THE MODIFIABILITY OF TRIGGERED STEPPING REACTIONS: EFFECTS OF ENVIRONMENTAL DEMANDS.

by

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A thesis submitted in conformity with the requirements for the Degree of Master of Science
Graduate Department of the Institute of Medical Science
in collaboration with the
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The purpose of this thesis was to determine whether perturbation-evoked forward stepping reactions can be modulated to accommodate obstacles, whether such modulation occurs automatically, and which features are modulated.

Compensatory stepping reactions were evoked in healthy young adults by unpredictable horizontal movement of a large platform. In the first study, subjects were well able to modulate their forward stepping reactions to clear a high frontal obstacle while recovering balance, even in the earliest trials. A large anticipatory postural adjustment (APA) was used along with a laterally directed step to maintain medio-lateral stability. The second study included a second obstacle condition which constrained lateral foot placement. Subjects then upregulated the APA amplitude in order to guarantee medio-lateral stability.

The results provide evidence that triggered stepping reactions can be modulated to deal with environmental constraints, and that large, functional APAs can contribute significantly to balance control during compensatory stepping.
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LIST OF TERMS

a-p antero-posterior

APA anticipatory postural adjustment

APR automatic postural response

BOS base of support

CIS change in support

CNS central nervous system

COM centre of mass

COP centre of pressure

CPG central pattern generator

FIP feet-in-place

m-l medio-lateral
CHAPTER 1 - INTRODUCTION

The underlying goal of this work is to develop further understanding of human balance and its control, in order to improve older adult’s balance control and prevent falls. Injuries from falls in the elderly, along with their social and psychosocial consequences, are a prevalent and significant health-care problem (Tinetti et al., 1988; Tinetti and Speechley, 1989; Black et al., 1993; Maki et al., 1996). Considering the increasingly aging population, this problem is only expected to become much greater in magnitude, and identifying the underlying factors and mechanisms of falls will become even more important in an effort to reduce their incidence and consequences. Although environmental and behavioural factors are a consideration in precipitating falls, what ultimately determines whether or not a fall occurs is the ability of the central nervous system (CNS) to respond to the loss of equilibrium (Maki and McIlroy, 1996).

Although previous work has tended to focus more on early ‘feet-in-place’ (FIP) responses to destabilization, stepping movements offer a much greater capacity for balance recovery (Maki and McIlroy, 1997; Maki and McIlroy, 1999b), and indeed are a common response, even when the postural disturbance is quite small (Maki and Whitelaw, 1993; Maki et al., 1993; McIlroy and Maki, 1993c; McIlroy and Maki, 1995a; Maki and McIlroy, 1997). Compensatory stepping reactions differ in a number of fundamental ways from volitional stepping (McIlroy and Maki, 1993c; McIlroy and Maki, 1993b; McIlroy and Maki, 1995a; McIlroy and Maki, 1996b; Rogers, 1996; Maki and McIlroy, 1997; McIlroy and Maki, 1999a), and these distinctions suggest that stepping in reaction to balance loss is more automatic and stereotypical in nature than volitional stepping movements. Although the effects of prior instruction, practice and predictability of perturbation (McIlroy and Maki, 1993a; Burleigh et al., 1994; McIlroy and Maki, 1995a; Burleigh and Horak, 1996) on compensatory stepping have been explored, little has
been done on how these reactions may be modified in response to environmental constraints (Horak and Nashner, 1986; Maki and McIlroy, 1997; Zettel et al., 1999). It remains unclear as to whether these responses can be successfully modified to deal with surrounding obstacles, and what exactly the modulations may entail.

The purpose of this thesis then is to provide insight into the capacity of and the mechanisms employed by the CNS to accommodate for nearby environmental constraints. Given the preference to utilize stepping to recover balance, and knowing from everyday experience that we continuously encounter environmental obstructions that may impede the execution of such movements, determining how we deal with such limitations becomes an important issue. To our knowledge, previous work in compensatory stepping has always provided ample, unobstructed space for the completion of balance movements. The consideration of obstacles, however, will provide a more genuine understanding of day-to-day activity, and potentially lead to more effective intercessions to reduce the incidence and effects of falls. As well, by further challenging the CNS to recover from external balance perturbations by means of rapid triggered stepping reactions, we can examine potential limitations in the control of these responses.

The following sections will provide an overview of the concept of balance, along with reactive and predictive postural control strategies. A review of modifications to volitional movement in response to obstacles will be given, and a summary of CNS control of balance will be provided. The chapter will conclude with what is known so far about the modulation of compensatory movement.
CHAPTER 2 - REVIEW OF THE LITERATURE

2.1 Postural Control

Although little of everyday conscious thought may be directed towards maintaining a stable posture, it is by no means a small task. The CNS must continuously monitor the current motion of all the body segments, anticipate any upcoming self-generated or external perturbations, and suitably react to any unexpected ones. Additionally, the system itself is inherently instable, with about two thirds of the body's mass positioned above the lower limbs (Winter et al., 1990), and involves only a narrow support basis. From a biomechanical standpoint, the goal of the CNS is to regulate the body centre-of-mass (COM) movement relative to the base of support (BOS) (Horak and MacPherson, 1995; Maki and McIlroy, 1996). Therefore, maintaining equilibrium can be achieved by manipulating either of these parameters. The motion of the COM itself can be controlled through the generation of joint torques via the ground reaction forces of the supporting limbs (Maki and McIlroy, 1996), or equilibrium can be recovered by expanding the BOS through stepping or grasping to encompass the COM movement. Expansion of the BOS can potentially increase the moment arm for the ground reaction forces to act about the COM as well (Maki and McIlroy, 1997; Maki and McIlroy, 1999b), further increasing the effectiveness of this approach. Either of these control efforts can be instituted predictively in anticipation of a change in COM motion, or reactively, in response to an unforeseen destabilizing event to the body equilibrium. The different roles and importance of predictive and reactive balance control will be covered in more detail in section 2.2 and 2.3.

There are many occasions, however, when the COM does not lie directly over the BOS during human motion, yet stability is maintained. A prime example of this is during locomotion (Shimba, 1984; MacKinnon and Winter, 1993), where the COM
passes only along the medial border of the foot, or even outside of that border. Indeed, gait has been described as a continuous state of the COM falling down, with the stride of each foot arresting its fall until the next step (Winter, 1991). An important consideration in the relationship between the BOS and COM are the inertial effects of motion. In this case, a more dynamic stability measure is appropriate, which accounts for both COM motion and forthcoming BOS changes (Pai and Patton, 1997; Maki and McIlroy, 1999b). Even during quiet stance, stability is not a static task. The body COM is in continual motion as the body naturally sways, and varying muscle forces act to direct the centre of pressure (COP), the focal point of the ground reaction force, to compensate for such fluctuation, (Horak and MacPherson, 1995).

2.2 Reactive Postural Control

Despite rather extensive research in the area, there is still much to be understood about postural control. Attempts have been made to classify postural reactions generated in response to externally generated perturbations. In order to elicit balance-correcting responses, an assortment of methods have been utilized to provide a postural perturbation. A postural perturbation has been defined as a sudden change in conditions that displaces the body posture away from equilibrium (Horak et al., 1997), and can be mechanical or informational in nature. Informational, or sensory, perturbations are perceptions of instability, rather than actual disequilibrium. Examples would include vestibular stimulation, moving visual fields, or somatosensory perturbations by muscle vibration. Mechanical perturbations, on the other hand, are forces acting on the body, which either directly alter the motion of the COM, or prevent the appropriate establishment of the BOS beneath the COM (Maki and McIlroy, 1996). They can be either self-induced, such as pulling on a handle or lifting a leg, or externally delivered, the methods for which are wide and varied. The use of translating
and rotating platforms, waist-pull perturbations, slippery or unstable support surfaces, and actual pushes to the body have all been used in experimental paradigms to investigate responses to postural disturbances.

Early balance studies focussed on feet-in-place (FIP), or fixed support, reactions in response to balance disturbance. These stereotypical patterns of muscle activation, termed muscle synergies (Shumway-Cook and Woollacott, 1995), seek to maintain the COM within a static BOS. Through coordinated muscle activity, torques produced about the joints of supporting limbs counteracts the destabilization. Prime examples of this include the ankle and hip strategy, both elicited in response to antero-posterior (a-p) disturbances (Horak and Nashner, 1986). The ankle strategy is characterized by whole body sway about the ankle, and corresponds to relatively small perturbations. The hip strategy comprises trunk flexion or extension about the hip, and is induced with larger perturbations or when standing on a reduced support surface. These automatic postural responses (APRs) can be modified to some degree (Horak and Nashner, 1986; McIlroy and Maki, 1993a; Burleigh et al., 1994; McIlroy and Maki, 1995a; Burleigh and Horak, 1996). For example, when the perturbations are predictable, the magnitude of the APR can be accordingly modulated. Due to their 'automaticity' and rapid onset (70-140 ms depending on the conditions of the perturbation (Horak and Nashner, 1986)), they provide a first line defense against balance disturbances.

In the face of more robust perturbations, fixed support reactions may not be sufficient to contain the COM motion. In light of this, more recent studies have shifted to include change-in-support (CIS) reactions to perturbations (Do et al., 1982; McIlroy and Maki, 1993b; McIlroy and Maki, 1993c; Maki et al., 1993; McIlroy and Maki, 1995a; McIlroy and Maki, 1996a; Rogers, 1996; Maki and McIlroy, 1997; Maki and McIlroy, 1999b; Maki and McIlroy, 1999a). These responses are typified by a change in the BOS, either by compensatory stepping or grasping. Whereas FIP reactions are able to restore
balance from small perturbations, compensatory limb movements afford a much greater degree of stabilization. Although originally thought that CIS reactions were measures of last resort, deferring to a CIS only after the FIP response was fully overwhelmed (Horak, 1992, Shumway-Cook, 1995 #94), this view was based on paradigms which either intrinsically (instructions to not step) or extrinsically (not possible to step) constrained the response of the subject. However, when stepping is not impeded and subjects are permitted to respond naturally, CIS reactions are a prevalent response to postural perturbation (McIlroy and Maki, 1993c; Luchies et al., 1994), and occur well before stability limits are approached (McIlroy and Maki, 1993c; Maki and McIlroy, 1997).

FIP and CIS responses are not in opposition to one another, and the use of either is not the result of a 'this-or-that' schema. Indeed, these responses are not discrete or sequential (Maki and McIlroy, 1997), but are combined in various manners in the efforts of postural control (Shumway-Cook and Woollacott, 1995). For instance, a compensatory step, with a typical onset of 150-250 ms after platform perturbation (McIlroy and Maki, 1995a), is always be preceded by the earlier ankle strategy response. This occurs despite the fact that the ankle strategy is opposing the COM motion that, to some degree, is necessary to perform a step. As mentioned previously, though, APRs can be subject to modulation, and when subjects are encouraged to step as opposed to not step, the response in the ankle musculature has been seen to drop by approximately 40% (McIlroy and Maki, 1993a). As well, FIP responses that are not followed by a step often display asymmetries in the frontal plane that represent a preparation for stepping, presumably if the need so arises (Maki et al., 1993).

2.3 Predictive Postural Control

The CNS can often successfully anticipate forthcoming postural demands, as dictated both by external constraints (i.e. environmental conditions) and internal
constraints (i.e. characteristics of the body) (Massion, 1992). Whereas reactive postural adjustments rely on sensory feedback to detect an imbalance and initiate the response, predictive control instead acts in expectation of a forthcoming perturbation, thereby preemptively countering the equilibrium disturbance. This control, acting in a feedforward manner, acts to maintain equilibrium and stabilize body segments as required. Although forces exerted by the external environment on the body may be the more obvious case, self-initiated movement can also cause a perturbation. Reaction forces acting between body segments, along with possible changes in the body mass distribution due to changes in body geometry or load manipulations, lead to postural disturbances (Massion, 1992). Actions generated in an effort to counter expected disturbances, termed anticipatory postural adjustments (APAs), have been shown to precede or occur simultaneously with a variety of volitional movement in a wide range of cases, as reviewed by Massion (1992).

The production of an APA is likely to be affected by the expected magnitude and direction of the perturbation, voluntary action associated with the perturbation, and the postural task at hand (Aruin et al., 1998). Movements of the lower limb are of particular interest when considering APAs. Not only will leg movement shift the whole body COM, similar to what occurs with upper limb and trunk movement, but has an even greater impact on stability as it is also usually involved with supporting the body weight. Upon leg lift, a significant reduction in the BOS width can be expected, and body support then becomes the sole responsibility of the remaining support limb. If this change in equilibrium is not adequately accounted for, instability will ensue and reactive measures will become necessary. To this end, the APA seeks to drive the COM towards the stance limb prior to a leg lift (Rogers and Pai, 1990; Massion, 1992; Mouchnino et al., 1992), as well as during gait initiation (Breniere et al., 1987; Nissan and Whittle, 1990; Brunt et al., 1991; MacKinnon and Winter, 1993; Jian et al., 1993) and thereby promote lateral
stability. Moreover, although this control is acting in a feedforward manner, the APA can be scaled quite accurately to the forthcoming volitional movement (Crenna et al., 1987, Rogers, 1992 #95; Lyon and Day, 1997).

Since APAs act predictively, it follows that the CNS must possess some idea of what disturbance is forthcoming to be successful. Therefore, novel or unexpected movements may be exempt from anticipatory control, as the unfamiliarity prohibits the CNS from making any accurate estimation of accompanying postural disturbance. The organization of anticipatory movements relies on previous experience, and this is demonstrated by the development of anticipatory behaviour in children (Ledebt et al., 1998).

Despite the accuracy and consistency of APAs in volitional stepping, they are commonly absent or extremely reduced during compensatory stepping (McIlroy and Maki, 1993b; McIlroy and Maki, 1995a; Rogers, 1996; McIlroy and Maki, 1999a), although there is some recent evidence to dispute this (Maki and McIlroy, 1999a; McIlroy et al., 1999). While the need, then, to recover m-l stability upon landing seems to cause little if any problems for young subjects, older subjects appear to have more difficulty with this (Maki and McIlroy, 1996). The rapid onset and execution of compensatory movements may preclude the need or capability for any substantial m-l COM motion adjustment prior to the step. The CNS may also be reluctant to employ an APA due to potential error in approximating the compensation for the forthcoming perturbation, and therefore, view them as an additional possible source of perturbation (Aruin et al., 1998). Moreover, unpredictable perturbations may prevent the CNS from making any informed and reliable estimate of the upcoming movement.

