoulder muscle activation were adjusted according to the perturbation magnitude and direction, which were varied unpredictably. In spite of the differences in timing and magnitude, the pattern of recruitment (relative onset of the primary arm muscles) remained the same in both compensatory and noncompensatory tasks (Fig. 7).

The modulation of the arm response according to the degree and direction of instability seems to parallel results described earlier with regard to stepping reactions. In both instances, the CNS appears to be able to respond rapidly and accurately to unpredictable perturbation. For grasping, however, there is the added complication of variation in target (handhold) location. We have found that unpredictable variation in the handhold location, prior to perturbation onset, leads to a loss of ability to direct the initial trajectory toward the handhold but does not delay response initiation (McIlroy et al, unpublished research). Based on these findings, we have proposed that (1) the compensatory grasping trajectory is preplanned by cortical neural pathways similar to those controlling noncompensatory grasping and (2) the very rapid initiation and amplitude scaling of the trajectory are controlled by transcortical or subcortical pathways similar to those that are thought to be involved in the control of the early fixed-support postural responses.

Interactions Between Fixed-Support and Change-in-Support Reactions

Sequential Versus Parallel Control

It has been suggested that change-in-support reactions, such as stepping, occur when the earlier fixed-support reactions fail to restore equilibrium and that the stepping response will be appended to the earlier reactions. Our data suggest that this is not the case. The stepping response is often initiated very early, even when subjects are instructed to try not to step (Table). For backward stepping, the asymmetry in vertical loading of the two legs, which is a biomechanical marker of the
beginning of the response, was found to begin as early as 160 milliseconds after onset of platform acceleration,\textsuperscript{12} with the underlying muscle activation likely occurring at least 50 milliseconds prior to the change in loading.\textsuperscript{19} Given that the earliest muscle activation associated with the fixed-support reaction began at a latency of 105 milliseconds, it is clear that the step can be initiated well before the completion of the early fixed-support reaction.

Thus, in contrast to the view that the responses are sequenced, it appears that the stepping response may be initiated almost in parallel with the early fixed-support reaction. Parallel, rather than sequential, control is clearly evident in the compensatory arm reactions. As noted earlier, the activation of the shoulder muscles is coincident with the onset of the fixed-support reactions arising at the ankles.\textsuperscript{14} Presumably, the CNS initiates the change-in-support response early to safeguard stability. This explanation is consistent with observations, noted earlier, that stepping and grasping often occur in early trials even when the perturbation is small. Potential costs of an early change-in-support reaction (eg, “unnecessary” stepping or grasping) can apparently be avoided by aborting the reaction, prior to grasping a handhold or placing the foot.\textsuperscript{41} Stepping reactions apparently can even be aborted prior to lifting of the foot.\textsuperscript{10-12} In such cases, there is a lateral “weight shift” that is very similar in timing and pattern to that recorded during trials in which forward or backward stepping actually occurs. Such evidence of aborted stepping is most prevalent during early trials, where subjects have been instructed to try not to step, and there is a progressive decrease in the magnitude of the lateral “weight shift” as the subject gains familiarity with the perturbation.\textsuperscript{10,11} Responses that appear to be similar, when viewed in the sagittal plane, may actually be seen to involve quite different postural strategies, in terms of preparation for stepping, when the lateral asymmetry is examined.

**Modulation of the Fixed-Support Ankle Strategy**

The demands associated with the fixed-support and change-in-support reactions can conflict. For example, the fixed-support reaction acts to arrest the motion of the COM, whereas some progression of the COM is necessary to execute a step. In addition, the muscle activation required to unload and lift the swing limb may well conflict with the activation associated with the fixed-support reaction. Given the overlap in timing that has been observed within the fixed-support and change-in-
support reactions, there must be a mechanism for resolving these conflicting demands. Our studies indicate that, for anteroposterior perturbation, the early fixed-support “ankle strategy” will persist even when the compensatory stepping reaction is preplanned; however, it appears that the gain of the early response can be modulated. When subjects were instructed to step in response to forward platform translation, the magnitude of the initial (50-millisecond) response in the tibialis anterior muscle was reduced by about 40%, compared with “constrained” trials in which subjects were instructed to try not to step. This difference, due to instruction, occurred regardless of whether the subjects actually stepped or did not step in the constrained trials, and it suggests a centrally mediated change in the gain of the ankle reaction due to preplanning. Burleigh and colleagues have since reported similar findings for ankle responses to small backward platform translations. Although Burleigh and Horak concluded that the ability to predict platform velocity is required to suppress the early ankle reaction, the suppression in our study occurred under conditions in which platform velocity was unpredictable. Apparently, there have not yet been any studies of the possible modulation of ankle responses due to compensatory arm reactions; however, it can be noted that the early fixed-support reaction at the ankle always persists, at normal latency, despite the presence of the arm reaction. The persistent and automatic nature of the early fixed-support “ankle strategy” is also supported by a study of the interactions between early responses to postural perturbation and concurrent volitional (non-stepping) body movement.

