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Balance mechanisms during standing and walking in young and older adults

by

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Abstract

Maintaining balance is controlled by two different processes: feed-forward and feedback control. Feed-forward control is used prior to performing voluntary movements whereas feedback control is used to correct for unexpected perturbations. Studies suggested that age-related changes in postural responses may contribute to increased risk of falls in older adults. To address whether Tai Chi training can induce improved patterns of feed-forward control, voluntary arm elevations during standing were performed. Compared to age-matched controls, smaller displacements of the center of pressure were found among older adults who practice Tai Chi. This may suggest adapted feed-forward control induced by training. To investigate feedback control, perturbations were applied while walking with various arm constraints. Context-dependent modulation in response amplitude was found with changing levels of postural threat in older adults, comparable to young adults. Delayed onset latencies and frequent inhibition of Soleus may suggest less effective balance strategies employed in older adults, and an increased risk of falling.

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Chapter 1- General Introduction

1.1 Introduction

Recent evidence shows that the major injuries that occur among older adults are due to falls (Canadian Institute of Health Information, 2006). Falls are also the leading cause of injuries that led to hospitalizations among older adults (Canadian Institute for Health Information, 2004). Approximately 85% of older adults were hospitalized with fall-related injuries and 40% of admissions to long term care facilities were the result of falls (Canadian Institute of Health Information, 2004; Scott et al. 2005; Zuckerman, 1996). Of those older adults who had falls, 47% of the seniors sustained injuries such as sprains or fractures. In fact, 90% of the hip fractures among older adults were due to falls (Scott et al. 2005; Zuckerman, 1996). The majority of older adults who had hip fractures were restricted in their functional mobility; only 12.9% of the seniors regained their previous level of ambulatory function (Zuckerman, 1996).

Whereas muscle weakness or reduced functional mobility were associated with falls among those older adults in long term care facilities, older adults in the community fall due to environmental factors (Gallagher and Brunt, 1996; Rubenstein et al. 1994). Environmental risk factors such as walking while carrying objects or with assistive devices, or walking on uneven surfaces around or over obstacles were common risk factors leading to falls, accounting for nearly half of the falls reported among older adults who live in the community (Gallagher and Brunt, 1996; Public Agency of Canada, 2005). The results from these studies therefore suggest that the ability to maintain balance is critical in order to reduce the incidence of falls when older adults encounter destabilizing activities.

Generally, balance is controlled through two main strategies: anticipatory and reactive control. Anticipatory control refers to adjusting balance in an anticipatory manner prior to voluntary movements, whereas correcting balance following unpredicted perturbations is referred to as reactive control (Massion, 1992; Patla, 2003). Anticipatory control is involved in the activation of the postural muscles which precedes voluntary movements to counterbalance postural instability such as when reaching up to cupboards while standing. When we reach up to cupboards, forces induced by the arm movements accelerate the body's COM (Center of Mass) downward and backward. Anticipatory adjustments serve to act in a direction to oppose these forces so as to minimize the displacement of the body's COM prior to arm movement (Bouisset and Zattara, 1981; Maki, 1993; Massion, 1992). Reactive control involves muscle activations of the body to correct balance following unpredictable perturbations (Patla, 2003). Sudden perturbations applied to the body act as a destabilizing force, resulting in the displacement of the body's COM beyond its base of support (BOS) (Maki and McIlroy, 1996; Winter 2005). In this event, rapid activation of the muscles in the legs and arms are critical in order to place the COM inside of the BOS safely so that potential falls are prevented (McIlroy and Maki, 1995; Misiaszek, 2003; Misiaszek and Krauss, 2005). The next two parts of the introduction will describe these two balance strategies, focusing on the older population, to establish the foundation of the thesis.

1.2 Balance Control

1.2.1 Concepts of Anticipatory and Reactive control

Early activations of the postural muscles in order to stabilize the body are called anticipatory postural adjustments (APAs), as the timing of the responses occurs in advance of the voluntary movements (Massion, 1992). Studies on APAs indicate that the purpose of the APA is to minimize destabilization and counterbalance forthcoming voluntary movements in an efficient manner (Bouisset and Zattara, 1987; Massion, 1992). APAs associated with voluntary movements can be commonly observed in movements of the arms during standing (Belenkiy et al. 1967; Lee et al. 1987; Inglin and Woollacott, 1988; Maki, 1993; Woollacott and Manchester, 1993). When subjects were asked to raise one arm rapidly, the onset of activity in the muscles of the legs and trunk preceded the activation of anterior deltoid (AD) by as much as 50-100 ms (Belenkiy et al. 1967; Lee et al. 1987). A similar result also shows that early EMG activity in the gastrocnemius (GA) of the moving leg minimized the displacement of the

COM when subjects were asked to raise one leg laterally to a 45 degree angle (Mouchnino et al. 1990). Anticipatory responses, a specific pattern of postural muscle activation which precedes voluntary movements, are acquired through learning or past experience of postural disturbances. For instance, anticipatory changes in EMG (electromyographic) activity occurred in the gastrocnemius to ensure stability during fast backward trunk flexion in trained gymnasts, but did not occur in naïve subjects (Pedotti et al. 1989). APAs thus play an important role in stabilizing the segments of the body prior to voluntary movements. It was suggested that anticipatory adjustments are centrally organized as part of motor acts since APAs that precede voluntary movements occur to ensure balance when body segments are displaced (Horak et al. 1984; Massion, 1992). Since activations of the postural muscles are time locked to the voluntary movements, signals from supraspinal centers to the spinal cord have been suggested to contribute to APAs (Brown and Frank, 1987; Gahery and Massion, 1981).

In contrast, those responses elicited in the muscles of the trunk and limbs following unexpected perturbations are called reactive (Misiasezek, 2006; Patla, 1993; 2003; Woollacott and Tang, 1997). The patterns of muscle activations following those unexpected perturbations were observed extensively in studies of standing balance. When the support surface is perturbed during standing, ankle and hip strategies are commonly used to minimize the displacement of the COM and to realign the body segments within the BOS (Horak and Nashner, 1986; Horak et al. 1989). The ankle strategy refers to controlling the COM forward or backward by rotating about the ankle joint to slow or small perturbations, whereas the hip strategy refers to controlling the COM using flexion or extension of the hip joint to fast and large perturbations or when standing on a narrow base (Horak et al. 1989). Unless subjects are asked not to take a step, they will most likely use the stepping strategy to restore the COM by changing the BOS. Whereas ankle and hip strategies are used to decelerate the motion of the COM, the stepping strategy is used to alter the BOS (Maki et al. 2003).

When we experience sudden destabilizing forces such as unexpected movements of the support surface or backward pulls of the waist, short latency and coordinated corrective responses are evoked in the muscles of the legs and arms to regain balance (Maki and McIlroy, 1997; Marigold et al. 2003; McIlroy and Maki, 1995). Following disturbances, the onset of the evoked EMG responses, usually between 70-100 ms, preceded the onset of deviation in the trajectory of the body’s COM during standing (Horak and Macpherson, 1996) and walking (Misiaszek, 2003). Due to those early corrective reactions that were between simple segmental reflex and voluntary postural responses range, Misiaszek (2006) suggested that regulation of corrective reactions is mediated by spinal cord, brainstem or long loop pathways. This observation is consistent with the suggestions made by Dietz (1992) and Horak and Macpherson (1996). Another important characteristic of reactive strategy is the comparable onset latencies evoked in the muscles of the legs and arms during standing (McIlroy and Maki, 1995) and walking (Dietz et al. 2001; Marigold et al. 2003; Misiaszek, 2003; Misiaszek and Krauss, 2005). For instance, the onset of the evoked response in TA (tibialis anterior) and PD (posterior deltoid) had onset latencies of 90 ms and 88 ms respectively when subjects received support-surface translations while standing (McIlroy and Maki, 1995). During walking, corrective responses to perturbations applied to the torso also had comparable onset latencies of 84 ms in TA and 80 ms in PD (Misiaszek, 2003). These similar onset latencies evoked in the muscles of the legs and arms suggested that common central mechanisms may be involved in generating corrective reactions (Misiaszek, 2003).