Conversely, the lack of anticipatory control could be an overall reflection of the limited modifiability of these compensatory reactions. Although APA's typically precede loading and unloading of the upper limb when self-initiated, they are absent when the
event is externally triggered, even under highly predictable circumstances (Struppler et al., 1993; Aruin and Latash, 1995; Scholz and Latash, 1998). The concurrent absence of anticipatory control in compensatory stepping, then, suggests the response may rely more on external cues (e.g. COM motion) in comparison to volitional movement. If CIS reactions are indeed reflexive and stereotypical in nature, higher centers of the CNS may be incapable of imposing any significant degree of modulation. In contrast to these findings, though, it was recently shown that an APA could precede rapid withdrawal of the lower limb from a noxious stimulation (McIlroy et al., 1999).

2.4 Substrates of Postural Control

The control of posture represents a complex and challenging task that utilizes a broad range of sensory feedback and structures throughout the CNS. Loci involved in postural control have been identified through studies of patients with specific lesions of the CNS and animal preparations. The adaptability of balance control strategies to situational demands can also provide insight into CNS control. This topic, however, is covered separately in section 2.5.

Sensory feedback regarding postural state of the body arises from three sources: visual, vestibular, and somatosensory. Visual information is important to feedforward control while navigating difficult and unfamiliar environments (Dietz, 1992; Hollands et al., 1995; Hollands and Marple-Horvat, 1996) and for detecting motion of the body relative to extrapersonal space (Horak et al., 1989). During quiet stance with vision removed postural sway does increase, but at low frequencies (Diener and Dichgans, 1988). The function of vision during compensatory stepping remains unclear. When vision is removed in postural-perturbation tasks, there is little effect (Ledin and Odkvist, 1991; Dietz et al., 1992), suggesting it is not central to the task.
The vestibular apparatus within the inner ear is comprised of the two otolith organs and three semicircular canals aligned orthogonal to one another. Movement of fluid within the canals provides feedback of angular acceleration and velocity of the head, while the otolith organs detect linear acceleration and orientation to the field of gravity (Kelly, 1991). The vestibulospinal tract provides a direct pathway between the vestibular receptors and alpha motoneurons for control of neck, trunk, and limb musculature. While patients with bilateral vestibular loss can be studied to investigate the function of this sensory system (Allum et al., 1988; Horstmann and Dietz, 1988), tilting the head backwards has also been used to modify vestibular information (Diener et al., 1986), along with galvanic stimulation (Inglis et al., 1995). While important to the function of stabilizing the head and gaze, the vestibular system's part in postural control is unresolved: some results suggest that it makes significant contributions to postural control, while other work proposes it has a lesser role (Dietz, 1992). It appears that the vestibular system is also not responsible for initiating perturbation-cued stepping responses, but may have an important interaction with visual system during the execution of these reactions (Do et al., 1988; Hoshiyama et al., 1993).

Somatosensory feedback includes proprioception provided by receptors in the muscles and joints, and cutaneous sensation. Muscles contain two receptor types that provide feedback about muscle stretch (muscle spindles) and muscle tension (golgi tendon organs). While golgi tendon organs lie in series with the muscle at the junction of the muscle and tendon, muscle spindles are within the muscle itself and are parallel to the muscle fibers. Muscle spindles also receive efferent input, which regulates its sensitivity and allows for length changes to match that of the surrounding muscle. They provide the feedback which drives monosynaptic and polysynaptic reflexes (Gordon and Ghez, 1991). As well, receptors exist within the joints that provide information position and rate of change of the joint. Muscle vibration (Magnusson et al., 1990) and leg
ischemia paradigms (Diener et al., 1984) have been used to manipulate the feedback from this sensory system. Based on such work, it appears that proprioceptive cues are particularly important in the triggering of initial responses to evoked perturbations. Another type of somatosensory feedback, cutaneous sensation from the soles of the feet provide, also provides specific direction and phase dependent roles during compensatory stepping (Maki and McIlroy, 1999a; Perry et al., 2000).

While sensory systems detect an imbalance, the musculoskeletal system is responsible for enacting force to control the body. Skeletal muscles are controlled via alpha motoneurons arising in the ventral horn of the spinal cord, one per motor unit. A motor unit is comprised of the motor neuron and the muscle fibers it innervates, the number of which can vary. The rate at which the motor neuron fires, and the pattern of firing, dictates the amount of tension produced in the muscle, along with the viscoelastic properties of the tendons and connective tissues (Ghez, 1991b). Since muscles are only capable of pulling, motion about a joint is produced by at least two muscles acting in opposition to one another.

As mentioned, multiple loci within the CNS contribute to balance control, including the spinal cord, brain stem, cerebellum, basal ganglia, and cerebrum. This is evidenced through animal preparations and patients with specific CNS lesions. Animal preparations permit direct manipulation to CNS structures, either by directly removing or 'knocking-out' loci or severing higher sections of spinal cord and brain. While complete transection of the spinal cord at the thoracic level of cats still allows for the production of complex, coordinated movements of the limbs (e.g. walking on a treadmill with body weight supported), independent, unsupported stance cannot be maintained for any meaningful period of time (Shumway-Cook and Woollacott, 1995; Macpherson et al., 1997; Fung and Macpherson, 1999). Additionally, the ability to generate appropriate reactions to perturbations of stance is lost. Although these and other animal preparation
studies are useful, their results may not be entirely applicable to humans for several reasons. The obvious reason is variations in CNS organization and development between species, but besides this, these tests apply to quadrupedal stance, and may not necessarily transfer to bipedal stance as in humans. As well, there may be some reorganization of the CNS when recovery is allowed after the lesion, and sensory related input can differ considerably (Van de Crommert et al., 1998).

Studies of patients with neurological lesions provide inferences to what role the damaged structures in their CNS play. Parkinson's disease has its CNS origins in the basal ganglia. Deficits in the spatial and temporal organization of the response imply that the basal ganglia are important to the sensorimotor integration of postural control (Horak et al., 1992; Beckley et al., 1993; Horak et al., 1996). As well, Parkinsonian patients demonstrate an improper scaling of compensatory balance reactions (Beckley et al., 1991), and temporospatial characteristics of APAs prior to volitional movement are also impaired (Latash et al., 1995). Alzheimer patients may also have basal ganglia abnormalities, however, recent studies have shown that they do not share all the same deficits as those with Parkinson's (Chong et al., 1999b; Chong et al., 1999a). Patients with cerebellar lesions, while manifesting the general symptoms of hypotonia and ataxia, can also have related abnormalities with gait and truncal control, depending on the exact location of the lesion (Ghez, 1991a). As well, when presented with a series of predictable perturbations, they cannot learn to scale their postural responses predictively (Horak and Diener, 1994). Other common neurological diseases, such as stroke, do not have invariant lesion locations, and therefore may not be as useful when trying to attribute postural deficits to specific loci in the CNS, unless imaging can be used to identify the lesion sites.

There is some evidence linking the premotor motor area and supplementary motor area to the production of APAs. As reviewed by Massion (1992), patients with
lesions within these regions demonstrate impaired APAs during arm lifting while standing and in bimanual load lifting. These results support the idea that voluntary movement produces a motor program for the prime movement along with an independent but coordinated motor program for the APA required the supplementary motor area (Ghez, 1991c). There has also been some contradictory evidence linking the basal ganglia to this function as well (Massion, 1992). Regardless, it does seem that supraspinal structures play an important role in the modulation of APAs.

Compensatory stepping may have origins in the central pattern generator (CPG), which is a neural network capable of producing cyclical pattern of flexor and extensor action (Duysens and Van de Grommet, 1998). Evidence for the existence of CPGs comes primarily from cat preparations, with some limited additional evidence from primates and man (Duysens and Van de Grommet, 1998). It has been speculated that the patterns of muscle activation in triggered stepping reactions arise from the same neural network thought to be involved in control of gait, with the initiation and scaling of the response controlled by transcortical or subcortical pathways associated with the control of early FIP responses (Maki and Mcllroy, 1997).

Movements can also be distinguished into four types in terms of their responses to environmental stimuli (Schmidt and Lee, 1999). At one end of the spectrum are monosynaptic reflexes, such as the stretch reflex, which comprises an afferent input from a muscle spindle synapsing directly on to an alpha motor neuron of the same muscle within the spinal cord. These are extremely rapid responses (30-50ms), and can be modified to some degree by higher centers, but never fully suppressed (Schmidt and Lee, 1999). The long-loop reflexes, which are generated in response to afferent feedback travelling to higher brain centers, follow the monosynaptic responses temporally (50-80ms), and can be suppressed. At the other end of the spectrum lies voluntary movement, which has much slower onset latencies, but has a high degree of
modifiability. Somewhere between reflexive and voluntary behaviour lies triggered reactions. They are faster in onset (80-200ms) than voluntary reactions, but can also produce highly coordinated responses. As well, they can be triggered by various receptors, unlike the simple stretch reflex. The APR is an example of this type, and so is compensatory stepping. Like triggered reactions, they can be modified to some extent, however the degree to which has not been fully defined.

2.5 Modifiability of Postural Reactions

Studies of modulation of postural reactions have primarily considered effects of prior instruction, practice, and predictability of perturbation (McIlroy and Maki, 1993a; Burleigh et al., 1994; McIlroy and Maki, 1995a; Burleigh and Horak, 1996). When conditions are predictable, or prior instructions direct the type of response, the triggered APR can be appropriately modified via supraspinal control. It has been proposed that the CNS uses a feedforward control for the response, capable of increasing or decreasing the gain substantially as the case may be (McIlroy and Maki, 1993a; Burleigh et al., 1994; Burleigh and Horak, 1996). Modulation of the APA is also purported to be partially regulated by ongoing afferent information regarding the nature of the perturbation (Burleigh et al., 1994; Burleigh and Horak, 1996). With increased familiarity with translational support-surface perturbations, there is decreased incidence of stepping and number of steps taken, if any (Maki and McIlroy, 1997). Additionally, the APA, absent in early trials, begins to appear, albeit in a reduced form (McIlroy and Maki, 1995a).

There are limited examples of postural reactions modified to environmental features. Lower limb studies have considered a reduced surface-support area for the foot (Horak and Nashner, 1986), which elicits the hip strategy as opposed to the ankle strategy. However, this strategy is not immediately manifested, but instead requires learning and explicit instructions not to step (Maki and McIlroy, 1997). Another example
includes the adoption of a gliding or 'surfing' strategy while standing on a slippery surface, as opposed to a typical APR (Zettel et al., 1999). Furthermore, the sole reliance on an ankle or hip strategy may also be considered as an adaptation to environmental stepping constraints (i.e. lack of space to step), given the natural preference to step.

Compensatory upper limb movements inherently entail environmental accommodation. Grasping must be adjusted to exactly match available handholds in the nearby area. Furthermore, these targets may vary widely in location. Comparatively, compensatory upper limb reactions share some similarities with lower limb, in terms of prevalence and being scaled to the perturbation, but differ in that they exhibit a faster onset time (McIlroy and Maki, 1995b; Maki and McIlroy, 1997). Arm trajectories are remarkably consistent and accurate, despite unpredictable perturbations altering the initial position of the upper limbs and body (Maki et al., 1998). Also, these reactions can be rapidly corrected on-line, such as when a potential target location is withdrawn suddenly following the perturbation (McIlroy and Maki, 1999b). Although compensatory responses of the leg are a greater challenge to stability, some shared similarities between the upper and lower limb suggest that compensatory stepping may also share the same degree of modulation.

2.6 Accommodation of Volitional Movement to Obstacles

Although there have been no studies of obstacle clearance during compensatory stepping, accommodation of volitional movement to obstacles and environmental constraints has been well studied (Chen et al., 1991; Patla et al., 1991; Patla and Rietdyk, 1993; Chen et al., 1994b; Chen et al., 1994a; Hollands et al., 1995; Patla and Prentice, 1995; Hollands and Marple-Horvat, 1996; Patla et al., 1996; Chen et al., 1996; Chou and Draganich, 1997b; Chou and Draganich, 1997a; McFadyen and Carnahan, 1997; Armand et al., 1998; Taga, 1998; Austin et al., 1999; Brunt et al., 1999; Brunt et
al., 2000; Gelat and Breniere, 2000; Chou et al., 2001). These studies have included the use of physical barriers, level changes, and 'virtual' obstacles, as well as directed areas of foot placement. The majority have studied obstacle avoidance during steady state gait, while a few have considered it from quiet stance or gait initiation (Brunt et al., 1999; Brunt et al., 2000; Gelat and Breniere, 2000). Furthermore, most have reported COM control only in the sagittal plane, while frontal plane control has received attention in only a few obstacle crossing studies (Chou et al., 2001).

One of the primary findings regarding obstacle crossing during gait is that it is done so with much caution. For example, substantially increased foot clearances act to reduce the possibility of obstacle contact, while reduced speed of the foot and COM during crossing serve to minimize the potential consequences of a trip (Chen et al., 1991; Patla and Rietdyk, 1993; Austin et al., 1999). These adjustments become more pronounced with increases in obstacle size, but are more sensitive to height increases rather than width. Modifications are even made in response to the apparent fragility of the obstacle (Patla et al., 1996). Similar modulations of sagittal COM motion have been demonstrated for several different obstacle conditions when stepping from quiet stance (Brunt et al., 1991; Brunt et al., 1999; Gelat and Breniere, 2000).