Subordination of the Fixed-Support Hip Strategy

The fixed-support “hip strategy” has, in recent years, received much attention and has been purported to be an important functional element of the postural repertoire for dealing with perturbation in the anteroposterior plane. Our studies of young adults do not appear to support this view, however, suggesting instead that stepping is a preferred strategy. In contrast to the “ankle strategy,” which relies primarily on ankle torque to stabilize the body, the hip strategy involves the use of the hip flexors or extensors to generate shear forces at the feet that act to decelerate the COM. (It is important to note that hip motion itself does not necessarily constitute a hip strategy, as classically defined.) A hierarchical model has been proposed, wherein the hip strategy occurs when the stabilizing capabilities of the ankle strategy are exceeded and the stepping strategy emerges when the hip strategy is unsuccessful in keeping the COM over the BOS (Fig. 8).
Comparison of the trained fixed-support “hip strategy” [Fig. 9A] with forward stepping responses (Figs. 9B and 9C) [McIlroy and Maki, unpublished research). All responses were evoked by 600-ms backward platform translation [acceleration=0.4 m/s², velocity=0.12 m/s, displacement=0.036 m in Figs. 9A and 9B; acceleration=3 m/s², velocity=0.9 m/s, displacement=0.27 m in Fig. 9C]. Hip strategies were evoked, after approximately 7 to 10 training trials, by instructing subjects to balance, without stepping, on a narrow (10-cm) beam, according to the methodology of Horak and Nashner. The stepping response shown in Fig. 9B was recorded, in the same subject, in the first training trial on the beam. The stepping response shown in Fig. 9C was recorded in a subject standing on a normal surface [no instructional constraints]. The stick figures show the body posture at 333-ms intervals, starting approximately 200 ms prior to perturbation onset. Symbols P, A, FO, and FC indicate onset of platform acceleration, initiation of the stepping response [onset of left-right asymmetry in vertical limb loading], foot-off, and foot-contact, respectively. Note the large hip flexion and associated hip torque generated during the trained hip strategy and the absence of these features prior to foot-off in the stepping trials [in each panel, data are shown for the left leg, which was the stance limb for both stepping trials].

replicated this experiment and found that although it is true that the hip strategy can be learned, the natural preference is to step. In the first trial, and throughout the learning process, subjects prevented themselves from falling by stepping off the beam (McIlroy and Maki, unpublished research). Furthermore, there is no evidence, in the early “learning” trials, of substantial hip motion or hip torque that would be compatible with the classical hip strategy (Figs. 9A and 9B). Likewise, it seems doubtful that the hierarchy of responses illustrated in Figure 8 occurs under normal conditions. To date, we have seen no evidence, when subjects are allowed to respond “naturally,” of substantial hip motion or torque that would be compatible with the sequencing of a classical hip strategy and step initiation (Fig. 9C). Finally, our data do not support the view that the step is initiated when the COM exceeds the limits of the BOS. As indicated in Figure 8, stepping is often initiated in response to small COM displacement, within the “zone” attributed to the ankle strategy, even when the perturbation is modest and the subject is instructed to try not to step. In early trials, when behavior is unconstrained, stepping is initiated at even smaller COM displacements.
Age- and Pathology-Related Changes
A small number of investigators have recently begun to study changes in compensatory stepping associated with aging. Studies of problems specific to visual or vestibular disorders, peripheral neuropathy, or central neurological lesions will be of equal significance in increasing our understanding of the control mechanisms and in developing new diagnostic and therapeutic approaches. Few such studies, however, have been performed to date. In one study involving three patients, there was little effect on step initiation due to vestibular deficit.29 Another study68 examined self- and perturbation-triggered step initiation in six patients with Parkinson’s disease. Interestingly, there was further evidence of distinctions between compensatory and noncompensatory stepping, showing that dopaminergic therapy improved anticipatory force generation during self-initiated stepping but not when stepping was evoked by postural perturbation.68 Apparently, there have not yet been any studies of age- or pathology-related changes in compensatory grasping, although we are currently beginning experiments in this area.