1.2.2 Decline of balance control with aging

The reduced capacity to maintain balance during daily activities experienced by older adults is reflected in high incidences of falls and related injuries, which are the major concerns in this older population. There are several key factors that contribute to the changes that occur with aging in balance control in older adults, for example, musculoskeletal, neurological, and sensory changes. Such contributors to falls are complex and interactive, increasing the risk of falls with the combination of co-morbidities among older adults (Public Health Agency of Canada, 2005).

The effects of aging associated with musculoskeletal changes showed that reduced muscle strength, in particular, in the muscles of the lower legs, was one of the common risk factors resulting in falls (American Geriatrics Society, 2001; Public Health Agency of Canada, 2005). Changes known to cause muscle weakness included decreased muscle mass, reduced muscle fibres, loss of motor units, and decreased maximal force production (Campbell et al. 1973; Faulkner et al. 2007). In particular, the decreased number of muscle fibres, both type I and II, gradually started in people age 50 and over, resulting in the loss of 50% of the fibres by the age of 80 in the muscles of the limbs (Faulkner et al. 2007). A loss of motor units was also shown to contribute to muscle atrophy, which is a typical physiological change that occurs during the aging process (Faulkner et al. 2007; Thompson; 1994).

The decline in the musculoskeletal system that occurs with advancing age is related to the increased risk of falling. For instance, the risk of falls increases 4-5 times in older adults who have muscle weakness and 2.4 times in older adults with musculoskeletal diseases such as osteoarthritis (Rubenstein and Josephson, 2002). While many studies have shown that the decline of the musculoskeletal system is associated with the risk of falls, a study by Maki and McIlroy (1996) raised possibilities that musculoskeletal changes with normal aging may not play a critical role in failure to execute balance reactions.

This was supported by previous studies on reactive strategies following backward perturbation at the waist (Luchies et al. 1994), translational perturbations during beam tasks (Alexander et al. 1992), or support surface translations during standing (McIlroy and Maki, 1996). In those studies, joint range of motion, muscle forces, and movement speed observed in older adults were not different from those observed in young adults. They suggested that, in healthy older adults, the subtle changes in the musculoskeletal system that occur with aging may not largely affect the capacity of generating compensatory responses. It appeared that coordinated responses evoked in the muscles as well as adaptive capabilities to modulate balance reactions, rather than the deficits in musculoskeletal systems, may primarily be responsible for generating ineffective reactive strategies in healthy older adults.

Sensory inputs such as visual, vestibular, and somatosensory systems play an important role in controlling postural stability among older adults. Studies have shown postural stability can be strongly influenced by changing sensory systems (Horak et al. 1989; Horak, 2006; Maki and McIlroy, 1997). For instance, when visual inputs were reduced or augmented suddenly while subjects were standing on a force platform, older adults did not adapt to changing visual conditions as well as the young adults did, and they demonstrated an increased sway (Teasdale et al. 1991). Woollacott et al. (1986) also showed that half of the older adults tested could not control their balance during conflicting sensory inputs (i.e. rotation of the surface platform and visual surround). This increased postural instability appears to be an indication of the difficulty that older adults have reweighing sensory inputs under changing environments.

As expected, age-related changes associated with the sensory system can increase the risk of falling. Impaired visual functions such as a decreased depth perception, decreased acuity or contrast sensitivity increased the risk of fall by 2.5 times among older adults (Rubenstein and Josephson, 2002). Proprioceptive functions, which are a key factor in determining the position of the distal limbs, can contribute to falls with changes associated with aging (Goble et al. 2008). Declines in proprioceptive acuity, particularly in the lower limbs such as the knee joint (Barrack et al. 1983) and ankle joint (Verschueren et al. 2002), were positively correlated with the occurrence of falls over the previous year (Lord et al. 1999). In addition, several studies suggested deterioration in the peripheral or central vestibular systems, for example; a reduced number of hair cells in the labyrinthine (Rosenhall, 1973), deteriorated function in vestubulo-ocular reflex (Paige, 1992), and slow reaction time in optokinetic nystagmus (Dizio and Lackner, 1990) were associated with postural instability in older adults. As a result, older adults who have bilateral vestibular hypofunction showed an increased occurrence of falls and fall-related injuries (Herdman et al. 2000).

Other factors known to contribute to the increased risk of falls include deteriorative changes associated in the nervous system such as a decreased number of neurons (Lipsitz and Goldberger, 1992), reduced neurotransmitters such as dopamine (Scheibei, 1985), and decreased nerve conduction velocity (Stelmach and Worringham, 1985). These changes have been shown to delay information processing, resulting in a slow reaction time among older adults (Lord et al. 1991; 1994). In addition, increased reaction time has been shown in older adults during complex cognitive or postural tasks that require information processing (Teasdale and Simoneau, 2001; Maylor and Wing, 1996). A study by Teasdale and Simoneau (2001) showed such an increased reaction time when older subjects were asked to respond verbally to an auditory cue in the absence of vision during standing. The decreased postural stability of older adults was also observed during their performance of various types of memory tasks (Maylor and Wing, 1996). Shumway-Cook et al. (1997) showed that older adults with a history of falls had more difficulty with maintaining postural stability following platform perturbations while performing concurrent cognitive tasks. In fact, older adults who have cognitive impairments increased their risk of falls by 1.8 times (Rubenstein and Powers, 1999).

In summary, deficits associated with musculoskeletal, neurological, sensory, and cognitive functions with aging are closely associated with changes in controlling balance. Particularly, environments where reweighing of sensory inputs is required due to either reduced or conflicts of sensory inputs may restrict the ability of older adults to reorganize their balance reactions.

1.2.3 Effect of training on balance

Recent studies on fall prevention reported that those exercise programs which are aimed at improving balance are effective in reducing the incidence of falls and fall-related injuries among seniors (Gillespie et al. 2009; Howe et al. 2007). For instance, exercise programs focused on improving balance, muscle strength, endurance and flexibility showed a 22% reduction in the occurrence of falls and a 15% reduction in the risk of falls (Chang et al. 2004). Gillespie et al. (2009) concluded from the studies reviewed that individualized prescribed programs targeted on balance and muscle strengthening were effective in enhancing balance among older adults. Although many studies have identified the positive effects of exercise programs, it is important to select appropriate approaches that are suited to the condition of older individuals. Exercise interventions for older adults who are independently mobile, or who live in the community will be different from those for older adults who are frail and use walking aids or live in long term care facilities (Public Health Agency of Canada, 2005). Thus, more research is needed to determine the types, intensities, and durations of the training programs that are most effective for older adults in dealing with different types of mobility and balance problems (Scott et al. 2004).

To date, there is compelling evidence that a specific type of exercise, that is, Tai Chi, can be a significant factor in improving postural stability among older adults. Tai Chi is a traditional Chinese form of exercise that requires continuous movements of the body position (Taylor-Piliae and Haskell, 2007). As Tai Chi is slow and gentle, unlike many other exercise programs, it may be appropriate for active older adults as well as older adults who are more frail (Lan et al. 1998). The positive benefits of Tai Chi were reported in various outcome measurements of balance or falls. Compared to non Tai Chi practitioners, older adults who practiced Tai Chi showed increased proprioceptive acuity in detecting joint position sense (Tsang and Hui-Chan, 2003; 2004) and a reduced fear of falling and risk of falls (Gagnon and Flint, 2003). A 15-week Tai Chi randomized controlled study by Wolf et al. (1996) demonstrated that the risk of falls was reduced by 47.5 % among older adults who participated in Tai Chi training, compared to those who received education and a computerized balance training program. Another Tai Chi study supported the fact that Tai Chi was the only group exercise program that improved balance among the studies evaluated (Gillespie et al. 2009). Similar improvements in older adults with balance disorders were observed in studies by Gatts and Woollacott (2006; 2007). Compared to a control group who received axial mobility exercises, stretching, and balance/awareness education, a 3-week Tai Chi training group showed early TA EMG activity of the perturbed leg following slip-like perturbations at heel strike. In addition, a reduced incidence of tripping was found in the Tai Chi group, indicating that older adults who practice Tai Chi are more stable following unpredictable perturbations than their age-matched control group. As described above, the majority of studies on Tai Chi have focused on the benefits of Tai Chi exercise in improving balance, including aspects of reactive control to unpredictable perturbations. However, few studies have addressed whether or not the effects of Tai Chi could also be related to enhanced patterns of anticipatory strategies. Anticipatory strategies are used to ensure the postural stability that is necessary prior to voluntary movements. The coordination of muscle activities in postural responses prior to voluntary activities is important, otherwise, older adults are likely to encounter environments in which they are unstable. Thus, the question arises whether postural adjustments of Tai Chi practitioners would yield distinct differences in their organization of anticipatory balance. The main purpose of the first study was to identify whether adaptation would occur as a result of Tai Chi training in the control of voluntary movements.