For the most part, there is little difficulty in accommodating obstacles during volitional movement, provided it is known about well enough in advance. Alterations to the step width and length, and even avoidance of low obstacles can be accomplished within the same step cycle of gait, while cued directional changes requires planning in the previous step (Patla et al., 1991). However, when the available time to respond to an obstacle is decreased, as in the case with rapidly appearing obstacles, failure rates become markedly larger when available response time is within 400ms of predicted foot contact, and suffer further with additional decreases in available time (Patla et al., 1991; Chen et al., 1991). These times coincide roughly to just prior to foot lift, and this is also
the period where visual sampling primarily takes place for planning the next step placement (Hollands et al., 1995; Hollands and Marple-Horvat, 1996).

The elevated foot clearance during obstacle crossing can be attributed primarily to flexion of hip, knee, and ankle, but there is also a contribution made from elevation of the hip (Patla and Rietdyk, 1993). The differences in swing trajectory for obstacles of different heights can be seen immediately at time of toe-off. Also, the moments of the lower limb joints, mainly at the knee and hip, are modified prior to foot lift as well in response to obstacles or level changes. These changes have been termed anticipatory locomotor adjustments (McFadyen and Winter, 1991; McFadyen et al., 1993; Patla and Prentice, 1995; McFadyen and Carnahan, 1997). Based on these early adjustments and visual sampling times, feedforward control does seem to play a role in obstacle avoidance during voluntary movement.

While modulation of movement in the sagittal plane have been well demonstrated in response to obstacles, the only study found to consider frontal plane motion during obstacle crossing was during steady-state gait (Chou et al., 2001). While antero-posterior (a-p) COM motion was reduced and vertical COM motion increased in response to higher obstacles, there was little, if any, indication of altered m-l motion. Such invariance may indicate the importance of controlling frontal plane COM motion, in order to maintain stability during obstacle crossing.

2.7 Objectives & Hypothesis

Given the prevalence, apparent preference, and potential of compensatory stepping in the recovery of balance, further understanding of these responses is required. To date, little work has considered how these rapid triggered stepping reactions may be modulated in response to environmental constraints (i.e. obstacles). Given the pervasiveness of obstacles in our everyday surroundings, a more complete
understanding of these movements may be achieved with the inclusion of environmental restrictions. The objectives of this thesis, then, were to determine: 1) whether forward compensatory stepping reactions could be modified to accommodate a nearby, high, frontal obstacle, and at what success rates; 2) how and when these modulations are implemented, and what this implies about CNS control of these reactions; 3) baseline information regarding postural responses to obstacles to eventually be compared against older subjects and other clinical populations, in an effort to further understand age-related changes and balance impairments. As well, a better understanding of the CNS can be gained by challenging its control of these responses with a more difficult environment.

Given the modifiability of upper limb movements, and that obstacles are constantly encountered and managed in unpredictable, everyday life, it was hypothesized that subjects would be able to successfully restore equilibrium following a forward perturbation while still avoiding a high frontal obstacle. A lack of m-l anticipatory control in compensatory stepping, however, would present significant difficulties in maintaining frontal plane stability following the extended swing times necessary to traverse the obstacle. Based on the consistent absence of APAs and their potential interference in a-p stability control it seemed unlikely that any significant predictive control would be implemented prior to the step. Instead, we hypothesized that modulations would rely on other more reactive measures, such as multiple stepping, or diagonally directed foot placement.
3.1 Introduction

It is well known that volitional and locomotor stepping movements can be successfully modulated to accommodate environmental constraints, as demonstrated by the adaptations implemented when stepping over obstacles (Chen et al., 1991; Patla et al., 1991; Patla and Rietdyk, 1993; Chen et al., 1994a; Chen et al., 1996; Patla et al., 1996; McFadyen and Carnahan, 1997; Brunt et al., 1999). However, the extent to which stepping movements can be modulated when executed as rapid triggered reactions is unclear. Previous studies have indicated that compensatory stepping reactions, triggered by postural perturbation, differ in some fundamental ways from volitional stepping. For example, these triggered stepping reactions are initiated and executed much more rapidly than even the fastest efforts to step in response to a visual cue (Mcllroy and Maki, 1993c; Mcllroy and Maki, 1996b; Maki and Mcllroy, 1997). Furthermore, the mediolateral (m-l) anticipatory postural adjustments (APA) that invariably precede volitional stepping movements are commonly absent, or severely truncated, during perturbation-evoked stepping (Mcllroy and Maki, 1993b; Mcllroy and Maki, 1995a; Rogers, 1996; Mcllroy and Maki, 1999a). If, as it appears, triggered stepping reactions are more automatic and stereotypical in nature than volitional stepping movements, then the capacity of the central nervous system (CNS) to modulate these triggered reactions in response to demands imposed by obstacles or other environmental constraints could be limited.

Previous work on modifiability of triggered stepping reactions has been limited primarily to effects of prior instruction, practice and predictability of perturbation (Mcllroy and Maki, 1993a; Burleigh et al., 1994; Mcllroy and Maki, 1995a; Burleigh and Horak, 1996), rather than effects of environmental constraints. It has been demonstrated,
however, that alterations in the size of the support surface can affect strategy selection, i.e. use of ankle, hip or stepping strategies (Horak and Nashner, 1986; Maki and McIlroy, 1997). It has also been demonstrated, in a study of compensatory upper-limb (reach and grasp) reactions evoked by unpredictable perturbation, that even the earliest portion of the limb trajectory is modulated in accordance with the handhold location (McIlroy and Maki, 1995b; Maki and McIlroy, 1997; Maki et al., 1998). While some environmentally-driven modulations appear to require learning (e.g. implementing a hip strategy when standing on a shortened surface (Maki and McIlroy, 1997)), the modulation of limb trajectory to match handrail location, during compensatory grasping, appears to occur automatically in the very first trial (Maki and McIlroy, 1997).

Although the arm-reaction studies (McIlroy and Maki, 1995b; Maki and McIlroy, 1997; Maki et al., 1998) indicate that it is possible for the CNS to modulate rapid triggered upper-limb movements to meet environmental demands, the control of triggered lower-limb movements to avoid obstacles is much more complex, due to the increased challenge of maintaining stability during stepping. Any modifications made to the spatial and temporal properties of the foot movement must not compromise the capacity of the step to arrest the motion of the body's center of mass (COM) induced by the perturbation. Furthermore, the CNS must also deal with the lateral instability that is created when the swing foot is lifted, i.e. due to the tendency of the body to fall toward the unsupported side (McIlroy and Maki, 1999a). One of the control issues of particular interest pertains to the use of the m-l APA to counter this lateral instability, by propelling the COM toward the stance leg prior to leg-lift (Breniere et al., 1987; Rogers and Pai, 1990; Do et al., 1991; Mouchnnino et al., 1992; Jian et al., 1993; Lyon and Day, 1997; Mille and Mouchnnino, 1998). The task of stepping forward over a large obstacle requires prolongation of the swing phase (Patla and Rietdyk, 1993), which could result in excessive m-l COM motion if not countered by a large APA. Conversely, delaying initiation of swing phase, due to
inclusion of an APA, could allow excessive perturbation-induced antero-posterior (a-p) COM motion to occur, which could compromise a-p stability as well as the capacity to avoid contact with the obstacle.

The present study was undertaken to determine: 1) whether perturbation-evoked forward stepping reactions can be modulated to accommodate a challenging, high obstacle, 2) whether such modulation occurs automatically (i.e. in the very first exposure to the task), and 3) which specific stabilizing features of the stepping reaction are modulated. A primary focus was on the modulation of the m-l APA and the lateral step distance. In view of the potential costs of including a prolonged APA (i.e. a-p instability or failure to clear obstacle due to delay in foot-lift), it was hypothesized that APAs would not be used to control lateral stability during obstacle clearance. Instead, it was hypothesized that lateral stability would be maintained by altering the step direction (i.e. incorporating more lateral displacement) or by executing additional steps in the lateral direction.

The main focus of the study was on compensatory stepping responses evoked by highly unpredictable perturbation. In addition, to address effects of the capacity to preplan the reaction, we studied perturbation-cued responses elicited under predictable perturbation conditions, as well as volitional light-cued responses. A high obstacle was used so as to challenge stability, i.e. by forcing a substantial increase in the duration of the single-limb support phase. Results demonstrated a remarkable capacity for immediate and effective alterations to compensatory stepping reactions. Surprisingly, lateral stability was maintained through a combination of both APA execution and lateral step placement. Moreover, this "hybrid" control was not dependent on prior practice, appearing even in the very first trial.
3.2 Materials and Methods

Compensatory stepping reactions were evoked by sudden, unpredictable horizontal movement of a large (2mx2m) moveable platform (Maki et al., 1996). Cued forward-stepping reactions were elicited by visual cue and by backward platform translation. Each platform translation comprised a 300ms square-wave acceleration pulse followed immediately by an equal and opposite deceleration pulse. Tests were performed both with and without an obstacle. The obstacle was a narrow bar (3.5cm diameter, 150cm in length) placed transversely in front of the subject (2.5% of body height from the toes) at a height equal to 15% of body height that was attached to and moved with the platform. For safety, the bar was padded with foam rubber and affixed in such a way to release upon contact. Eleven healthy, naive, young adults (ages 21-30, height 160-188cm, weight 54-106kg) were tested. All were right-hand and right-leg dominant and reported no medical conditions affecting balance. Each subject provided written informed consent to comply with ethics approval granted by the institutional review board.

Subjects began all trials in a standard foot position (11% of body height between heel centers, 14° angle between medial borders of feet; McIlroy and Maki, 1997) at the center of the platform, with vision focused straight ahead on a target (or, in visual-cue trials, an array of light-emitting diodes) mounted on the platform at eye level approximately 1m away. A safety harness, designed to prevent falls without providing somatosensory feedback that might influence balance control, was worn. A lightweight rod (3cm diameter, 40cm length) was held behind the buttocks, arms relaxed at full length, to deter arm movement. In the initial unconstrained trials, subjects were instructed to do whatever came naturally to prevent themselves from falling while avoiding contact with the obstacle. To control attentional variation, subjects counted backwards out loud by serial three's (starting at a random number given at the start of the
trial), and were instructed to continue counting until the platform stopped moving. In the cued trials, subjects were told to take one step forward over the obstacle with their right leg as soon as they detected the stimulus (no counting task). The cue was rendered either visually (light-emitting diodes) or by perturbation (large backward platform movement; 3.0 m/s², 0.9 m/s). In all tasks, subjects were instructed to minimize extraneous movement, to avoid moving their arms and to hold their final position for two seconds.

In the main experiment, each subject performed four blocks of unconstrained trials (two blocks with the obstacle, two blocks without). Each block comprised 17 trials: three large (3.0 m/s², 0.9 m/s), three medium (2.0 m/s², 0.6 m/s), and three small (1.0 m/s², 0.3 m/s) backward translations, two translations (one small, one large) in each of the forward, left and right directions, and two "catch" trials in which the floor did not move. Order of testing the obstacle (O) and no-obstacle "control" (C) conditions was balanced both within and across subjects (half performed O/C/C/O and half performed C/O/O/C). To allow effects of learning to be assessed, a series of three identical unconstrained trials (large backward translation) was administered immediately before and after the end of the main experiment; half of the subjects performed these trials under the obstacle condition and half performed these trials with no obstacle. After completing the unconstrained trials, six perturbation-cued and six light-cued obstacle trials were performed, the order also counterbalanced across subjects. The protocol, as detailed above, pertains to eight of the 11 subjects. The other three subjects performed a longer protocol in which an additional long-obstacle condition was included (not analyzed here); in two of these subjects, this was the first unconstrained condition tested.

Two forceplates (Kistler model 9281; AMTI model OR6-5) embedded flush with the surface of the moving platform were sampled at 200 Hz to determine center of foot pressure (COP), COM and step timing. The forceplate signals were also monitored
online, prior to each cued stepping trial, to prevent anticipatory leaning or weight shift
(the subject was given verbal feedback, if required, to move the a-p and m-l COP within
±4% of the average values recorded during an unperturbed-stance trial). Accelerometer
signals were used to correct the forceplate measures for inertial artifacts arising from the
platform motion. Video recordings from four high-resolution cameras (shuttered at
1/500s) were used to code postural behavior (i.e. failure to clear the obstacle, number of
steps taken), to determine foot placement and to verify foot-off (FO) and foot-contact (FC)
values determined from the forceplates. Time of FO was identified by swing-leg
unloading (vertical ground-reaction force < 5% of body weight) and time of FC was
defined by an analogous increase in loading. Step onset was defined to occur when the
m-l COP displacement (relative to the pre-stimulus position) exceeded 4mm (McIlroy and
Maki, 1999a). All timing values were defined relative to onset of platform acceleration
(0.1m/s²) or visual cue.

The analyses focussed primarily on the effect of the obstacle on swing duration
(FO to FC), swing-foot placement (a-p and m-l step distance) and the characteristics of
the APA. Foot placement was determined by resolving (to within ±1cm) the position of a
reflective marker placed on the foot (fifth metatarsal head) relative to a grid marked on
the floor. APAs were defined to occur if the initial m-l COP displacement (>4mm) was
directed toward the swing leg (McIlroy and Maki, 1999a). The APA was characterized in
terms of the duration of the swing-side COP excursion, peak amplitude of the COP
excursion and approximate time-integral, i.e. 0.5 x duration x amplitude (see schematic
drawings, Figure 3.3).

Secondary analyses addressed possible modulation in the step timing (onset, FO,
FC; also, unloading phase duration, defined as time from end of APA to FO), the initial
(pre-stimulus) COM position and the early "automatic postural response" (APR) that
precedes step initiation. The APR, which involves active generation of ankle torque to
decelerate a-p COM motion, was characterized by the maximum velocity of the COP in the forward direction (McIlroy and Maki, 1993a). We also characterized the impact of the step modulations on the COM motion, up to time of FO and FC. Absolute a-p and m-l COM velocity and displacement were determined via successive integrations of the corresponding ground-reaction shear force with respect to time, starting at stimulus onset (Maki and McIlroy, 1999b; McIlroy and Maki, 1999a). To determine COM motion relative to the platform, platform velocity and displacement (measured using a linear potentiometer) were subtracted from the absolute COM measures. The initial COM position was estimated by averaging the pre-stimulus COP (500ms interval prior to stimulus onset).