Effects of Aging on Incidence of Stepping
Researchers examining responses to backward pulling forces applied at the waist found that older subjects were more likely than younger subjects to take multiple backward steps in responding to the perturbation.34,36,37 In individuals with a history of falling, there were often problems in the initiation and control of the compensatory stepping, and the stepping response was often insufficient to prevent loss of balance.34,35 Our studies of forward and backward compensatory stepping in response to platform perturbation have also shown an increased tendency for older adults to take multiple steps.42 On the basis of a study of backward stepping, it has been suggested that the execution of small, rapid multiple steps may represent a “conservative” strategy, in allowing increased opportunity to correct for instability.37 It seems unlikely, however, that this strategy would apply to forward stepping responses, which tend to involve relatively large initial steps.42

In our study,42 many of the multiple-step responses apparently emerged as a consequence of events that arose after the initiation of the first step, rather than as a strategy planned in advance. In particular, in over 30% of stepping reactions in older adults, the later steps were directed so as to recover lateral stability, even though the perturbation was in the anteroposterior direction (Fig. 10).12 This response was rarely seen in young adults, even though the characteristics of the initial step were remarkably similar in both age groups. These findings suggest that the lateral stepping may reflect an impaired ability to control the lateral displacement of the COM during the stepping response. Interestingly, there is recent evidence that an impaired ability to control lateral stability may distinguish elderly “fallers” from “nonfallers.”80 Recent work by Rogers68 appears to support this view; however, in contrast to our results, Rogers found evidence of differences in the initial step of the response. Older subjects with a history of falling tended to include a lateral displacement in the initial step in responding to a forward pulling force applied at the waist. Attempts to compensate for lateral instability in this manner could represent a predictive strategy, which may have been facilitated by the more predictable perturbation conditions used in that study. It is also possible that such an adaptation is specific to subjects with a recent history of unsteadiness and falling; the older adults we tested were not recent fallers.

Effects of Aging on Response Initiation
In general, our results showed little evidence of age-related differences in the timing of the stepping responses, although the older subjects exhibited small delays (40 milliseconds, on average) in response initiation.42 Our findings appear to contradict the results of Luchies and colleagues,36,37 who reported earlier foot-lift (by up to 100 milliseconds) in older subjects. The discrepancy may lie in methodological differences. In our study, perturbation direction was varied unpredictably.
ably, subjects were allowed to respond in what we considered to be a "natural" manner (no instructional constraints), and we focused on the earliest trials, where the perturbations were still relatively novel, to better simulate responses evoked by unexpected disturbance in daily life. In light of evidence that aging can affect adaptive capabilities, some elderly subjects in the study by Luchies and colleagues may have reached their stability limits sooner because they were less able to adapt their responses to take advantage of the more predictable features of their testing paradigm. Differences in instructional set may also account for the differences in findings. Although Luchies and colleagues did not report the instructions given to the subjects, it appears that the subjects may have been encouraged to resist stepping. In this situation, younger subjects may devote greater effort to resisting stepping and thus they may tend to delay step onset because they are less apprehensive about losing balance. The small delay in response observed in our study may reflect impaired ability to rapidly discriminate onset of instability and may be related to age-related reduction in sensitivity to peripheral sensory inputs or increased central processing and conduction time.

**Effects of Aging on Anticipatory Control**

Older adults appear to be less likely to include anticipatory elements in the compensatory stepping response. Although this finding may reflect an age-related impairment in adaptive capability, we believe that it is unlikely to affect functional stability in daily life. As noted earlier, unconstrained responses to novel perturbations almost always lack an ML APA, and the ML APAs that do occur, in some experimental trials, are too small or brief to provide any functional benefit with regard to lateral stabilization. Thus, in spite of the greater prevalence of ML APAs in young adults, there was no corresponding increase in lateral stability at time of foot-contact, as reflected by the ML displacement and velocity of the COM. Inclusion of the ML APA phase could actually jeopardize safety by delaying the stepping response, particularly when coupled with the age-related delay in response onset noted above. These factors might account for the reduced frequency of ML APAs in elderly persons.