1.3 Balance during walking

1.3.1 The added challenge of maintaining balance while walking

Maintaining postural stability during walking is a complex task that requires controlling the center of mass (COM) within a changing base of support (BOS) while keeping an upright posture (Marigold and Misiaszek, 2009; Patla, 2003; Winter, 2005). One of the major challenges of balance is that the mass of the body is inherently unstable during bipedal gait (Maki and McIlroy, 1996; 1997; Patla, 2003; Winter, 2005). Due to the fact that the COM is located two thirds of the height of the body above the support surface and the BOS is relatively small, controlling the COM during walking is mechanically complex (Horak and Macpherson, 1996; Patla, 2003). Another distinctive difference of gait is the regulation of the relationship between the COM and the BOS (Maki and McIlroy, 1996). Typically, the COM is kept inside of the unchanging BOS during standing. When we initiate gait, displacement of the COM must occur to be positioned ahead of the BOS. During walking, regulating the body's COM within the changing BOS is required to ensure postural stability so that the body can successfully progress continuously to an intended destination (Horak and Macpherson, 1996; Maki and McIlroy, 1997). As shown in studies of gait trajectory, acceleration of the COM forward and toward to the medial border of the stance limb loads the stance limb as the swing limb unloads. Due to the fact that the duration of the single-limb support phase constitutes 75-80% of the step cycle duration and the COM lies within the changing BOS only for a short period, it creates difficulty for postural stability and increases the likelihood of falling during human gait (Winter, 2005). In addition, in order to move the COM smoothly, the forces acting on the body must be coordinated with respect to the external forces generated from gravity and the surrounding environment (Horak and Macpherson, 1996; Winter, 2005).

As described in the previous chapter, two main balance strategies are used to control the body's COM while progressing toward a destination during walking. Anticipatory control is used to identify any potential destabilizations along a trajectory in order to place the body's COM safely to the next BOS in advance. Identifying upcoming disturbances such as obstacles, uneven surfaces, or moving threats primarily relies on visual information. The combination of using those on-line references (i.e. sensory inputs) as well as experience acquired in the past, aids to anticipate the consequences of forthcoming movements and establish accurate location of the next COM position (Patla, 2003; Misiaszek, 2006). In contrast, reactive control is used to recover the body's COM following unexpected perturbations. Hill et al. (2001) reported that the time taken to recapture the falling COM inside of the BOS was approximately 2 s following perturbations of the trunk during walking. Thus, fast corrective reactions are an essential requirement to ensure stability. The detection of unexpected perturbations during ongoing movements as well as any errors occurring during balance reactions (i.e. when subsequent corrections are necessary if the first attempt was not successful) is largely affected by sensory information. Any reduced or conflicting sensory information from visual, vestibular, and proprioceptive systems can affect the process of determining the next foot placement and the location of the COM.

1.3.2 Task dependent modifications

When the body encounters balance disturbances, complex and robust patterns of muscle activations in the muscles of the legs and arms occur to regain stability (Misiaszek, 2006). Studies on compensatory reactions demonstrated early responses in the arm muscles at similar latencies to the leg responses, indicating responses from the whole body are critical in maintaining balance (Dietz et al. 2001; McIlroy and Maki, 1995; Misiaszek, 2003). The functional roles of the arms, such as elevating them to readjust the backward center of mass, bracing them against falling, or using them to grasp supports are important in restoring balance during standing (McIlroy and Maki, 1995; Maki et al. 2000) and walking (Dietz et al. 2001; Misiaszek, 2003; Tang and Woollacott, 1998). Results from these studies demonstrated that corrective arm reactions were commonly observed despite the dissimilarity of the perturbation methods or the familiarity of the perturbations applied (Maki and McIlroy, 2005; Misiaszek, 2003). That is, early responses in the arm muscles consistently occurred across all subjects even when the perturbations were small (Dietz et al. 2001; Maki and McIlroy, 1997; Marigold et al. 2003; Misiaszek, 2003). Thus, the responses evoked in the arm muscles were involved in assisting balance, thereby minimizing the degree of instability and preventing falls to perturbations during standing (McIlroy and Maki, 1995; Maki et al. 2000) and walking (Dietz et al. 2001; Misiaszek, 2003; Tang and Woollacott, 1999).

Walking balance becomes challenging under several conditions, such as when subjects are involved in certain tasks such as carrying groceries while stepping on an icy surface or irregular terrain. Under those conditions, whole body corrective responses, i.e. activations of the muscles in the legs as well as in the arms, are often limited. Thus, constrained segments of the body following perturbations may result in changes to the corrective strategies selected. Recently, evidence showed that corrective reactions following perturbations were enhanced when the arms were restricted in regaining balance (Misiaszek and Krauss, 2005). In that study, perturbations to the torso during treadmill walking showed context-dependent modulation of corrective responses under different arm tasks. When the arm use was restricted by crossing the arms in front of the chest, response amplitudes evoked in the leg muscles were increased (Misiaszek and Krauss, 2005). However, the response amplitudes of the leg muscles were decreased when subjects were holding handles (Misiaszek et al. 2000). These results suggest that corrective strategies can be modulated according to the required task demands.

There is considerable evidence that postural stability can be facilitated when additional sensory inputs are provided at the fingertip during standing (Jeka, 1997; Lackner et al. 2001) or when handles are provided during walking (Misiaszek et al. 2000). Given this, using mobility aids may provide mechanical stability and additional sensory inputs. However, recent studies showed that using assistive devices such as canes or walkers may produce adverse conflicts such as collisions between the legs and mobility aids, thus increasing the risk of falling and fall related injuries (Bateni et al. 2004a; Bateni et al. 2004b; Bateni and Maki, 2005). Furthermore, conflicts between mobility aids held and external supports during balance recovery were noted (Bateni et al. 2004b). In the study of Bateni et al. (2004b), young subjects continued to hold canes rather than grasping stable handles in response to platform perturbations, even when the objects being held did not directly provide stability. However, little attention has been paid to whether arm constraint during walking can interfere with or alter the corrective strategies in older adults. Studies on whether holding supports actually decreases or inhibits the capacity for generating adequate corrective responses will be very important for older adults, particularly older adults who rely on mobility aids. Presumably, older adults who use mobility aids may encounter more challenges in controlling balance during unexpected postural disturbances.

1.3.3 The impact of aging

Balance tasks that we commonly encounter in daily activities can be more demanding for older adults. The difficulty with maintaining stability during walking is reflected in the fact that approximately 70% of falls resulting in injury in older adults occurred during slips, trips, or going up or down stairs (Public Health Agency of Canada, 2005). To date, several studies showed age-related changes in balance reactions to unpredictable perturbations (Maki and McIlroy, 1997; Maki et al. 2000; McIlroy and Maki, 1996; Tang and Woollacott, 1998; 1999). The main findings of these studies were 1) delayed onsets with small response amplitudes, requiring longer burst durations, 2) limited capacity to modulate the amplitude of responses across the step cycle, 3) increased number of extra steps to recover balance, thus creating possibilities of collisions between the swing and stance limbs, and 4) increased tendency to use the arms. As such, changes observed in corrective responses among older adults are likely a result of inaccurate or inefficient initial corrective responses; thus, additional corrective strategies are required to stabilize the body by taking additional steps, elevating the arms, or grasping external supports more frequently (Tang and Woollacott, 1998; Maki et al. 2000).