The analysis focussed on forward stepping reactions evoked by large backward platform translation. For the main experiment (unconstrained compensatory stepping), repeated-measures analysis of variance (RMANOVA) was used to analyze the effect of the obstacle on the primary dependent variables (swing duration; APA amplitude, duration and time-integral; a-p and m-l step distance), as well as the secondary variables described above, and frequency of APA occurrence was analyzed using the Fisher exact test. To assess possible learning effects, RMANOVA was also used to analyze differences associated with the presence or absence of the obstacle in the first three unconstrained trials, and to compare these first three unconstrained trials with the last three. Finally, to assess effects of the opportunity to preplan a cued reaction, RMANOVA was used to compare unconstrained and perturbation-cued obstacle responses. Light-cued trials were used primarily as a benchmark for comparison, with regard to the size and magnitude of the APA. Where necessary, rank transformations were used to normalize the data and/or stabilize the variance, prior to performing each ANOVA (Conover and Iman, 1981). Trials where there was a failure to clear the obstacle were excluded from the analyses (N=11), as was one trial in which subject stepped "high" even
though no obstacle was present. Three trials were lost due to technical problems. Although we initially planned to examine multiple stepping as a possible control strategy, only one of the successful-clearance obstacle trials involved multiple steps (perturbation-cued trial); therefore, we elected to exclude all trials that involved multiple steps (11 non-obstacle trials, 1 obstacle trial). Numbers of trials included in the analyses are indicated in Figure 3.2 (see caption).

3.3 Results

Despite the fact that the perturbations were highly unpredictable, subjects were well able to modulate their forward stepping reactions to accommodate the obstacle while recovering balance. Moreover, this modulation did not require prior practice: 9 of 11 subjects cleared the obstacle in their first attempt. Over all unconstrained large-perturbation trials, failure to step over the obstacle occurred in only 12.2% (11/90) of cases. None of the failures was due to insufficient foot clearance. Instead, failures appeared either as a small initial step "under" the bar (followed by a step over the bar with the contralateral leg) or a step "through" the bar (contact with the upper shin). In all of the 79 unconstrained trials where the obstacle was cleared successfully, equilibrium was recovered by taking a single step (right leg in 73% of trials, left in 27%).

Although it is clear that profound modulation of the foot trajectory was necessary to step over the obstacle, the focus of this paper is on the modulations used to maintain stability during these stepping reactions, rather than the trajectory control. Example data are shown in Figure 3.1. The representative obstacle and no-obstacle trials shown in the figure illustrate many of the findings detailed below, pertaining to modulation of the APA and step placement, as well as effects on the COM motion. Descriptive statistics are summarized in Figures 3.2 to 3.4.

Modulation of unconstrained compensatory stepping: main experiment
As anticipated, the obstacle necessitated a much longer swing duration, in comparison to the no-obstacle condition (368ms vs. 157ms, p=0.0001; compare filled and unfilled bars in Fig. 2a). Contrary to our expectations that APAs would not be used to counter lateral instability arising from a prolonged swing phase, large APAs did in fact occur in the obstacle trials. Overall, subjects were more likely to include an APA when the obstacle was present: 100% (56/56) of successful-clearance trials versus 82% (51/62) of no-obstacle trials (p=0.0007). Furthermore, as shown in 3.3, the APAs that occurred during obstacle trials were on average much larger, by a factor of two or more, in terms of peak amplitude and time-integral, in comparison to no-obstacle trials (p's<0.0002). Average APA duration was also larger, by 50% (72ms), during the obstacle trials (p=0.0003).

The APAs occurring during obstacle trials were clearly more effective in propelling the COM toward the stance leg prior to foot-off: in comparison to no-obstacle trials, there was almost a threefold increase in COM displacement toward the stance leg (p=0.001; Fig. 4a) and the direction of the COM velocity was actually reversed (i.e. moving toward stance side rather than falling toward swing side; p=0.0005; Fig. 4b). However, even these large APAs were insufficient to counter the increased tendency of the COM to fall laterally during the prolonged swing phase: lateral COM displacement was three times greater (p=0.002; Fig. 4a) and COM velocity was nearly doubled (p=0.005; Fig. 4b) at FC, compared to no-obstacle trials. It is unlikely that systematic differences in pre-perturbation posture contributed to these findings, as the average difference in m-l COM position (relative to the stance or swing side) was only 0.003m, in comparing obstacle and no-obstacle trials.

Results did not strongly support our expectations that the cost of including a larger APA would be a delay in foot-lift and an associated tendency for the COM to fall farther forward. Although the duration of the APA was 72ms larger, on average, for the obstacle
condition, the delay in foot-lift was partially offset by a 15ms reduction in step-onset time (p=0.060) and 25ms reduction in the unloading phase (i.e. interval from end of APA to FO; p=0.0001). As a result, the average time to FO was only 32ms later than in the no-obstacle condition (p=0.061; Fig. 2a) and there was essentially no difference in the forward COM displacement at FO (p=0.94; Fig. 4c). Surprisingly, the forward COM velocity at FO was actually reduced, by about 17%, during obstacle trials (p=0.002; Fig. 4d). This effect could possibly be due to a larger early response at the ankle, although observed effects of the obstacle on APR magnitude were modest at best (5% increase in forward COP velocity in obstacle trials, p=0.11). It is unlikely that systematic differences in pre-perturbation posture affected the COM motion, as the average difference in initial a-p COM position was only 0.003m, in comparing obstacle and no-obstacle trials.

Although the delay in FO was small, there was a large delay in FC in the obstacle trials (244ms, 40%; p=0.0001; Fig. 2a) and an associated increase in forward COM excursion at FC (0.083m, 31%; p=0.0001; Fig. 4c). Clearly, the major contributor to this delay was the increased swing duration during obstacle trials, rather than the delay in FO. There was no obstacle-related difference in the forward COM velocity occurring at FC (p=0.54; Fig. 4d).

Modulations of step distance apparently helped to counter the instability arising from the increased a-p and m-l COM motion that occurred prior to landing, during the obstacle trials. In comparison to no-obstacle trials, the mean lateral displacement of the swing-foot, at landing, was three times larger (difference of 0.061m, p=0.032) and the anterior displacement was increased by 25% (0.120m, p=0.0001) during obstacle trials (Fig. 2b).
Modulation of unconstrained compensatory stepping: initial and final trials

The same trends that emerged in the main experiment were also evident during the subjects' very first three trials (compare unfilled bars to adjacent hatched bars in Figs. 2 to 4). As in the main experiment, lateral instability arising from the doubling of swing duration (required to clear the obstacle) was countered by increasing the APA amplitude ($p=0.0008$), duration ($p=0.037$) and time-integral ($p=0.003$) and by stepping more laterally ($p=0.026$), in comparison to no-obstacle trials. The larger APA moved the COM toward the stance limb to a greater extent prior to FO ($p=0.018$); however, the COM still fell farther ($p=0.034$) and faster ($p=0.05$) toward the swing side, prior to landing. The effect of the obstacle on a-p stability was also similar to the main experiment. The obstacle led to a 251ms delay in FC ($p=0.005$) and an associated increase of 0.06m in forward COM displacement, which was apparently compensated for by an increase of 0.075m in forward step length; however, it should be noted that neither the COM nor the step-length result achieved statistical significance (obstacle vs. no-obstacle, $p's>0.13$). Again, the delay in FC was due primarily to the increase in swing duration, rather than a delay in FO due to the increased APA duration. (As in the main experiment, the delay in FO due to the longer APA was offset by about 20ms due to an earlier step onset; however, there was only a 5ms reduction in the unloading phase). The FO delay, which was only 41ms, was not associated with any increase in forward COM displacement or velocity prior to FO ($p's>0.31$).

Remarkably, the modulations required to maintain stability during the obstacle clearance appeared in the very first trial, without prior practice or exposure to the perturbation. Three of the four subjects who performed the obstacle task in their very first trial stepped over the obstacle successfully, and all three generated large APAs (APA time-integral $>0.003\text{m-s}$). In contrast, for four of the five subjects who performed the no-obstacle task in their very first trial, APAs were either absent (two subjects) or very small.
(time integral<0.001m-s). (The fifth subject in this group behaved unusually in that he appeared to abort an initial effort to step, after completely unloading one leg, prior to stepping with the opposite leg.) Modulation of step placement also appeared to occur in the first trial: lateral foot displacement was much larger in the obstacle-first subjects (>0.15m), in comparison to the subjects who did the no-obstacle condition first (≤0.05m).

These early modulations of the stepping response were clearly effective: all subjects who stepped over the obstacle required only a single step to recover equilibrium.

There was little evidence, on average, that subjects learned to modulate their obstacle responses any more effectively with practice. In comparing the initial three trials to the final three trials, there were no statistically significant differences in any of the APA, COM, step distance or step timing measures described above (p's>0.07; compare diagonally-hatched bars in Figs. 2-4). Although there was an apparent trend toward allowing faster forward COM motion to occur at FC in the later trials (p=0.069; Fig. 4d), this same trend was evident in both obstacle and no-obstacle trials. An apparent tendency to step with smaller lateral displacement in the later trials was not statistically significant, presumably due to the large variability in these data (p=0.27; Fig. 2b).

**Modulation of cued stepping reactions**

In the perturbation-cued obstacle trials, perturbation characteristics were not varied, and subjects were given prior instruction to step and allowed to focus attention on this task (no counting task), all in an effort to promote the capacity to preplan the reaction. As shown in Figure 3.2a (horizontally-hatched vs. unfilled bars), these factors resulted in a much more rapid step onset and execution compared to unconstrained (main experiment) obstacle stepping: average step onset time was reduced by 56ms (p=0.002), APA duration by 47ms (p=0.011), unloading time by 19ms (p=0.01) and swing duration by 23ms (p=0.015). As a result, FO occurred 121ms earlier (p=0.0001) and FC occurred
144ms earlier (p=0.0003). Despite these changes in timing, the size (time-integral or amplitude) of the APA was not significantly altered (p's>0.32; Fig. 3), nor was the lateral placement of the foot (p=0.29; Fig. 2b). Furthermore, there was no change in m-l COM displacement or velocity, either at FO or FC (p's>0.3; Figs. 4a, 4b).

In contrast to the absence of changes in lateral-stability control, allowing subjects greater potential to preplan their stepping reaction did significantly alter the COM control in the sagittal plane. As illustrated in Figures 3.4c and 3.4d, all of the forward COM displacement and velocity measures were diminished (p's<0.04), in comparison to the unconstrained (main experiment) compensatory-step obstacle responses, with one exception: average velocity at FO actually increased by over 50% (p=0.0001). The reduction in forward COM motion at FC was associated with a reduction of 0.063m in forward step length (p=0.030; Fig. 2b).

Volitional light-cued obstacle stepping trials were included primarily to provide a baseline for comparison of APA control, on the premise that volitional control over the speed of the COM motion permits maximum expression of the APA. In these trials, the APAs were, on average, roughly twice as large as the APAs occurring during unconstrained (main experiment) compensatory obstacle stepping (0.0169m-s vs. 0.0073m-s, p=0.0001). This was achieved by both a larger APA amplitude (0.11m vs. 0.064m, p=0.0003) and duration (310ms vs. 216ms, p=0.0001). The result of such a large APA was to propel the COM three times farther toward the stance side by FO (0.034m vs. 0.011m, p=0.0001) and to greatly increase the speed of this COM motion (0.158m/s vs. 0.033m/s, p=0.0001). As a result of these adjustments, the COM did not fall toward the unsupported side during swing phase (m-l COM displacement at FC was 0.038m toward the stance side). Consistent with the fact that the large APA appeared to obviate the need for further lateral stabilization, lateral foot placement was much reduced in
comparison to unconstrained (main experiment) compensatory stepping (0.022m vs. 0.091m, \( p=0.011 \)).

3.4 Discussion

By introducing an obstacle into a paradigm used to study compensatory forward stepping reactions, we were able to examine the degree to which rapid triggered stepping movements can be modulated to deal with environmental constraints. The high obstacle placed in front of the subject forced a more than twofold increase in swing duration, during which time the COM would fall substantially farther, both forward and laterally, in the absence of appropriate predictive or reactive stabilization. Prior to this study, it was unknown whether the neural substrates that govern the control of rapid perturbation-evoked stepping reactions would permit the degree of modifiability needed to move the foot over a challenging obstacle while also meeting requirements for decelerating unpredictable, perturbation-induced motion of the COM. The results demonstrated a remarkable capacity for immediate and effective alteration to these stepping reactions, not only in avoiding the obstacle but also in recovering equilibrium in an efficient and controlled manner.

Contrary to the experimental hypothesis, the control of lateral stability was found to involve APA execution, as well as lateral step placement. Control of a-p stability appeared to primarily involve increase in a-p step distance, although there also appeared to be modulations aimed at initiating the step and unloading the swing foot more rapidly and increasing deceleration of the COM prior to foot-lift. This complex combination of adjustments appeared to require no prior practice or exposure to the perturbation, and did not change substantially over the course of repeated trials. Greater opportunity to preplan the reaction, during perturbation-cued trials, led to faster and shorter steps; however, the modulations of APA and lateral step placement remained intact. It appears
that the CNS is able to use exteroceptive visual information to alter key control parameters even when the time course of the perturbation-induced COM motion cannot be predicted. Clearly, the control is much more complex that the simple “release” of a stereotypical or “ballistic” movement pattern, as suggested in studies of “stumbling” reactions (Dietz et al., 1986).

Previous studies of obstacle avoidance have been restricted to volitional stepping and gait (Patla et al., 1991; Patla and Rietdyk, 1993; Chen et al., 1994a; Chen et al., 1996; Patla et al., 1996; McFadyen and Carnahan, 1997; Brunt et al., 1999) and have tended to focus on the control of the foot clearance, more so than the concomitant postural adjustments required to maintain stability. Two exceptions are the work of Armand et al (Armand et al., 1998), who included foot-placement requirements for a-p stability in developing a multi-objective optimization model of stepping over obstacles during locomotion, and the recent work of Chou et al (Chou et al., 2001), who characterized the COM motion occurring during such responses. Interestingly, in contrast to the present findings, Chou et al (Chou et al., 2001) found that the need to step over a high obstacle did not lead to increased m-l COM motion, nor was there any change in step width. These findings, pertaining to locomotion, suggest a predictive control of the m-l COM motion analogous to the APA control occurring during step initiation. The present results, however, suggest that predictive control of the m-l COM motion is less effective during rapid stepping reactions evoked by postural perturbation, as an increase in step width was apparently needed (in addition to the APA) in order to recover lateral stability in this situation.