**Factors Contributing to Age-Related Changes**

The age-related impairments in compensatory stepping described do not appear to be a consequence of impaired musculoskeletal function. Luchies and colleagues have found that the flexion-extension joint torques, as well as the joint range of motion, required to execute rapid backward compensatory steps are well within the capabilities of "normal" older adults. In addition, we have found that the compensatory stepping movements of "normal" young and older adults are quite similar in speed of motion. Because compensatory responses do not appear to require maximal muscle forces or a large range of motion, modest age-related reduction in musculoskeletal capacity may not pose a problem in generating these responses. However, readers should note that the studies to date have only examined responses up to the time of foot-contact. In addition, the possible effects of age-related decreases in hip abductor and adductor strength have not yet been examined. Weakness in these muscles could possibly contribute to the problems that older adults appear to have in controlling lateral stability during compensatory stepping. Ongoing work in our laboratory is aimed at determining the specific contributions of age-related decrements in musculoskeletal capacity, sensory function, and neural information processing to impaired control of compensatory leg and arm movements.

**Summary**

By removing constraints on postural behavior during experimental testing, it becomes evident that change-in-support strategies, involving compensatory stepping or grasping movements of the limbs, are very prevalent reactions to instability, even at small perturbations, and likely play a more important functional role in maintaining upright stance than has generally been appreciated in the past.

Change-in-support reactions are clearly not just strategies of last resort. Both stepping and grasping reactions can be initiated very early, well before the COM is near the stability limits of the BOS. For anteroposterior perturbations, the fixed-support ankle strategy persists despite the occurrence of change-in-support reactions, a finding that may reflect the importance of this strategy in providing an early defense against destabilization. The role of the fixed-support hip strategy, however, appears to be limited to special task conditions that preclude the option of stepping or grasping.

Compensatory stepping and grasping reactions are initiated and executed much more rapidly than the fastest noncompensatory (volitional) efforts. In addition, unplanned compensatory stepping reactions frequently lack the anticipatory control elements that invariably occur during volitional stepping. Even when anticipatory adjustments are present, they are too small or brief to have a functional impact during rapid compensatory stepping.

Lateral destabilization complicates the control of compensatory stepping, due to anatomical restrictions on lateral lower-extremity movement and the effects of perturbation-induced COM displacement on the preparatory unloading of the swing limb. Cross-over steps appear to predominate, in young adults without balance...
impaired, under task conditions that discourage preplanning of the stepping response. The demands associated with this response (eg, prolonged one-limb stance), however, are likely to cause problems for individuals with balance impairments.

Sensory feedback is expected to become increasingly important when unpredictable conditions preclude preplanning of the step or grasp. The fact that swing-limb unloading is often aborted after step initiation suggests that feedback is used to modulate the response on-line, in contrast to the view that the step is released as an immutable motor program. Evidence to date suggests that planar pressure feedback is one of the more important sources of sensory feedback for the control of compensatory stepping.

Although older adults may be able to generate rapid compensatory stepping reactions, they are more likely to require multiple steps to recover equilibrium. Aging appears to bring particular problems in controlling lateral stability during the execution of the step, which may be of specific relevance to the problem of lateral falls and associated hip fractures. Although older adults appear to be less likely to include predictive (anticipatory) elements in the stepping response, this is unlikely to have an impact on the ability to respond to unexpected perturbation during activities of daily life.

Increased understanding of change-in-support arm and leg reactions may soon lead to development of new diagnostic and therapeutic approaches for detecting and treating specific causes of imbalance and falling. In assessing balance, clinicians need to be aware of the importance of characterizing change-in-support, as well as fixed-support, reactions and of the need to use unpredictable test conditions to prevent adaptations that are unlikely to occur in daily life. In treating balance impairments, interventions such as training programs should address specific elements of compensatory stepping or grasping reactions that are found to cause difficulty (eg, lateral weight transfer, rapid foot or arm movement, cross-over steps). The ability to assess CNS control of change-in-support reactions though tests of compensatory grasping in seated patients may present new opportunities for testing and training balance across a wider range of patients than is currently feasible.

**Acknowledgments**

We gratefully acknowledge the assistance of Stephen D Perry and Geoff R Fernie in the preparation of this article.

**References**


12 McIlroy WE, Maki BE. Task constraints on foot movement and the incidence of compensatory stepping following perturbation of upright stance. Brain Res. 1993:616:30-38.


40 McIlroy WE, Maki BE. Changes in early “automatic” postural responses associated with the prior planning and execution of a compensatory step. Brain Res. 1995;631:205-211.


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