1.4 Summary, hypotheses and projects

Unintentional falls are the leading cause of severe injuries among those aged 65 and over, affecting 180,000 seniors annually in Canada (Public Health Agency of Canada, 2005). In addition, fall-related injuries accounted for more than $980 million in direct health care costs in Canada. This trend is most likely to increase as the aging population grows, reflecting an increasing proportion of the population sustaining fall-related injuries.

Given the large impact on seniors that fall-related injuries have, it is important to understand the balance strategies to postural disturbances that may arise during daily activities. For instance, when we reach and grasp objects from a cupboard, anticipatory responses in the leg muscles are required to stabilize our body prior to executing voluntary arm movements. In contrast, when meeting unexpected disturbances (e.g. slips or trips), rapid and complex corrective responses in the leg muscles as well as elevating or grasping arm reactions are required to regain balance. Both preplanned and unexpected postural disturbances require whole-body reactions in order to perform movements successfully while maintaining balance. The purpose of this thesis was to investigate whether adaptive patterns of balance strategies can occur among older adults. The purpose of the first study was to investigate whether the properties of feed-forward strategies can be adapted if older adults are involved in certain types of physical activities, such as Tai Chi. We hypothesized that improved patterns of anticipatory responses would occur as a result of training in older adults. Specifically, we hypothesized that training induced changes following Tai Chi can also lead to improved functional balance outcomes. Therefore, the adaptive pattern of muscle activations to forthcoming perturbations would be organized more like young healthy adults than with older adults who do not practice Tai Chi. In the second study, feedback strategies to perturbations of the torso during walking were investigated to address whether corrective responses in the leg muscles would modulate to the changes of the arm tasks. We hypothesized that corrective strategies employed in older adults would be similar to those observed in young adults. The results of these studies will help to understand the regulation of balance strategies that may be impaired in older adults, thereby identifying better approaches to reduce the incidence of falls.

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Chapter 1 – Adaptations in anticipatory postural control of older adults who practice Tai Chi

2.1 Introduction

Anticipatory postural adjustments (APAs) precede the activation of focal muscles involved in generating self-initiated movements. The main purpose of these APAs is to stabilize the center of gravity within the base of support in order to maintain equilibrium. For example, the early activation of postural muscles to counteract the forthcoming mechanical perturbation induced by voluntary arm movements has been well described (Bouisset & Zattara, 1987; Inglin & Woollacott, 1988; Maki, 1993; Woollacott & Manchester, 1993).

There is clear evidence of age-related deterioration of anticipatory postural abilities. Maki (1993) reported larger relative amplitude of anticipatory changes in the ground reaction forces prior to arm elevations in older adults with a history of recurrent falls. Inglin and Woollacott (1988) demonstrated delayed onset latencies of postural and focal muscles when older subjects were asked to either push or pull on a handle in response to light signals while standing. These age-related changes in the APAs may limit the capacity for controlling destabilizing events such as bending and reaching during daily activities, which may then lead to an increased risk of falling.

A number of studies have demonstrated that APAs can be modified with training. For example, trained gymnasts utilized an anticipatory activation of distal leg muscles when performing a fast backward trunk movement that was not observed in untrained subjects (Pedotti et al. 1989). Presumably, the training of the gymnasts resulted in a long-term adaptation of APA control that was more efficient than the untrained subjects in stabilizing the body as the gymnasts were clearly more efficient in controlling the projection of the body centre of gravity. Similarly, trained dancers stabilize the trunk and head during leg lifting by performing an anticipatory counter-rotation of the trunk to compensate for the impending ankle joint rotation (Mouchnino et al. 1990). Taken together these studies suggest that APAs can be modified with training to provide improved postural control during voluntary movements. However, each of these studies involved young healthy adults, trained for specific high-performance activities. It is not clear whether similar adaptations would occur after training in the anticipatory control of balance of older adults.

Recent studies have indicated a clear relation between balance or strengthening exercise and improved balance control, suggesting that training is important in fall prevention in older adults (Marigold et al. 2005; Tinetti, 2003). Moreover, Tai Chi training is suggested to be an effective exercise program for falls prevention in older adults (Wolfson et al. 1996). Wolfson et al. (1996) compared groups who received computerized balance training and education to a group that received Tai Chi training and found Tai Chi training was related to a 47.5 % reduction in the rate of falls and a reduced fear of falling. A Cochrane Review reported Tai Chi training is an effective training method in reducing the incidence of falls and related injuries (Gillespie et al. 2003). In more recent studies, Gatts and Woollacott (2006, 2007) also suggested that Tai Chi training resulted in improved patterns of corrective strategies following perturbations during walking in older adults who have balance impairments. Taken together these results suggest that Tai Chi training is associated with enhanced postural stability and a reduced risk of falling following external perturbations. However, it is not clear whether Tai Chi training leads to adaptations in anticipatory postural strategies in older adults. A priori the expectation is that this type of training, which involves planned and slow movements that challenge postural stability, will lead to improved anticipatory postural control. Specifically, we hypothesized that the timing and patterning of anticipatory postural adjustments in older adults who practice Tai Chi will be more similar to those in young adults, compared to healthy older adults who do not practice Tai Chi.

2.2 Materials and Methods

2.2.1 Subjects

A total of forty eight volunteers participated in the study and provided written informed consent. The procedures were approved by the Health Research Ethics Board at the University of Alberta. Of the forty eight subjects, twenty-two were older adults who had practiced Tai Chi, fifteen were older adults who had been involved in other forms of regular activity for more than a year (OA), and eleven were young adults (YA) who have been involved in regular activity for more than a year. Ten of the subjects who practiced Tai Chi were assigned to a short-term Tai Chi (STC), twelve were assigned to long-term Tai Chi (LTC) group based on the years of experience. The average experience of practicing Tai Chi was 2.15±0.78 yrs for STC and 9.83±4.83 yrs for LTC. The mean (± standard deviation) age of each group was 65.1±3.51 yrs for STC, 70.4±8.10 yrs for LTC, 68.6±6.29 yrs for OA, and 26±2.50 yrs for YA.

Prior to participation in the study interested subjects were first screened for neurological, musculoskeletal or metabolic disorders including diabetes via a telephone interview. In addition, the Community Healthy Activities Model Program for Seniors (Steward et al., 2001) activity questionnaire was used to identify physically active older adults. This questionnaire assesses frequency and duration of various leisure and non- leisure activities that are commonly performed by older adults using the most recent 4 week period. “Active” was defined as at least 30 minutes of moderate physical activity 4 days per week. After the interviews, subjects with osteoarthritis or osteoporosis were included as these diagnoses represent common diseases of a typical older population. A total of 7 older adults with osteoarthritis or osteoporosis participated (STC=2, LTC=3, OA= 2). None of the young adult subjects reported any medical history that fell into the exclusion criteria.

2.2.2 Clinical Measures of Balance

Functional balance control was assessed using three clinical assessments: Functional Reach (FR), Berg Balance (Berg), and Community Balance and Mobility Scale (CB&M). The Functional Reach (FR) test was used to determine the maximal distance that subjects can reach forward while standing (Duncan et al. 1990). Subjects were asked to stand comfortably and raise one arm with a fist parallel to a yardstick on the wall and lean as far forward as possible without losing their balance. The point of the third metacarpal was recorded, and the trial was excluded if they touched the wall or took a step. Three trials were recorded and averaged. The Berg Balance test was chosen as this test is used frequently in clinical settings (Berg et al. 1989). This measure was comprised of 14 movements including maintaining a posture during sitting, standing, turning, and transferring, with scores ranging from 0 to 56. The

Community Balance and Mobility Scale (CB&M) is a measurement developed for individuals with traumatic brain injury, particularly individuals who have high level ambulatory skills but have problems with balance (Howe et al. 2006). A total of thirteen tasks, scores ranging from 0 to 96, included items that required complex motor skills such as walking and looking, descending stairs while carrying a basket, and lateral dodging. This test was included as these balance tasks may represent the activities that are encountered daily by older adults who live independently in the community. Before the clinical assessments were performed, each test was explained and demonstrated by the researcher. During the tests, a spotter as well as the researcher performing the assessment remained in close proximity to the subjects to ensure safety. No falls were reported during the functional balance tests.