A principal hypothesis of the present study was that APAs would not be included when stepping over the obstacle. The rationale was based primarily on functional considerations, i.e. the delay in foot-lift resulting from inclusion of the APA could jeopardize the ability to clear the obstacle and could also lead to a-p instability by
allowing the forward falling motion of the COM to accelerate over a prolonged interval of time. One could also argue that neural constraints (e.g. time required for cortical processing of an APA (Massion, 1992)) might preclude APAs during rapid triggered reactions; however, recent evidence suggests that it is possible for the CNS to incorporate large functional APAs into such reactions when necessary. Specifically, large APAs were found to occur in hemiparetic subjects when executing a compensatory step with the weight-bearing leg (Maki and McIlroy, 1999a), and were also found to occur, at very rapid latency (70ms), prior to withdrawing the foot from a noxious stimulus while standing (McIlroy et al., 1999). The present findings provide further evidence that large, functional APAs can be included in rapid triggered foot reactions when demanded by task conditions. Although the APAs that occur during unobstructed compensatory stepping are typically too brief and too small to have a substantial impact on the COM motion (McIlroy and Maki, 1999a), the APAs that occurred during the obstacle trials clearly had a much more substantial influence, actually reversing the tendency of the COM to fall toward the swing side by time of foot-off and causing a threefold increase in COM displacement toward the stance leg.

The APA magnitude was characterized in terms of the time-integral of the m-l COP displacement (i.e. the COP impulse) which is roughly proportional to the resulting change in lateral COM momentum. Although increased duration and amplitude of the COP displacement associated with the APA both contributed to the increase in time-integral during obstacle trials, the change in COP displacement amplitude made a much larger contribution. One would expect a limited capacity to increase the APA duration because of the aforementioned costs of delaying foot-lift. Indeed, during light-cued volitional stepping, where there were no such costs, the APA duration was 44% (94ms) longer. Interestingly, the fact that compensatory steps were initiated 15-20ms earlier
during obstacle trials helped to reduce the delay in foot-lift due to the APA, as did a 25ms reduction in the limb-unloading phase.

While the need for rapid foot-lift appears to limit the degree to which APA duration can be increased, it is unclear by what criteria the CNS selects or regulates the APA amplitude. One might expect the CNS to generate the largest APA possible, particularly when the perturbation is unfamiliar, in order to reduce the risk of incurring lateral instability during the swing phase. Generation of a maximal APA would require the m-l COP to be driven at a maximum rate of change. It appears, however, that this did not occur during the unconstrained trials, as substantially larger rates were seen during perturbation-cued trials (0.754 m/s vs. 0.471 m/s; p=0.0001). Interestingly, despite the difference in rate of COP change, the APA amplitude (peak m-l COP displacement) was very similar in both task conditions. This apparent invariance in APA amplitude is unlikely to reflect limitations due to strength or other biomechanical factors, as much larger amplitudes occurred during light-cued trials. It could, instead, indicate that APA amplitude is a regulated parameter; however, more work is needed to resolve this question.

We expected that the inclusion of larger APAs would result in greater forward excursion of the COM, due to a delay in FO. In addition, potential conflict between the execution of the APA and the early automatic response (APR) at the ankle (McIlroy and Maki, 1993a; Burleigh et al., 1994) could lead to further increase in forward COM motion if the APR were diminished as a result of this conflict. This appeared not to be the case. The large APAs in the obstacle trials were not accompanied by diminished APRs, nor was there a greater forward excursion of the COM at FO. In fact, the forward COM velocity was actually reduced at FO. The capacity of the CNS to increase APA magnitude with minimal delay in foot-lift clearly helped to minimize any tendency for forward COM motion to increase. The fact that the forward COM velocity was actually lower, at FO, during obstacle trials could be the result of a facilitated “ankle strategy” (a
modest increase in rate of APR-related COP displacement was, in fact, observed) and/or increased use of a “hip strategy” (not measured in this study) (Runge et al., 1999).

Although these early modifications to the AFA and APR reduced the destabilizing COM motion occurring prior to foot-lift, these changes were not sufficient to counter the increased tendency of the COM to fall, both laterally and forward, during the prolonged swing phase. An increase in lateral and forward displacement of the swing foot apparently served to compensate for this continuing COM excursion. Given that modulation of foot placement appears to afford much greater potential for decelerating COM motion (Maki and McIlroy, 1999b), it is surprising then that the early APA and APR modifications were included at all. It may be that proactive modulation of the APA and APR provides an additional margin of safety. Alternatively, it may be that the early and late modifications arise independently through separate control mechanisms. Whereas task-dependent modulation of the APA and APR “gain” must be planned predictively, it is possible that the modifications to swing-foot placement occur reactively, in response to sensory information about the ongoing and evolving state of instability. Previous studies have shown that older adults who experience difficulty in controlling lateral stability when stepping in response to unpredictable a-p perturbation will decelerate the lateral COM motion by taking an additional step in the lateral direction, rather than modulating the placement of the initial a-p step (McIlroy and Maki, 1996a). Presumably, this occurs because the initial direction of the first step is defined by the direction of the initial a-p instability, whereas the lateral COM motion arises too late to allow the step direction to be changed substantially. The obstacle trials differ in that they afford more time to modulate the step trajectory prior to foot-contact, not only because the prolonged swing duration allows more time to react but also because the larger and more rapid increase in lateral COM motion may allow earlier detection of the onset of lateral instability.
Another possible explanation is that the adjustments to the APA and APR actually serve as a mechanism for controlling the step trajectory, by defining the foot-off COM conditions (a-p and m-l position and velocity) that lead to an appropriate step direction through the subsequent "ballistic" falling movement of the body. (Lyon and Day, 1997) demonstrated that subjects are able to scale the m-l COM parameters in such a fashion when required to step either directly forward or diagonally; however, that study involved preplanned volitional movements. It seems unlikely that the CNS would be able to utilize this type of predictive control as successfully in responding to unpredictable perturbation, particularly in the earliest trials where the time course of the perturbation-induced COM motion is completely unfamiliar.

An important aspect of the compensatory-step modulation that was not addressed in the present study is the control of the swing-foot trajectory. Issues such as the control of obstacle clearance, possible dynamic effects of the altered limb motion on stability and the nature of the trajectory control (predictive versus reactive, "ballistic" versus continuous regulation) remain to be examined in future studies. Another important issue is the predictability of the task. Although perturbation conditions were highly unpredictable in the present study, the location and nature of the obstacle were known well in advance of the first perturbation exposure. Our ongoing work is aimed at addressing the potential for the CNS to utilize this prior information in the control of compensatory stepping, in contrast to situations where the obstacle is encountered unexpectedly. Overall, this line of investigation is expected not only to provide increased understanding of the neural control of these functionally important balancing reactions, but also to lend new insight into how the design of our living environments may increase falling risk and exacerbate difficulties faced by balance-impaired individuals.
3.5 Conclusion

The results provide unequivocal evidence that rapid triggered stepping reactions can be modulated, without prior practice, to deal with environmental constraints. The obstacle that was used presented a significant challenge, requiring a doubling of the usual swing duration, yet the CNS was able to alter the step trajectory so as to clear the obstacle without compromising the ability to decelerate the a-p COM motion induced by a large unpredictable perturbation, as well as lateral COM motion resulting from the leg-lift itself. The fact that this occurred without prior practice or exposure to the perturbation suggests that the CNS is able to automatically incorporate exteroceptive visual information into the control of rapid compensatory stepping reactions. Surprisingly, the control of lateral stability was found to involve a combination of both APA execution and lateral foot placement. The CNS was able to incorporate a large APA with minimal delay in foot-lift; however, this was insufficient to counter the increased tendency of the COM to fall during the prolonged swing phase. The fact that the APA was included at all may indicate a hybrid control, in which predictive APA control provides the initial attempt to compensate for the forthcoming COM motion, and control of the step placement provides additional stabilization as required. The step placement could be controlled predictively, or could be modulated reactively using sensory discharge related to the ongoing COM motion.
Figure 3.1: Example data from representative obstacle and no-obstacle trials: a) spatial characteristics of the center-of-mass (COM) motion and step placement, and b) spatial-temporal characteristics of the center-of-pressure (COP) and COM displacement. Both obstacle (heavy line, square symbols) and no-obstacle (thin line, circular symbols) responses are from the main experiment (same subject). Positive values indicate forward excursion, for antero-posterior (a-p) measures, and excursion toward the swing-leg side, for medio-lateral (m-l) measures; zero corresponds to the starting position. All measures represent motion relative to the platform; time zero corresponds to onset of platform acceleration (0.1m/s²). The inset in panel A.2 depicts the COM trajectories from panel A.1. Symbols mark the onset of the stepping response (R), foot off (FO) and foot contact (FC). The anticipatory postural adjustment (APA) is defined by the initial m-l COP excursion toward the swing-leg side (panel B.1), which acts to propel the COM toward the stance-leg side prior to FO (panels B.2, B.3). Note the increase in APA amplitude and duration during the obstacle trial, which resulted in greater movement of the COM (increased displacement and velocity) toward the stance-leg side prior to FO; however, the COM still fell farther toward the unsupported side, as well as farther forward, by time of FC as a result of the prolonged swing duration. Note also the increase in forward and lateral step distance during the obstacle trial (panel A.2).
Figure 3.2: Effect of obstacle on step characteristics: a) step timing, and b) step distance. Means and standard deviations are shown separately for the main-experiment "control" (no obstacle) trials (N=62) and for the obstacle trials occurring during the main experiment (N=56), the first block of three unconstrained trials (N=11), the last block of three unconstrained trials (N=12) and the perturbation-cued stepping trials (N=65). To simplify the data presentation, we have not shown the no-obstacle data from the first block of unconstrained trials (N=8) or from the last block (N=8); these data did not differ significantly from the main-experiment no-obstacle responses (p’s>0.23). Timing of step onset, foot-off and foot-contact is defined relative to onset of platform acceleration (0.1m/s²). Positive values indicate forward excursion, for antero-posterior (a-p) step distance, and excursion toward the swing-leg side, for medio-lateral (m-l) step distance. Note the increased swing duration due to the obstacle and the resulting delay in foot contact, as well as the increase in step distance (forward and toward the swing-leg side). Note also the more rapid response (step onset, foot-off and foot-contact) in the perturbation-cued trials.
Figure 3.3: Effect of obstacle on characteristics of the anticipatory postural adjustment (APA): a) amplitude, b) duration and c) approximate time-integral (0.5xamplitude x duration). These measures are based on the initial medio-lateral (m-l) displacement of the center of foot pressure (COP) toward the swing-leg side (see inset schematic drawings). Trial numbers and data presentation are as indicated in Figure 3.2. Note the increase in all three APA characteristics due to the obstacle trials. Although (for simplicity of data presentation) we have not shown the first-block no-obstacle trials, it should be noted that the effect of the obstacle on APA modulation was even more pronounced in these early trials, primarily because the no-obstacle APAs were even smaller in these early trials (mean amplitude 0.022m, duration 121ms, time-integral 0.0016m-s) compared to the main experiment (amplitude 0.027m, duration 144ms, time-integral 0.0026m-s).
Figure 3.4: Effect of obstacle on center-of-mass (COM) motion at time of foot-off and foot-contact: a) medio-lateral (m-l) displacement, b) m-l velocity, c) antero-posterior (a-p) displacement and d) a-p velocity. Positive values indicate forward excursion, for a-p measures, and excursion toward the swing-leg side, for m-l measures; displacements were computed relative to the starting position. Trial numbers and data presentation are as indicated in Figure 2. Note that the larger APAs in the obstacle trials (see Figure 3) were associated with greater movement of the COM toward the stance-leg side prior to foot-off, as well as a reversal of the COM velocity; however, the COM still fell further and faster toward the unsupported side during the prolonged swing phase (as indicated by the values measured at foot-contact). Note also that the forward velocity of the COM prior to foot-off was reduced, in comparing main-experiment obstacle and no-obstacle trials, but there was still greater forward COM excursion by time of foot-contact during the obstacle trials.
4.1 Introduction

Compensatory stepping is a prevalent response to postural perturbation, even when the disturbance to balance is quite small (McIlroy and Maki, 1993c; Luchies et al., 1994). Although these rapid triggered stepping reactions can very be effective in countering the instability induced by the perturbation, the act of lifting the foot to step can actually give rise to instability in the lateral direction, due to the tendency of the body's center of mass (COM) to fall toward the unsupported side (McIlroy and Maki, 1999a). In volitional stepping, this lateral instability is invariably countered by an anticipatory postural adjustment (APA) that precedes foot-lift. This APA, which manifests as an initial displacement of the center of foot pressure (COP) toward the swing-leg side (Breniere et al., 1987; Jian et al., 1993; MacKinnon and Winter, 1993), acts to drive the COM toward the stance limb and thereby preserve lateral stability (Breniere et al., 1987; Rogers and Pai, 1990; Nissan and Whittle, 1990; Brunt et al., 1991; Jian et al., 1993; MacKinnon and Winter, 1993).

While the contribution of the APA to the control of lateral stability during volitional lifting of the leg is unequivocal, the role played during rapid triggered compensatory stepping reactions appears to depend on task conditions. Healthy subjects, when stepping on an unobstructed surface, will typically exhibit compensatory stepping responses in which the APA is either absent or greatly diminished in amplitude and duration (McIlroy and Maki, 1993b; McIlroy and Maki, 1995a; Rogers, 1996; McIlroy and Maki, 1999a). However, in a recent study, we demonstrated that much larger APAs occur when the compensatory stepping reaction requires an extended swing duration, i.e. when stepping forward over a high obstacle (Zettel et al., 2001). The apparent
dependence on swing duration is also supported by findings that larger APAs tend to occur during slower stepping reactions cued by small perturbations (Burleigh et al., 1994; Burleigh and Horak, 1996).