2.2.3 Recording and Data Acquisition

Anticipatory postural adjustments were recorded while subjects were asked to perform two tasks: 1) self-paced unilateral arm raises (SP), for which the subjects determine when they raise their arm, and 2) unilateral arm raises in response to a visual signal (RT). For the SP task, subjects stood with their arms at their sides and were instructed to raise one arm to a horizontal position as fast as they could without bending the elbow. Subjects initiated the movement at their discretion. Ten trials were recorded. For the RT task, subjects were asked to raise either their left or right arm as quickly as possible in response to a visual cue. Two light emitting diodes were placed in front of the subject at eye level. Subjects were asked to raise their left arm when the left light was illuminated and their right arm when the right light was illuminated. A total of 20 trials was performed, 10 for each arm. The order of light presentation and the timing of the cues were randomized within an interval of 1-10 seconds and unpredictable to the subjects. The RT task was included to measure the central processing time taken between the cue (e.g. light signals) and activation of the focal muscle and to identify any differences in the timing and the patterning of anticipatory strategies with tasks that have time constraints. The order the subject performed the tasks was randomized between subjects.

During the APA testing subjects stood with one foot on each of two 6-channel force plates (Bertec, FP4060). Electromyographic (EMG) activity was recorded from the right soleus, tibialis anterior (TA), rectus femoris, biceps femoris (BF), erector spinae and anterior deltoid (AD) using Ag/AgCl surface electrodes placed over the bellies of each muscle. The EMG signals were amplified and bandpass filtered at 30 Hz–3 kHz using Grass Model P511 amplifiers (Grass Instruments, Astro Med Inc.) before being digitized along with the force plate and cue signals at 500 Hz (CED Power 1401). Post hoc, the EMG signals were full-wave rectified and low-pass filtered (50 Hz, dual-pass 4th order Butterworth digital filter) while the force plate signals were low-pass filtered (50Hz) using custom written analysis programs (LabView, National Instruments).

2.2.4 Data Analysis

In this study, we were interested in the organization and timing of APAs relative to arm elevation. Consequently, our analysis was performed relative to the onset of AD muscle activity, the prime mover for the focal task. For each arm elevation performed a 1500 ms sweep was extracted from the trial data file starting 800 ms prior to the onset of AD muscle activity of the elevated arm. Onset latencies for all muscles were calculated relative to the onset of AD. In the RT task, reaction time was calculated as the time from cue onset to the onset of AD muscle activity. A muscle was deemed to be activated or deactivated for the movement if the EMG trace escaped the 95% confidence band around the baseline activity during quiet standing.

The center of pressure (COP) was calculated using the forces and moments from both plates and calculating a weighted average based on the vertical reaction forces. The medial-lateral (ML) and antero-posterior (AP) positions of the COP were then plotted relative to time for each sweep. The maximum excursion of the COP in the AP and ML directions was calculated for the time a) prior to and b) following the onset of AD activity.

2.2.5 Statistical Analysis

The Berg Balance Scale and CB & M scores were compared between groups using a Kruskal-Wallis one-way analysis of variance by ranks. When the Kruskal-Wallis analysis identified significant differences existed a minimum significant difference test was used to characterize the specific differences between groups. The Functional Reach test was compared between groups using a one-way analysis of variance (ANOVA).

The EMG and COP data were analyzed for each task (SP and RT) separately. One-way ANOVAs were employed to determine between group differences in the temporal outcome variables as well as the COP displacement variables. Any differences detected by the ANOVAs were then delineated using Bonferroni adjusted *t*-tests. For all tests significance was defined as $p < 0.05$.

2.3 Results

2.3.1 Functional Measures

Table 1 summarizes the data from the clinical measures of balance control used in this study. Both the CB&M and Functional Reach tests were able to distinguish the young healthy adults from the three older adult groups. However, none of the clinical measures identified any differences between the three groups of older adults.

Table 1. Clinical measures of balance.

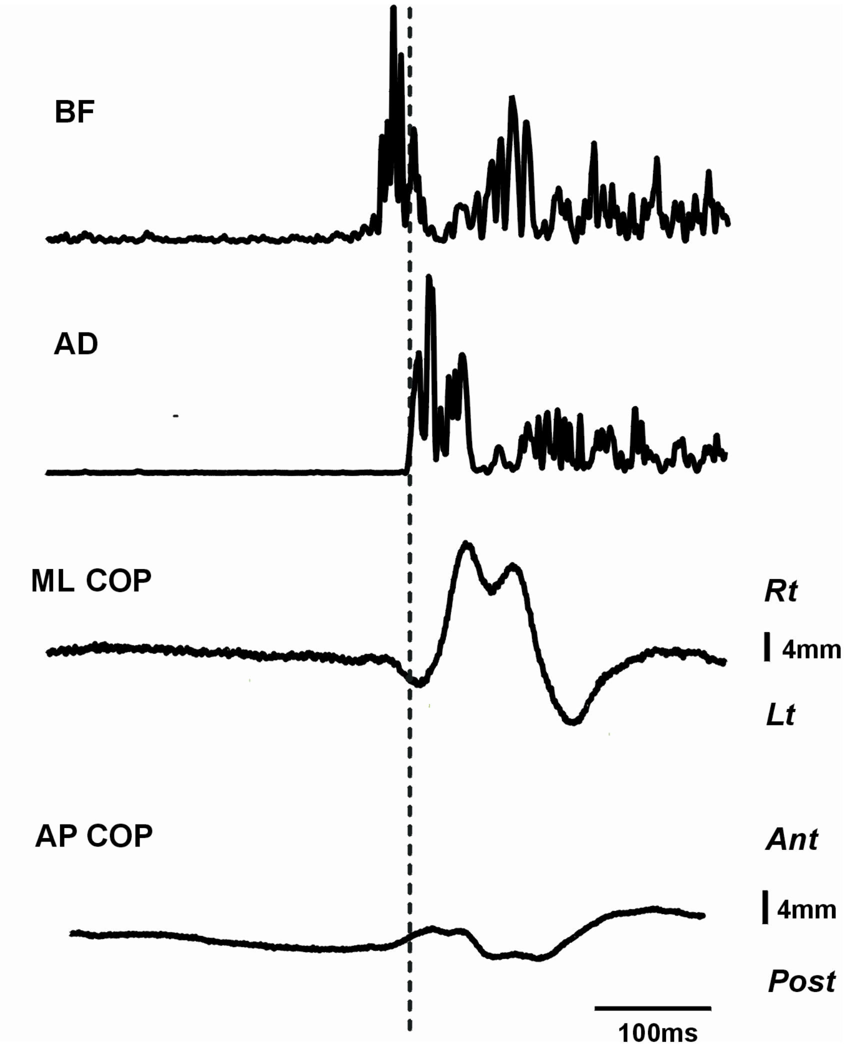
Group	CB&M Median (range)	Berg Median (range)	Functional Reach (cm) Mean (sd)
YA	92 (10)	56 (0)	36.9 (3.10)
OA	84 (34)	56 (1)	31.5 (4.85)
STC	76 (35)	56 (3)	31.2 (4.81)
LTC	85 (32)	56 (6)	31.6 (6.31)

2.3.2 Anticipatory Postural Adjustments

Figure 2.1 shows representative EMG and COP data from one LTC subject during a SP arm raise. These traces illustrate the general features of the behavior that were common to all subjects, regardless of group, and for both tasks. In this study we used the onset of activity in the prime mover AD as the time reference point, indicated by the vertical dashed line. The APA onset was indicated by earliest onset of EMG prior to AD onset. For this subject BF showed the earliest onset of activity. Of the muscles recorded BF or TA were the muscles activated earliest in all subjects, with BF being first to be activated in about 75% of cases. Furthermore, the earliest muscle activated was consistent between tasks within a subject. There was no difference between groups as to whether BF or TA was the earliest muscle to be activated.

We also characterized the motion of the COP in the ML and AP directions during two epochs. The first epoch was during the 800 ms prior to AD onset and the second was the 700 ms following. The pattern of motion of the COP was generally the same between subjects and tasks, but the specific details varied. For example, all subjects, regardless of grouping, demonstrated a backward and leftward shift of the COP prior to AD activation of the right arm. For the subject shown in Fig. 2.1 during the SP task the backward shift was a relatively slow drift and the leftward shift was more sudden immediately before AD onset. In some subjects the backward shift was more sudden and temporally similar to the ML shift. All subjects showed these types of motions prior to AD onset during the SP task. During the RT task subjects typically demonstrated a backward-leftward shift of the COP as well, however, in all cases these shifts occurred immediately prior to AD onset. At the time of, or shortly after, the AD burst onset the COP shifted forward and to the right, followed by a subsequent backward and leftward motion, before stabilizing at a final position prior to lowering of the arm. As no specific instructions were delivered as to how long to hold the arm in the raised position we did not characterize differences in the final position of the COP between tasks or groups. The general description of the COP motion given here for the SP task also applies for the RT task. The specific details of the waveform inflections varied between subjects and between tasks. For the purposes of this study we were interested in the maximal excursion of the COP during the task itself. Therefore, we measured the peak-to-peak displacement within the 700 ms window following the AD onset.

Figure 2.1: Example data from one older adult long-term Tai Chi practitioner (LTC) subject during a self-paced right arm raise.
The top two traces show the full-wave rectified and filtered EMG data from biceps femoris (BF) and anterior deltoid (AD). The bottom two traces depict the location of the centre of pressure (COP) in the medial-lateral (ML) and anterior-posterior (AP) directions.
The vertical dashed line is aligned to the onset of the AD burst associated with the primary arm movement.



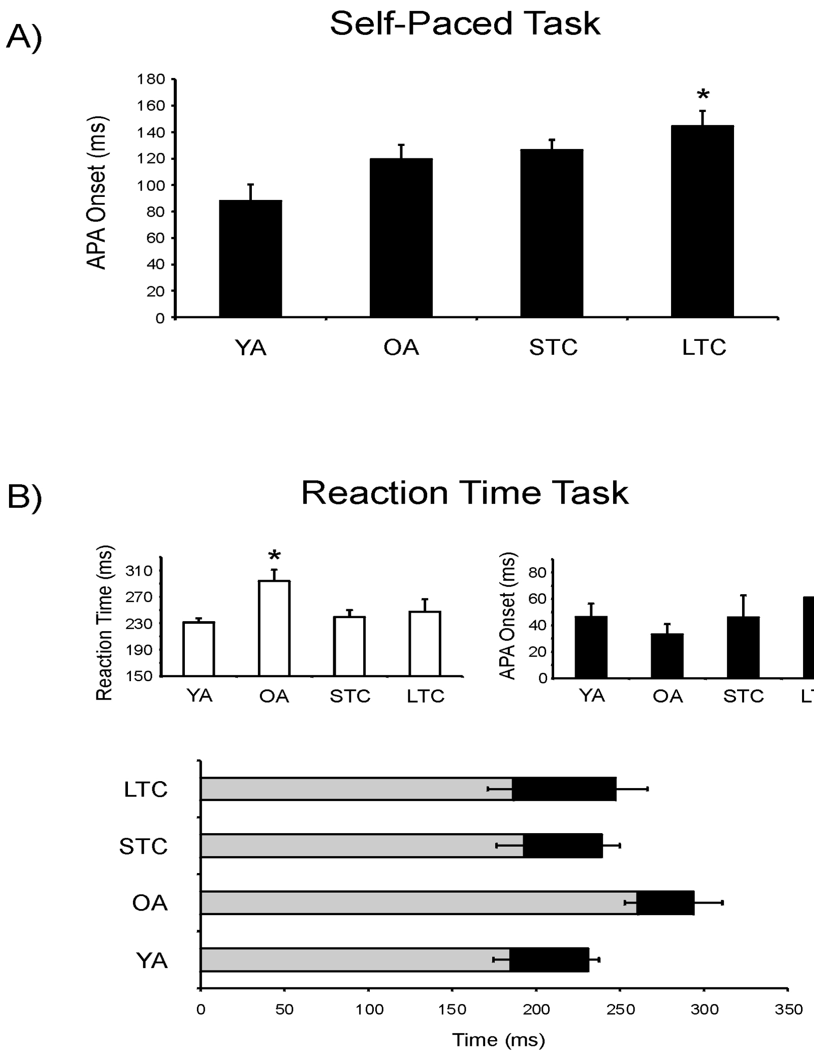
2.3.3 Temporal Features of the APA

Figure 2.2a depicts the timing of the APA onset relative to the onset of the AD burst during the SP task. Young adults typically activated their BF or TA muscles in closer temporal relation to AD onset than any of the other groups. The LTC group consistently engaged an APA at a greater time interval prior to AD burst onset than any other group. This was significantly greater than the YA group. The OA and STC groups also engaged their APA sooner than the YA adult group, but this difference did not reach significance.

Figure 2.2b displays the temporal characteristics measured during the RT task. The top left panel depicts the reaction times for each group. There was no significant difference in reaction time between the YA, STC or LTC groups. However, the OA group was significantly slower to raise their arm in response to the visual cue than all three other groups. The top right panel of Fig. 2b displays the time of APA onset relative to AD burst onset during the RT task. The OA group tended to engage the APA nearest in time to the onset of the AD burst, while the LTC group tended to engage the APA earliest of all groups. These differences were not significant, but were similar to the pattern observed in the older adult groups for the SP task. The lower panel of Fig. 2.2b redisplays the reaction time and APA onset data in the upper panels, but relative to the time of the visual cue. From this histogram it can be seen that the temporal events related to the RT task are not much different between the

Tai Chi groups and the young adults. However, the significantly slower reaction time of the OA group is accompanied by an APA onset that is also delayed and in closer temporal proximity to the activation of AD.

Figure 2.2: Group average data for the temporal data associated with the anticipatory postural adjustments (APA). A) Group average onset of the APA relative to the onset of the AD muscle activity for the self-paced task. The asterisk indicates that the LTC group had a significantly longer APA onset time than the YA group ($p<0.05$). B) The upper left histograms depict the average reaction times for each group for the reaction time task. The asterisk indicates that the OA group had a significantly slower reaction time than all other groups ($p<0.05$). The upper right histograms display the average APA onset times, relative the onset of AD activity. The lower panel shows the group average temporal features of the reaction time task relative to the onset of the visual cue. The black portion of the histograms indicates the period between the APA onset and the activation of AD. The rightward error bars represent the variation related to the reaction time, while the leftward error bars represent the variation related to the onset of the APA relative to the onset of AD activity. Error bars represent one standard error.