Such findings would suggest that the central nervous system (CNS) may scale the amplitude and/or duration of the APA to match the anticipated swing duration, which defines the potential degree of lateral instability that could arise during the single-limb support phase. However, we found that the APAs that occurred during compensatory stepping over an obstacle were insufficient to prevent a large lateral excursion of the COM following the extended swing duration, and lateral placement of the swing foot was required to arrest the lateral COM motion (Zettel et al., 2001).

Why did the CNS not upregulate the APA sufficiently to reduce the lateral COM motion and avoid the need for lateral stepping? It is unlikely that the underscaled APAs represent an error due to unfamiliar or unpredictable task demands, as similar responses persisted over repeated trials and also occurred in trials where perturbations were predictable and subjects were given prior instruction to step. A more likely explanation is that the APA amplitude and/or duration were limited due to other factors. Certainly, one would expect increase in APA duration to be constrained by the need to initiate foot-lift rapidly, in order to counteract the imposed antero-posterior instability and to avoid contact with the obstacle. It is less clear why the APA amplitude would be constrained. One possibility is that an upper limit on APA amplitude was reached, due, for example, to biomechanical or neuromotor limitations on the capacity to generate the required muscle torques within the available timespan.

The purpose of this study was to determine whether, in fact, the previously observed failure to control lateral stability via APA control is due to a fundamental limitation on the extent to which APA modulation can be achieved during rapid triggered forward stepping reactions. To address this question, we endeavored to force the CNS to
upregulate the APA duration and/or amplitude by using laterally-placed obstructions to preclude the possibility of using lateral placement of the step to recover lateral stability. As in our previous study (Zettel et al., 2001), highly unpredictable perturbations were used to evoke the stepping reactions and a high obstacle was placed in front of the subject in order to increase the swing duration and associated challenge to lateral stability.

4.2 Materials and Methods

Six healthy, naive, young adults (ages 20-29, height 170-190cm, weight 58-110kg) were tested. All were right-hand and right-leg dominant and reported no medical conditions affecting balance. Each subject provided written informed consent to comply with ethics approval granted by the institutional review board.

Compensatory stepping reactions were evoked by sudden, unpredictable horizontal movement of a large (2mx2m) moveable platform (Maki et al., 1996). Each platform translation comprised a 300ms square-wave acceleration pulse followed immediately by an equal and opposite deceleration pulse.

Tests were performed under three conditions: 1) control (no-obstacle), 2) transverse obstacle (obstacle-only), and 3) transverse obstacle plus constraint to lateral step placement (obstacle-constraint). The obstacle was a narrow bar (3.5cm diameter, 150cm in length) placed transversely in front of the subject (2.5% of body height from the toes) at a height equal to 15% of body height. A piece of cardboard (7.5cm high, 150cm in length) was mounted vertically underneath the bar to discourage stepping under the bar. For safety, the bar was padded with foam rubber and both the bar and cardboard were affixed in such a way to release upon contact. Lateral step placement was constrained by means of two foam-rubber blocks (7cm high, 37cm wide, 68cm long) placed anterior and lateral to the subject, with posterior edges aligned with the axis of the
bar (Figure 4.1). The medio-lateral (m-l) distance from the lateral border of the subject's foot to the medial edge of the adjacent foam block was set at the average lateral step distance previously determined for unobstructed compensatory forward-step reactions evoked by backward platform translation (1.7% of body height) (Zettel et al., 2001). The obstacle and lateral constraints were attached to and moved with the platform.

Subjects began all trials in a standard foot position (11% of body height between heel centers, 14° angle between medial borders of feet; (Mcllroy and Maki, 1997) at the center of the platform, with vision focused straight ahead on a target mounted on the platform at eye level approximately 1m away. For safety, subjects wore a harness, designed to prevent falls without providing somatosensory feedback that might influence balance control, and safety handrails were mounted around the perimeter of the platform. A lightweight rod (3cm diameter, 40cm length) was held behind the buttocks, arms relaxed at full length, to deter arm movement. Subjects were instructed to do whatever came naturally to prevent themselves from falling while avoiding contact with the obstacle. Extraneous movement was to be minimized (including movement of the arms) and the final position was to be held for two seconds. To control attentional variation, subjects counted backwards out loud by serial three's (starting at a random number given at the start of the trial), and were instructed to continue counting until the platform stopped moving.

In the main experiment, each subject performed six blocks of trials (two blocks for each obstacle condition). Each block comprised 11 trials: three large (3.0 m/s²; 0.9 m/s), one medium (2.0 m/s²; 0.6 m/s) and one small (1.0 m/s²; 0.3 m/s) backward translation, plus two translations (one small, one large) in each of the forward, left and right directions. Order of testing the obstacle conditions was balanced both within and across subjects. Prior to the main experiment, each subject performed an initial series of three
identical familiarization trials (large backward translation), using the same obstacle condition as used in the ensuing block of main-experiment trials.

Two forceplates (Kistler model 9281; AMTI model OR6-5), embedded flush with the surface of the moving platform, were sampled at 200 Hz to determine ground reaction forces, COP location, COM displacement and step timing. Accelerometer signals were used to correct the forceplate measures for inertial artifacts arising from the platform motion. Video recordings from four high-resolution cameras (shuttered at 1/500s) were used to code postural behavior (i.e. failure to clear the obstacle, number of steps taken), to determine foot placement, and verify foot-off (FO) and foot-contact (FC) values determined from the forceplates. Time of FO was identified by swing-leg unloading (vertical ground-reaction force < 5% of body weight) and time of FC was defined by an analogous increase in loading. Step onset was defined to occur when the m-l COP displacement (relative to the pre-perturbation position) exceeded 4mm (McIlroy and Maki, 1999a). All timing values were defined relative to onset of platform acceleration (0.1m/s²).

The analyses focused primarily on the effect of the obstacle conditions on the step placement, APA characteristics and COM motion. Step placement was determined by resolving (to within ±1cm) the position of a reflective marker placed on the foot (fifth metatarsal head) relative to a grid marked on the floor. APAs were defined to occur if the initial m-l COP displacement (>4mm) was directed toward the swing leg (McIlroy and Maki, 1999a). The APA was characterized in terms of the duration and peak amplitude of the swing-side COP excursion (see schematic drawings, Figure 3). Absolute antero-posterior (a-p) and m-l COM velocity and displacement were determined via successive integrations of the corresponding ground-reaction shear force with respect to time, starting at perturbation onset (Maki and McIlroy, 1999b; McIlroy and Maki, 1999a). To determine COM motion relative to the platform, platform velocity and displacement (measured using a linear potentiometer) were subtracted from the absolute COM.
measures. The initial COM position was estimated by averaging the pre-perturbation COP (500ms interval prior to perturbation onset).

The statistical analysis focussed on forward stepping reactions evoked by large backward platform translation during the main experiment. Repeated-measures analysis of variance (RMANOVA) was used to analyze the effect of the obstacle condition on the primary dependent variables, i.e. APA amplitude and duration, COM motion and step distance. The same approach was used in secondary analyses, performed to explore possible differences in step timing and in initial (pre-perturbation) position. A priori contrasts were used to test planned comparisons between obstacle and control trials. The p-values for all significant effects are listed from the paired contrasts. Where necessary, rank transformations were used to normalize the data and/or stabilize the variance, prior to performing each ANOVA (Conover and Iman, 1981). Trials in which contact was made with an obstacle were discarded from analysis (N=9), as were trials involving multiple steps (N=17) or grasping of a safety handrail (N=1). Also excluded was one trial in which the subject stepped “high” even though no obstacle was present. These exclusions left a total of 99 trials available for analysis (33 no-obstacle, 34 obstacle-only, 32 obstacle-constraint).

4.3 Results

As in the previous study (Zettel et al., 2001), subjects were generally well able to modulate their stepping reactions so as to accommodate the obstacle while recovering balance, despite the unpredictability of the perturbations. The addition of the constraint on lateral foot motion did not adversely affect the ability to clear the obstacle: contact with the obstacle occurred in 5% (2/37) of obstacle-only trials and in 6% (2/35) of obstacle-constraint trials. In the latter task condition, subjects were successful in avoiding landing on the foam blocks used to constrain lateral foot motion in all cases. Within the
successful-clearance trials, balance was recovered by means of a single step in all obstacle-constraint trials (right leg in 66% of trials) and in all but one obstacle-only trial (right leg in 71% of trials). Multiple stepping occurred in 6% (2/34) of no-obstacle trials (right leg in 70% of trials).

Although it is clear that profound modulation of the foot trajectory was necessary to step over the obstacle, the focus of this paper is on the modulations used to maintain stability during these stepping reactions, rather than the trajectory control. Example data are shown in Figure 4.2. The representative obstacle and no-obstacle trials shown in the figure illustrate many of the findings detailed below, pertaining to modulation of the APA and step placement, as well as effects on the COM motion. Descriptive statistics are summarized in Figures 4.3 to 4.5.

As was anticipated, clearance of the obstacle necessitated a large increase in swing duration. With or without the lateral constraint, the presence of the obstacle more than doubled the swing duration compared to no-obstacle trials (p=0.0001); however, there was no significant difference between the two obstacle conditions (p=0.19). See Figure 4.4. The lateral constraints successfully deterred any lateral stepping, and actually resulted in more medially directed steps (0.027 m toward stance-limb side, on average) compared to no-obstacle trials (0.014 toward swing-limb side, p=0.003). For the obstacle-only trials, there was a large lateral foot displacement (0.061 m toward swing-limb side), and this was significantly different when compared to both no-obstacle (p=0.003) and obstacle-constraint trials (p=0.0001). See Figure 4.4.

The ability to maintain lateral stability in the obstacle-constraint trials, despite the severe restrictions on lateral step distance, was apparently due to an increase in APA amplitude. The m-l COP displacement associated with the APA was increased by 29% (p=0.02) compared to the obstacle-only condition (see Figure 4.3). For both obstacle conditions, the APAs were much larger than in the no-obstacle trials, with increases of
116% (p=0.0003) and 177% (p=0.0001) for the obstacle-only and obstacle-constraint conditions, respectively. Relative to the no-obstacle trials, the average duration of the APA also increased substantially, by 42-43% (p's<0.0008), when an obstacle was present; however, the average APA duration was virtually identical in comparing the two obstacle conditions (mean difference 3ms; p=0.85). There was little difference in the incidence of APAs, as they occurred in 91% (30/33) of no-obstacle, compared to all no-obstacle (34/34) and obstacle-only (32/32) obstacle-constraint trials.

The increases in APA in the obstacle trials appeared to significantly alter the subsequent m-l COM motion. Compared to no-obstacle trials, the COM was propelled three times farther toward the stance limb by time of foot-off (p=0.0008), and its velocity increased by a factor of six, in the obstacle-only trials (p=0.0001; Figure 4.5). The largest APAs, observed in the obstacle-constraint condition, caused the COM to move toward the stance limb even more rapidly, in comparison to the obstacle-only condition (p=0.02), however, there was no difference in m-l COM displacement (p=0.32). By time of foot-contact, the differences between the two obstacle conditions were even more pronounced. Although the COM was falling toward the swing-limb side by time of foot-contact in all task conditions, the velocity was reduced by more than a third in the obstacle-constraint trials, compared to obstacle-only trials (p=0.001). The COM displacement toward the swing-leg side was also much reduced: the COM had fallen 0.014m toward the swing-limb side in the obstacle-only condition by time of foot-contact, but remained displaced 0.010m toward the stance-limb side in the obstacle-constraint condition (p=0.002). In the no-obstacle trials, the tendency of the COM to fall toward the swing-limb side was much reduced due to the much shorter swing duration. Despite this fact, the large APAs that occurred during obstacle-constraint trials actually caused the lateral COM motion to be retarded to an equivalent or even greater degree, when
compared to the no-obstacle trials (no difference in m-l COM velocity, \( p=0.67 \); m-l COM displacement reduced, \( p=0.04 \)).

For both obstacle conditions, subjects were well able to control their a-p COM motion while clearing the obstacle, despite the fact that foot-off was delayed by about 55ms, on average, in comparison to the no-obstacle trials (due to inclusion of a longer APA). The control of the a-p COM displacement and velocity was virtually identical, on average, in the two obstacle conditions (no significant differences in displacement or velocity at foot-off or foot-contact, \( p>0.12 \); see Figure 4.5). In comparison to the no-obstacle trials, the forward COM velocity at foot-off was actually reduced by 18\% (\( p<0.03 \)). Nonetheless, by time of foot-contact, the forward COM displacement was 30\% higher (\( p=0.0001 \)) in the obstacle trials and the forward COM velocity was also, on average, 31\% larger (although this latter difference did not reach statistical significance; \( p=0.12 \)). This increase in a-p COM motion was apparently compensated for by an 30\% larger a-p step length compared to the no-obstacle trials (both \( p=0.0005 \)).

The observed differences in COM motion cannot be attributed to any systematic modifications to the stance position, as the pre-perturbation COM location in both the sagittal and frontal planes was equal in all three conditions (\( p>0.31 \)). It is also unlikely that any differences in COM motion between the two obstacle conditions were due to differences in step timing. The mean step onset (initial m-l COP displacement) and foot-off times were virtually identical, as were the average APA duration, time to unload the limb and swing duration (\( p>0.19 \); Figure 4.4). Although foot-off was delayed by 55ms in obstacle trials, it should be noted that the delay in foot-off due to the increased APA duration was partially offset by an earlier step-onset time, in comparison to unobstructed steps (mean difference 29ms; \( p<0.03 \)). The time taken to unload the limb following completion of the APA showed no significant differences among the three conditions (\( p=0.43 \)).
4.4 Discussion

By introducing environmental constraints on foot trajectory, we are able to challenge the capacity of the CNS to recover from external balance perturbation by means of rapid triggered stepping reactions, and thereby examine potential limitations in the control of these reactions. Previous results, in which a hybrid of APA and step-placement modulation was used to maintain lateral stability when stepping forward over an obstacle, suggested that there may exist a fundamental biomechanical or neural limitation that prevented greater reliance on APA control. However, the present results indicate clearly that this was not the case. When we prevented lateral foot placement, the CNS was in fact able to upregulate the APA amplitude and thereby control lateral stability without the benefit of lateral foot placement. By increasing anticipatory efforts to propel the COM toward the stance leg prior to foot-lift, the extent and speed of the falling motion toward the unsupported side during the swing phase were reduced sufficiently so that a laterally directed step was not required.

The net change in lateral COM momentum resulting from the APA is dependent on both the duration and amplitude of APA. Although the APA duration and amplitude were both increased when an obstacle was present, the duration was not increased further when larger anticipatory exertion was required, i.e. in the obstacle-constraint trials. Instead, greater anticipatory control relied on an increase in the APA amplitude. The striking congruency of step timing events between the two obstacle conditions suggests that the duration of the APA may have reached an upper limit defined by the task demands. Presumably, further delay in foot-lift, due to prolongation of the APA, could jeopardize ability to clear the obstacle and could also adversely affect the capacity of the step to decelerate the perturbation-induced COM motion (Maki and McIlroy, 1999b).

Despite the capacity to generate larger APA amplitudes, it appears that the CNS prefers to reduce anticipatory efforts if lateral foot placement is permitted. Why does the
CNS prefer to use a smaller APA? Presumably, execution of a large APA presents some cost or risk that the CNS would prefer to minimize or avoid, if possible. Potentially, the APA could interfere with the capacity of the early "automatic postural response" to decelerate the COM motion prior to foot-lift (McIlroy and Maki, 1993a; Burleigh et al., 1994); however, there was no evidence to support this. In fact, average a-p COM motion was virtually identical in the two obstacle conditions. We cannot rule out the possibility that muscular effort is a factor; however, previous findings suggest that safety takes precedence in situations where there is a substantial threat to stability. For example, observed foot clearances, when stepping over obstacles, are significantly larger than the trajectories predicted by energy-minimization models (Chou and Draganich, 1997a). The most likely possibility is that the CNS prefers the risks associated with underscaling the APA as opposed to overscaling. An excessively large APA could actually cause the COM to fall in the opposite direction, toward the stance-leg side. This could require a medially directed "crossover" step to stabilize the COM, and the resulting position (narrow BOS, legs crossed) could compromise the ability to maintain equilibrium or respond to any subsequent imbalance. Studies of APAs associated with upper-limb movements have suggested that the CNS will suppress APAs as a protection against their possible destabilizing effects in unstable situations (Aruin et al., 1998).

In contrast to previous findings that the APA is typically absent or severely truncated when executing compensatory stepping reactions on a level surface (McIlroy and Maki, 1993b; McIlroy and Maki, 1995a; Rogers, 1996; McIlroy and Maki, 1999a), the present study adds to the growing body of evidence indicating that it is possible for the CNS to incorporate large functional APAs into such reactions when demanded by task conditions (Maki and McIlroy, 1999a; McIlroy et al., 1999; Zettel et al., 2001). Moreover, the results demonstrate a remarkable capacity for the CNS to scale the APA successfully to meet stability demands imposed by environmental constraints on foot motion, despite a
large degree of unpredictability regarding the time course of the body motion imposed by external perturbation. While previous studies have suggested that the state of a-p instability may define the extent to which the APA is expressed or truncated (Crenna and Frigo, 1991; Burleigh et al., 1994; McIlroy and Maki, 1999a), we observed differences in APA amplitude that were clearly related to the task demands, and which occurred despite the fact that the a-p COM motion was virtually identical in the two obstacle conditions.

We previously hypothesized that the CNS would suppress the APA, in the presence of an obstacle, during compensatory stepping reactions in order to avoid delay in foot-lift. More rapid foot-lift would be expected to facilitate obstacle clearance and recovery of a-p stability; however, the results from the present and previous (Zettel et al., 2001) obstacle studies indicate that the CNS was able to minimize effects of the potential delay in foot-lift by initiating the step more rapidly and by exerting greater effort to decelerate the a-p COM motion prior to foot-lift. Thus, the costs of including the APA were minimized. The benefit of including the APA is a reduction in the degree of lateral stepping required. This provides an increased margin of safety to ensure that stability is re-established with a single step, which may be particularly important because the obstacle may well impede initiation of additional steps. We did, in fact, observe that additional steps almost never occurred after the initial clearance of the obstacle.

In contrast to the view that APA and step-width modulation represent distinct active control mechanisms, it is also possible that the adjustments to the APA actually serve to control the step trajectory, by defining the conditions at foot-off that lead to an appropriate step direction through the subsequent "ballistic" falling motion of the body. Specifically, the CNS may scale the APA in such a manner as to control the lateral fall of the body, and consequently control the lateral placement of the swing foot. The larger APAs observed in the obstacle-constraint trials could, in this way, cause the foot placement to be directed medially, away from the lateral obstruction. Evidence for such a
strategy has been demonstrated for volitional stepping to a target (Lyon and Day, 1997). However, it seems unlikely that the CNS could implement such a strategy as successfully in responding to unpredictable perturbations, particularly in the earliest trials where the time course of the perturbation-induced COM motion is completely unfamiliar. We have observed that similar scaling of the APA and step width occur even in the earliest trials and that there is negligible change over repeated trials (Zettel et al., 2001).

Given the potential consequence of errors in foot placement (i.e. falling), it seems likely that the CNS would utilize at least some degree of on-line control to ensure that the required foot placement is achieved. Such on-line modulation has been shown to occur during compensatory upper-limb movements (reach-and-grasp reactions), in experiments where handhold location was changed suddenly after initiation of the limb movement (McIlroy and Maki, 1999b). Even though the present results suggest that preventing lateral step placement may lead to an increased reliance on predictive control via APA modulation, it is noteworthy that the average foot-placement was biased medially, well away from the edge of the foam-rubber constraint. While this offset in average foot placement may represent a safety margin established to avoid contact with the constraint, it could also reflect efforts to maintain some potential for on-line adjustment in lateral step placement. In other words, the same hybrid control, involving both APA and step-placement modulation may still occur. In effect, the larger APA permits step-width modulation by shifting the equilibrium "operating point" to a more medial position, away from the constraints.

4.5 Conclusion

The present findings reveal a remarkable capacity of the CNS to modulate rapid triggered stepping reactions to meet demands for postural stabilization, despite highly unpredictable perturbation conditions and severe constraints on foot trajectory. While
there appeared to be a natural preference, when stepping forward over an obstacle, to use a hybrid strategy combining a moderately large APA with lateral step placement in order to maintain lateral stability, the CNS was able to upregulate the APA amplitude when laterally-positioned obstructions prevented lateral stepping. The larger anticipatory efforts were achieved by an increased amplitude of m-l COP excursion, which drove the COM toward the stance limb with increased momentum prior to foot-off and thus reduced the tendency of the COM to fall laterally toward the unsupported side during swing phase. The duration of the APA did not increase when lateral foot placement was constrained, which may reflect the fact that further delay in foot-lift could jeopardize ability to clear the obstacle or to decelerate the a-p motion of the COM induced by the perturbation. Although the increased APA amplitude could indicate increased reliance on predictive control, we propose instead that the larger APA may primarily serve to shift the targeted COM position for final equilibrium medially, away from the lateral obstruction, to maintain potential for on-line correction of step width. A finding that the mean step placement was also shifted medially, well away from the obstruction, is consistent with this interpretation.
Figure 4.1: Representation (to scale) of obstacle layout as described in the methods, viewed from above. The gray horizontal line represents the bar (3.5cm diameter, 150 cm length) placed at a distance equal to 2.5% of body height in front of the subjects, at a height equivalent to 15% of body height. Not seen in the diagram is the long cardboard piece (7.5cm high, 150cm length) mounted vertically in the frontal plane below the bar near floor level. For the obstacle-constraint trials, two large foam blocks (7cm high, 37cm wide, 68cm long) were placed ahead and to the sides of the subject. Note that all obstacles and constraints were mounted so that they were not in contact with the force plates.
A. Spatial trajectories

B. Temporal-spatial characteristics

Figure 4.2: Example data from representative obstacle-constraint, obstacle-only and no-obstacle trials: a) spatial characteristics of the center-of-mass (COM) motion and step placement, and b) spatial-temporal characteristics of the center-of-pressure (COP) and COM displacement. Both obstacle-constraint (heavy black line, diamond symbols), obstacle-only (heavy gray line, square symbols) and no-obstacle (thin black line, circular symbols) responses are from the main experiment (2 subjects). Positive values indicate forward excursion, for antero-posterior (a-p) measures, and excursion toward the swing-leg side, for medio-lateral (m-l) measures; zero corresponds to the starting position. All measures represent motion relative to the platform; time zero corresponds to onset of platform acceleration (0.1m/s²). The inset in panel A.2 depicts the COM trajectories from panel A.1. Symbols mark the onset of the stepping response (R), foot off (FO) and foot contact (FC). The anticipatory postural adjustment (APA) is defined by the initial m-l COP excursion toward the swing-leg side (panel B.1), which acts to propel the COM toward the stance-leg side prior to FO (panels B.2, B.3). Note the increase in APA amplitude and duration for both obstacle trials, which resulted in greater movement of the COM (increased displacement and velocity) toward the stance-leg side prior to FO; however, unlike the obstacle-only trial, the obstacle-constraint COM avoided the fall toward the unsupported side due to the larger APA amplitude; both obstacle conditions, however, had a comparable forward fall by time of FC as a result of the prolonged swing duration. Note also the increase in forward step distance for both obstacle conditions; the increased lateral step distance for the obstacle-only trial compared to the more medial foot placement of the obstacle-constraint condition (panel A.2).
A. APA amplitude

B. APA duration

Figure 4.3: Effect of obstacle and lateral constraints on characteristics of the anticipatory postural adjustment (APA): a) amplitude and b) duration. These measures are based on the initial medio-lateral (m-l) displacement of the center of foot pressure (COP) toward the swing-leg side (see inset schematic drawings). Means and standard deviations are shown separately for the main-experiment no-obstacle trials (N=33), obstacle-only trials (N=34) and obstacle-constraint (N=32) trials occurring during the main experiment. Note the increase in the duration from no-obstacle to both obstacle-only and obstacle-constraint; however, only the amplitude showed a further increase when foot placement was constrained laterally.
A. Step timing

![Graph showing step timing characteristics](image)

B. Step distance

![Graph showing step distance](image)

Figure 4.4: Effect of obstacle and lateral constraints on step characteristics: a) step timing, and b) step distance. Timing of step onset, foot-off and foot-contact is defined relative to onset of platform acceleration (0.1m/s²). Positive values indicate forward excursion, for antero-posterior (a-p) step distance, and excursion toward the swing-leg side, for medio-lateral (m-l) step distance. Trial numbers and data presentation are as indicated in Figure 4.3. Note the increased swing duration and increased forward step distance for both obstacle conditions. Note also the increased lateral step distance for the obstacle-only condition, compared to medially directed foot placement for the obstacle-constraint condition. Note also the remarkable congruency in timing between the two obstacle conditions.
Figure 4.5: Effect of obstacle and lateral constraints on center-of-mass (COM) motion at time of foot-off and foot-contact: a) medio-lateral (m-l) displacement, b) m-l velocity, c) antero-posterior (a-p) displacement and d) a-p velocity. Positive values indicate forward excursion, for a-p measures, and excursion toward the swing-leg side, for m-l measures; displacements were computed relative to the starting position. Trial numbers and data presentation are as indicated in Figure 4.3. Note that the larger APAs in the obstacle trials (see Figure 4.3) were associated with greater COM motion toward the stance-leg side prior to foot-off; however, the COM fell further and faster toward the unsupported side during the prolonged swing phase (as indicated by the values measured at foot-contact) for the obstacle-only, but not so for the obstacle-constraint trials. Note also that the similar reduction in forward velocity of the COM prior to foot-off for both obstacle conditions, but the greater forward COM excursion by time of foot-contact.
CHAPTER 5 - GENERAL DISCUSSION

5.1 Summary of findings

This dissertation has provided evidence that rapid triggered stepping reactions can be modified in response to nearby environmental constraints. Although prior work has also demonstrated that these reactions are modified in response to changes in task conditions, this study is unique in that it is the first to examine whether and how these responses are adapted to meet the demands due to obstacles and constraints on foot placement. It has also contributed to a growing body of evidence that anticipatory control can play a significant functional role in compensatory stepping, and provided further insight into the remarkable adaptability of CNS control over these responses.

This discussion will reply to the objectives and hypothesis initially set out for this work, i.e. the extent to which the objectives were met and the nature of the findings. Although a detailed discussion specific to each study was presented in Sections 3.4 and 4.4, this discussion will integrate the findings from the two studies, discuss their overall implications and limitations, and suggest directions for future work.

*Can rapid triggered stepping reactions be modified to accommodate nearby environmental constraints?*

There is now no doubt that young, healthy subjects can modulate their compensatory stepping responses to avoid contact with a high obstacle placed immediately in front of the feet. Even more remarkable was that the adaptations showed little, if any, detriment to the restoration of equilibrium. In both studies, subjects had success rates in clearing the obstacle close to or greater than 90% after receiving a large forward perturbation, and almost all successful-clearance responses clearances were done in a single step. Even among the failed trials, none were due to insufficient
foot clearance of the bar, but instead were manifested as an initial, short step under the obstacle. As well, subjects were equally, in not more so, adept at avoiding the obstacle when restrictions on foot placement were included.

Results from the first study suggested a dependence on a laterally directed step to augment a moderately large APA; however, lateral stepping was not essential to successful balance recovery. When lateral stepping was constrained, subjects were able to upregulate their anticipatory efforts to secure frontal plane stability during the extended swing duration, again while a-p balance recovery was virtually unchanged in comparison to obstacle trials where there was no lateral step restriction.