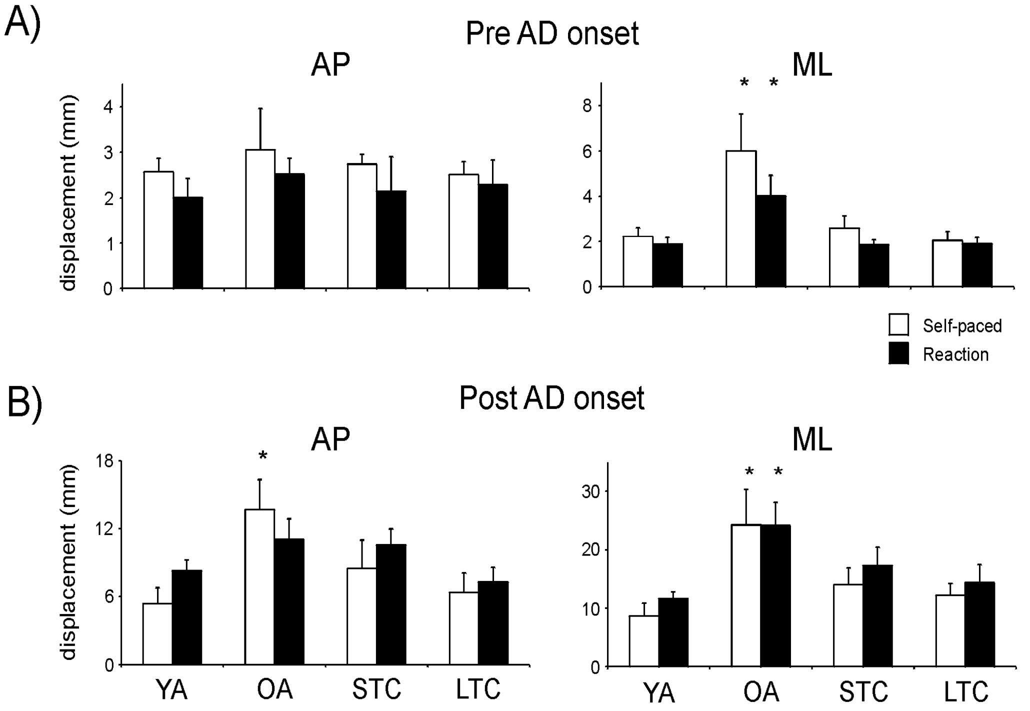


2.3.4 Motion of the COP

During both tasks (SP and RT) displacement of the COP was greatest in the ML direction. Moreover, substantially greater displacement occurred following the onset of the AD burst as the arm was raised and then held in position. Figure 2.3 depicts the peak-to-peak displacement of the COP prior to (Fig. 2.3a) and following (Fig. 2.3b) the onset of the AD burst. The data for the SP and RT tasks are displayed together for comparison, but this difference was not of interest for this study. Our focus is the comparison between groups within task. Prior to AD onset there were no differences between groups in the amount of fore-aft sway for either task (Fig. 2.3a). In contrast, the OA group had significantly greater ML motion of the COP prior to AD onset than all other groups during both tasks.

During the SP task, the OA group had significantly greater motion of the COP in both axes following the onset of AD activity than both the YA and LTC groups. The STC group tended to have greater motion of the COP than the YA and LTC groups, but less motion than the OA group. Neither of these differences was significant. During the RT task the motion of the COP in the AP direction was not significantly different between any of the groups, however, the OA and the STC groups tended to have greater displacement. The ML motion of the COP during the RT task resembled the data of the SP task, with OA showing significantly greater motion in this axis than both the YA and LTC groups and the STC group yielding an intermediate outcome, not significantly different from any of the other groups.

Figure 2.3: Group average data representing the maximum excursion of the center of pressure (COP) prior to (A) and following (B) the onset of AD activity for both tasks. The left panels in each pair display the displacement in the anterior-posterior (AP) direction, while the right panels display the displacement in the medial-lateral (ML) direction. The data from the self-paced task are displayed as the open histograms with the reaction task data represented by the closed histograms. The asterisks indicate significantly greater excursion of the COP in the OA group compared with the YA group for the same task ($p<0.05$). Error bars represent one standard error.



2.4 Discussion

In recent years there have been a number of studies investigating the benefits of Tai Chi as an exercise program, specifically related to falls prevention in older adults and other populations at risk of falling (Gillespie et al. 2003; Wolfson et al. 1996). In an attempt to understand the neural basis of the improvements gained through Tai Chi' studies have reported differences in the organization and latency of corrective reactions to perturbations during standing (Tsang and Hui-Chan, 2005) or walking (Gatts and Woollacott, 2006; 2007) or improvements in static balance as reported through various forms of posturography (Tsang and Hui-Chan, 2004; Tsang et al. 2004). The tacit assumption in these studies has been that the documented decreased risk of falling associated with Tai Chi exercise is related to improvements in reactive balance control. However, Tai Chi involves the voluntary adoption of a variety of postures and movements from one posture to the next. Consequently, it is probable that a substantial benefit from Tai Chi in the decreased risk of falling is gained through training and adaptation of anticipatory postural control that occurs prior to voluntary movement. For example, Tai Chi training has also been shown to influence the trajectory of the centre of pressure prior to gait initiation (Hass et al. 2004; Tsang and Hui-Chan, 2004; Tsang et al. 2004). This study is the first to investigate the difference in anticipatory postural control strategies between Tai Chi practitioners and non-practitioners to better understand the anticipatory control by which this form of exercise might improve functional balance control.

2.4.1 Temporal Adaptation of the APA

In this study rapid unilateral arm lifts were employed under two conditions, either a) at the subject's discretion (self-paced) or b) in response to a visual cue (reaction). The task itself, raising the arm from the vertical to the horizontal position, was the same in each case. Rather, it was the behavior prior to initiation of the movement that was under study. For both tasks subjects that practiced Tai Chi for greater than a year initiated postural motor activity in preparation of the focal movement earlier than young adults, relative to focal movement onset. The longer duration of the anticipatory adjustment in this group is not simply an effect of age as the long-term Tai Chi practitioners also initiated the preparatory motor activity earlier than the older adult non-practitioners for both tasks. The implication is that this group has adapted the timing of the preparatory balance adjustment through training.

Moreover, this longer period of anticipatory adjustment of the long-term Tai Chi group cannot be the result of a generalized prolongation or slowing of movement initiation. The long-term Tai Chi group initiated the focal movement at a comparable time to the young adult group, relative to the visual cue during the reaction task. In contrast, older adults that did not practice Tai Chi possessed a significantly slower reaction time and delayed onset of anticipatory adjustment during this task, comparable to previous findings (Inglin and Woollacott, 1988; Rogers et al. 1992). Indeed, the older adult non-practitioners initiated their anticipatory adjustments closer to the focal movement than even the young adults. Taken together these results suggest that long-term Tai Chi practitioners utilize a modified anticipatory postural strategy whereby the preparatory adjustment is initiated earlier relative to the focal movement, but without significantly impacting the timing of the focal movement itself. That is, the APA appears to be activated sooner during the preparatory phase (Haridas et al. 2005).

2.4.2 Limitations

As this study was a cross-sectional study, associations between Tai Chi and the outcomes of interests were limited by the fact that this study was measured at one time point. Therefore the results of the study were not indicative of the causality. However, the results of the study provide as evidence that the capacity of modifying anticipatory control exists in Tai Chi older adults and therefore helpful in generating hypotheses for future research. Another limitation of this study was that we only monitored a few muscles that might be involved in anticipatory postural control. Consequently, it is possible that the subjects activated other postural muscles earlier than those recorded. Regardless, that the postural muscles recorded here were activated with a different temporal relation between groups indicates that different strategies were employed.

2.4.3 Functional and Clinical Relevance

The functional consequence of the modified anticipatory strategy utilized by the Tai Chi practitioners appears to be reduced motion of the centre of pressure prior to and following the onset of the focal movement, compared to older adult non-practitioners. Indeed, Tai Chi practitioners, and particularly long-term practitioners, did not sway any more than young adults performing the same tasks. In contrast, older adults that did not practice Tai Chi swayed substantially more, as much as three times more, than young adults. This suggests that Tai Chi practitioners learn to minimize sway induced by voluntary arm elevation and that this is achieved in part by incorporating an earlier onset of the balance adjustment.