Although it was anticipated that subjects would be able to manage the obstacle, the success rate and efficiency with which that they were able to do it was surprising. The large, backward floor movements were quite destabilizing, and were included among an array of perturbations unpredictable in direction, magnitude, and time of onset. Additionally, subjects performed a secondary cognitive task to minimize any opportunity for preplanning, and the obstacle itself is high even by comparison to those used in studies of volitional obstacle clearance (Chen et al., 1991; Patla and Rietdyk, 1993; Patla et al., 1996; Chou and Draganich, 1997a; Brunt et al., 1999; Austin et al., 1999; Chou and Draganich, 1997b; Chou et al., 2001). Even more remarkable was that the CNS was able to implement these successful balance recovery strategies in the earliest trials, when conditions were most unfamiliar. The results from this work add to previous studies on the modifiability of rapid triggered stepping responses (McIlroy and Maki, 1993a; Burleigh et al., 1994; McIlroy and Maki, 1995a; Burleigh and Horak, 1996; Maki and McIlroy, 1997), but provide a new emphasis on the accommodation of environmental constraints.
How and when are these modulations implemented during the movement, and what does this imply about CNS control of these reactions?

A primary hypothesis of this study was that anticipatory control would not contribute significantly to the control of stability during these reactions. This was based on the typical absence of APAs in past compensatory stepping studies (Mcllroy and Maki, 1993b; Mcllroy and Maki, 1995a; Rogers, 1996; Mcllroy and Maki, 1999a), potential conflict with the APR (Mcllroy and Maki, 1993a; Burleigh et al., 1994), and possible neural constraints (Massion, 1992). The hypothesis was also based on functional considerations, i.e. that the delay in foot-lift resulting from inclusion of the APA could jeopardize the ability to clear the obstacle and could also lead to a-p instability by allowing the forward falling motion of the COM to accelerate over a prolonged interval of time. Despite this body of evidence against the possibility, large functional APAs were actually an integral aspect in the control of frontal plane stability. This adds to other recent evidence that large functional APAs can be included prior to rapid triggered stepping responses when demanded by task conditions (Maki and Mcllroy, 1999a; Mcllroy et al., 1999), and also has ramifications for the origins of these movements. It is widely suggested that APAs are only generated in association with volitionally generated primary movement. For example, externally triggered perturbations fail to elicit the same anticipatory response to unloading and loading of the upper limb as during self-initiation, even under highly predictable circumstances (Aruin and Latash, 1995; Scholz and Latash, 1998). There is also evidence that the origins of feedforward postural adjustments arise from the supplementary motor area (Massion, 1992). Therefore, the inclusion of APAs during compensatory stepping responses suggests that the control of these reactions can involve significant cortical input.

The inability to prevent a lateral fall of the COM by time of FC and apparent reliance on lateral foot placement in the first study suggested the possibility that the APA
had reached an upper limit, dictated perhaps by some neural or biomechanical constraint. The second study clearly refuted this possibility. When lateral foot placement was restricted, the CNS was able to increase anticipatory efforts through a larger lateral COP excursion toward the swing-leg side and secure frontal plane stability unaccompanied by lateral foot placement. Results from cued stepping trials also argued against the view that an upper limit on APA amplitude had been reached, indicating that the system was capable of generating both larger (light-cued trial) and more rapid (perturbation-cued trials) anticipatory COP excursion. It did seem, however, that the APA duration had reached a maximum for this given situation, as no further increase in duration occurred when lateral foot placement was restricted. Also, the APA duration underwent less of an increase than the amplitude when confronted with the obstacle compared to control trials. Given the time restrictions due to the need to initiate the step, it appears that the APA amplitude, as reflected in m-l COP excursion, has greater potential to control m-l stability during compensatory stepping.

It was also speculated that the inclusion of an APA would jeopardize a-p stability recovery efforts, either by directly interfering with the APR (McIlroy and Maki, 1993a; Burleigh et al., 1994), or by delaying the initiation of the step forward. However, the results here demonstrated that an effective APA could be elicited with no apparent compromise to the a-p stability control. In fact, there was some evidence that the APR was actually increased during obstacle stepping, leading to a reduction in forward COM velocity prior to foot-off in comparison to no-obstacle trials. It does not appear, then, that proactive (APA) control and reactive (APR) control were antagonistic, but were in fact well coordinated.

It was interesting that a faster onset time was made, presumably in an effort to offset a potential delay in foot-lift due to the increased APA duration. When subjects were cued to step to the perturbation, the onset times decreased even further. While the
mechanism behind this remains unclear, it is perhaps similar to 'gain' control of the APR (McIlroy and Maki, 1993a; Burleigh et al., 1994; Burleigh and Horak, 1996). The use of exteroceptive visual information prior to the trial could perhaps in some manner set the CNS to use a lower threshold for step initiation in response to forward perturbations, allowing not only for a modification to the magnitude of the APA and APR response, but also to react more quickly to specific sensory feedback. Although the differences in the onset times were small, in both studies they constituted approximately one-third of the increase in APA duration occurring in the obstacle conditions.

Results from these studies did not explain the apparent preference for the execution of a moderate APA in conjunction with a laterally directed step. While there are several possibilities, it appears that when the CNS is given the choice, it prefers to underscale the reaction, either for some benefit of the particular response, or for avoiding some risk associated with the execution of a larger APA. Most likely, the CNS refrains from producing a larger APA in the chance it may force a medial cross over step, which may eventually compromise stability.

5.2 Limitations

Although an objective of this research was to supply a more complete understanding of balance reactions in the everyday world by the introduction of an obstacle, there are limitations in the experimental paradigm that was used. First of all, subjects were well aware of an impending perturbation and most likely were in a heightened state of arousal. Also, repeated trials allowed familiarization with the moving floor, and it has been shown that responses are altered with progressive exposure to the perturbations (McIlroy and Maki, 1995a). Furthermore, arm motion was restricted during the responses, yet this can be an important aspect of balance control (McIlroy and Maki, 1995b; McIlroy and Maki, 1999b). However, this worked aimed to determine the
modifiability of the stepping response, and restricting upper limb movement was done in order to avoid any of the confounding effects of arm reactions on lower limb motion. There is also the question as to the ecological validity of support surface perturbations themselves; however, there has been no attempt as of yet to correlate any method of perturbation with what may be experienced in everyday life (Maki and McIlroy, 1997).

Although one can argue that support-surface translations replicate the biomechanics of typical falling situations in that they create a relative displacement between the center of mass and base of support, one must also consider that the pattern of visual, vestibular and somatosensory discharge associated with the perturbation-induced body motion will always be specific to the nature of the perturbation.

The obstacles used in these experiments also were a source of limitations. These were static, unchanging obstacles, clearly evident at the outset of the experimentation, and placed in only one direction relative to the participants. As well, participants were made well aware that the obstacles were designed to release or yield upon contact. The absence of any real threat to impeding their movement has motivational implications; however, the high success rate suggests that this was most likely not a factor.

The fact that the study was limited to healthy young adults is another limitation that may limit the generalizability of the findings. In addition, the sample size was relatively small. Although subjects did tend to show similar patterns of behaviour in the main experiment and statistically significant changes due to the obstacles were detected, there was some variation in individual subject responses. For example, some subjects displayed an increased tendency to step with the left leg, and some differences in responses based on the stepping leg side were detected. In addition, the possible confounding effects of varying subject height and weight were not covered in this thesis. The only previous studies investigating the effect of body size on compensatory stepping
considered only the effect of weight on the incidence of stepping (Rogers et al., 1996). It is not clear how body weight would effect the control of the APA and COM. However, although not reported, responses for the first study were normalized to height, and the analyses repeated after normalizing showed similar findings. Moreover, except for the early trials, the responses were compared within subjects and these within subject comparisons would be exempt from these concerns. However, a possible influence of weight on the response cannot be ruled out for the between subject comparison of the early trials.

The second study only included male subjects. There may well exist some differences in responses between sexes. However, the first study did use both males and females, and failed to demonstrate any significant sex differences. It possible, however, the relatively small sample size may have prevented the detection of more subtle discrepancies. Indeed, there have been some response inconsistencies in compensatory stepping attributed to sex (Maki et al., 1996), perhaps due to psychological or motivational disparities. This potentially limits the generalizability of the results, and its use as a potential comparison to other populations.

Another aspect not considered in this study was the possible interaction between the APA and limb dynamics. It may be that this anticipatory activity was also functioning to elevate the swing limb by elevating the pelvis; however, it is also clear that the APA modulations were strongly associated with changes in control of lateral COM motion. In particular, it would be difficult to explain the APA modulation occurring when lateral foot motion was constrained on the basis of limb elevation, as identical limb elevation was required in the obstacle-only and obstacle-constraint conditions.

Another limitation is that limb kinematics were not measured. Since the obstacle was placed so close to the feet, subjects could not rely on flexing the leg at the hip, as this would most likely resulted in obstacle contact. While not measured, there appeared
to be a tendency for swing limb abduction that may have predisposed a more lateral foot placement. However, this also applied for light-cued (volitional) stepping over the obstacle. In these trials, the foot was not placed laterally despite the need for a similar degree of abduction. Furthermore, the finding that prevention of lateral stepping necessitated other modulations in order to preserve lateral stability (i.e. increase in APA amplitude) would indicate that the lateral stepping was actively regulated so as to preserve lateral stability, and was not simply a consequence of a more abducted limb.

There were also some limitations in the measures used in the studies. In the first study, the size of APA was quantified by the product of the maximum lateral COP magnitude and the duration of the APA divided by two (area of a triangle). This provided a rough estimate of the time-integral, but was not the most accurate account. This same measurement was not included in the second study for this reason. It seemed more prudent to consider the duration and amplitude separately, as they represented different levels of contribution to the anticipatory effort. Although the COP is commonly used to quantify anticipatory efforts (Breniere et al., 1987; Jian et al., 1993; MacKinnon and Winter, 1993), it is also not clear the extent to which the COP measures used to quantify the APA reflect propulsion due to ankle, hip, or even other musculature; however, some work suggests that the hip abductors/adductors play a predominant role in controlling lateral motion of the COM (Rogers and Pai, 1990; Winter et al., 1993; Rogers and Pai, 1995). Further work is needed to clarify the neuromuscular control mechanisms, nonetheless, the COP measures showed a high correlation with m-l COM motion at FO in this study (e.g. across both studies correlation of ml COM velocity with APA duration and magnitude was 0.83 and 0.89, respectively (p's < 0.0001)).

In addition, the method for measuring step placement (overhead video recording of reflective fifth metatarsal marker against a floor grid) has a limited resolution (1cm). While the differences in foot placement between conditions were substantial enough to
be detected despite this limitation, it is likely that more subtle variations in foot placement
would not have been detected. Finally, motion of the COM was determined using
successive integrations of the ground reaction shear forces. This method of
measurement is prone to drift error (because errors in the signals are propagated and
amplified by the integration); however, the short duration of integration involved in
analyzing these rapid stepping reactions has been shown to result in reasonably good
agreement for both displacement and velocity estimates in comparison to kinematic
COM estimates (Maki and McIroy, 1999b).

5.3 Practical applications

The results of these experimentations provide a baseline response of young,
healthy individuals to eventually be compared against older and other clinical
populations. Such information could be used to further identify deficits associated with
impaired balance control, and in turn, develop measures that more strongly predict
prospective falling risk. As well, such measures could be used in clinical balance
assessments. Other potential benefits of this information include improved assistive
devices, helpful environmental modifications, and balance training protocols. For
example, training older subjects in known areas of weakness in balance control, such as
accommodating for nearby environmental constraints, may enhance their balance
recovery abilities. Given the apparent difficulties of m-l stability control during
compensatory stepping in older adults (Maki and McIroy, 1996; Maki and McIroy,
1999a; Rogers et al., 2001) and problems in APA control during stepping in other clinical
populations (e.g. Parkinson’s disease (Burleigh-Jacobs et al., 1997)), obstacles may be
used to encourage the use of predictive control. As well, recommendations may be
developed for the design of areas frequented by balance impaired individuals to
minimize the risk of a fall. Bathrooms, for example, are a high-risk area for falls, but
commonly present numerous obstacles that could interfere with compensatory stepping. Obstructions should be minimized, where possible. Otherwise grab-bars and handrails should be provided to allow grasping reactions to be used. It may also prove possible to minimize effects on compensatory stepping by suitable design of unavoidable obstacles (e.g. bathtub walls) or by heightening attention to the obstacle (e.g. through lighting or color coding). Further research is needed to evaluate the feasibility of these approaches.

5.4 Future work

The eventual goal of the current line of balance research is directed to the reducing the problem of falling in older adults. By gaining a more thorough understanding of balance control and associated age related deficits, more effective and efficient intercessions can be made. Future work will be aimed towards testing of healthy, older subjects, to determine what, if any, age related impairments exist to the modifiability of compensatory stepping with regard to environmental constraints. As well, other clinical populations, such as Parkinson patients, could be tested with this paradigm to further examine associated impairments of particular conditions. This may also provide more insight into the role of specific CNS structures, such as the basal ganglia, in balance control.

As well, these studies provided no information in regards to trajectory control of the foot, except for its final position. While it was not clear in this study whether on-line modifications were being made to the responses, this may be revealed by closer examination of the limb movement. Studies of volitional responses have shown a cautious approach to obstacle crossing, and it is not clear whether these same types of 'safety' measures are employed during compensatory stepping. Additionally, more complex and dynamic obstacle conditions will be studied to better emulate day-to-day conditions, and to gain insight as to how the CNS tracks and maps ongoing changes in
the immediate environment and uses this information in modulating compensatory balance reactions. Understanding the role of attention, and effects of age-related changes in attention and cognitive processing, is likely to be of prime importance in such studies.

5.5 Conclusions

The results of this thesis show a remarkable capacity for the modulation of rapid triggered stepping reactions in response to environmental constraints. Not only was the CNS able to adapt to a high challenging obstacle, but also to additional restrictions on lateral swing foot placement, even within the earliest trials. While previous results suggested compensatory stepping reactions evoked by unexpected or unfamiliar perturbations were not amenable to significant anticipatory control, this is clearly not the case. The modifiability of these reactions was far more extensive and successful than anticipated, and while it is was demonstrated that these are not simply stereotypical responses, the full potential of CNS control over compensatory reactions remains to be determined.
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