It is generally well accepted that with normal aging comes decreases in strength and central processing that might impact the efficacy of motor control tasks, including anticipatory postural adjustments. Consequently, one would expect that if the onset of anticipatory postural activity remains an unmalleable strategy acquired during our youth then this strategy would become less effective with age (Woollacott and Manchester, 1993; Rogers et al. 1992; Bleuse et al. 2006). Tai Chi practitioners exhibit a temporal adaptation to the onset of the anticipatory postural adjustments that appears to overcome this limitation. As Tai Chi challenges postural stability through repeated exposure to a variety of voluntary movements it appears that Tai Chi practitioners learn the limitations of existing strategies and adapt to overcome these limitations. Older adults that do not expose themselves to such challenges might continue to rely on the strategies of their youth. However, as muscles weaken and conduction times slow the strategies become less effective, leading to an increased sway induced by the arm elevation tasks and presumably increased risk of becoming unstable or even falling. The non-practicing older adults in this study were active, participating in many other activities including dancing, skating, walking and skiing. Despite this these older adults tended to sway considerably more during the arm elevation tasks than the young adults and the Tai Chi practitioners. The implication is that exercise and being active alone cannot account for the adaptations seen in the Tai Chi group. Rather, this suggests that specifically challenging balance control is required to effect the adaptations in the anticipatory balance system.

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Chapter 3: Context-Dependent Modulation of Balance Corrective Mechanisms During Walking in Young and Older Adults

3.1 Introduction

Regaining balance following unpredictable postural disturbances requires activation of the muscles from the whole body, including the arms and legs (Berger et al. 1984; Dietz et al. 2001; Marigold & Patla, 2002; Misiaszek, 2003; Misiaszek & Krauss, 2005; Tang & Woollacott, 1998). Recent studies showed responses elicited in the muscles of the arms served to correct balance during standing and walking. For example, early activation in the arm muscles was observed to stabilize the body following platform translation while standing (McIlroy & Maki, 1995). Misiaszek (2003) reported corrective reaction of the arms was observed in all subjects tested with similar onset latencies that occurred in the leg muscles following perturbations applied to the waist during walking. Other studies showed the functional role of the arms such as grasping handrails, outstretching the arms against falls on the ground, and elevating the arms to recapture backward falling of the center of mass (Marigold & Patla, 2002; McIlroy & Maki, 1995; Maki & McIlroy, 1997; Misiaszek, 2003; Tang & Woollacott, 1998).

As the tasks of the arms changed during walking, the corrective responses evoked in the leg muscles were also adapted. For instance, restricting the use of the arms resulted in an increase of the response amplitudes in the leg muscles (Misiaszek & Krauss, 2005). This study concluded that the general feature of the corrective responses, for example, the timing and patterning of the activations in the leg muscles, did not change. However, response amplitudes of the leg muscles were increased to cope with the constrained arms. In contrast, providing stable handles as an external support led to diminished reactions in the leg muscles following perturbations during walking (Misiaszek et al. 2000). Results from these studies demonstrated that the magnitude of the corrective responses elicited in the leg muscles was scaled to the tasks, showing well coordinated corrective strategies between the arms and legs in recovering balance in a context-dependent manner during walking.

To date, several studies demonstrated corrective strategies employed in older adults. Schillings et al. (2005) reported decreased response amplitudes in the perturbed leg muscles when unexpected trips were induced at early swing in older adults, compared to young adults. Tang and Woollacott (1998) showed corrective reactions elicited in older adults were less effective, such as with delayed onsets and attenuated amplitudes to slip-like perturbations during walking. In addition, older adults were 4 times more likely to elevate the arms to stabilize the body than young adults. Similar results were reported in the study by Maki et al. (2000). Frequent use of the arms was consistently observed in older adults when repetitive perturbations were applied during both standing and walking-in-place. An observational study using a video surveillance system also reported that approximately 70% of seniors used their arms during falling (Holiday et al. 1990). Taken together, these findings indicate that older adults tend to use multi-limb strategies, including the arms when encountering unexpected destabilization. However, whether similar adaptation in corrective strategies would occur between the arms and legs as shown in young adults is unclear. The purpose of this study was to investigate whether the regulation of balance reactions are preserved in a context-dependent manner in older adults. We specifically hypothesized that corrective reactions following perturbations during walking in older adults would modulate according to the imposed tasks, similar to young adults.

3.2 Materials and Methods

3.2.1 Subjects

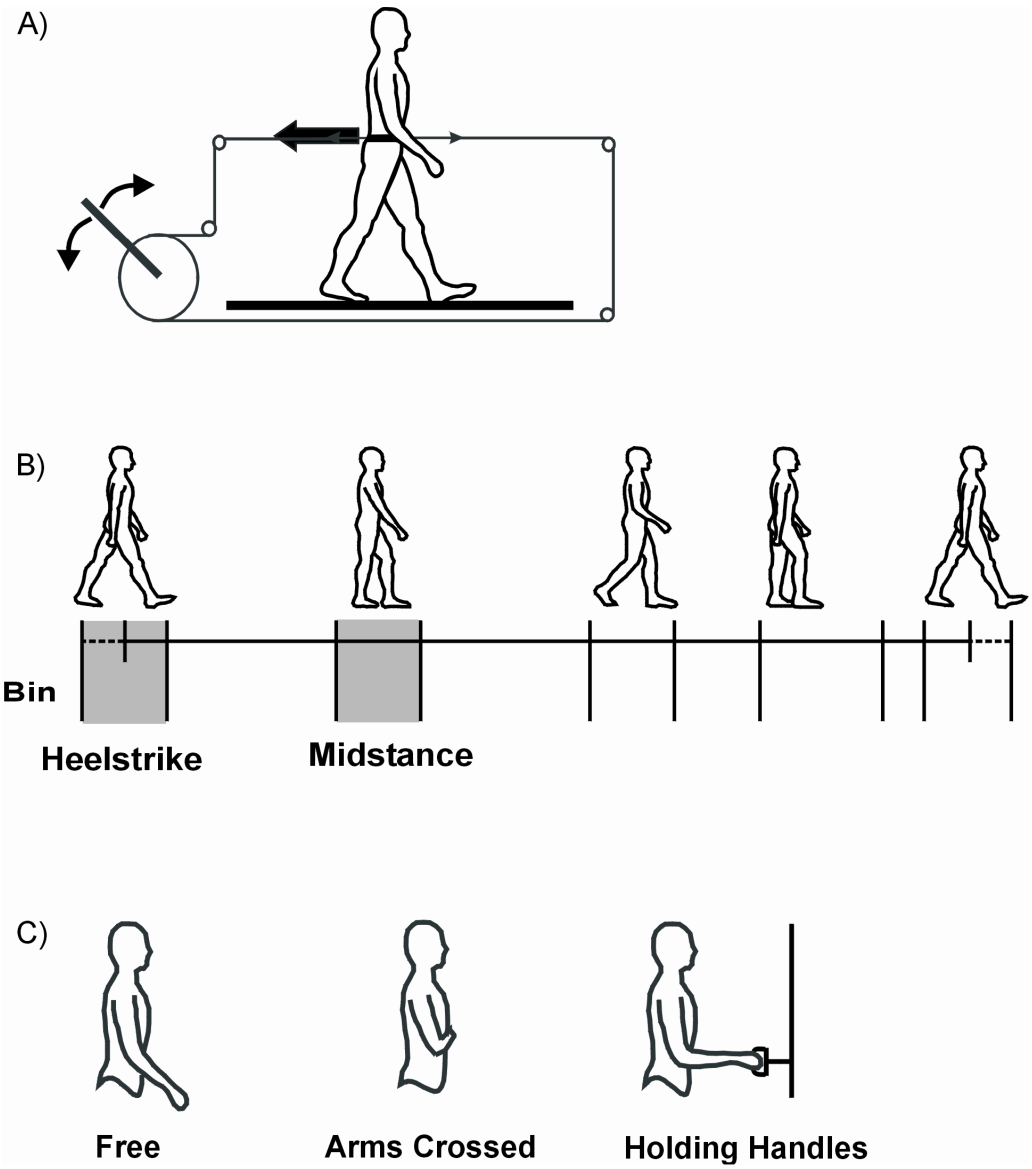
Twenty subjects (10 young and 10 older adults) participated in the study. The average age of the young adult group (YA) was 27.36±5.48 yrs and 68.40±5.36 yrs for the older adult group (OA). Subjects were excluded if they had any of the following conditions: cardiovascular (e.g. heart failure, chronic obstructive pulmonary disease), musculoskeletal, neurological or metabolic conditions (e.g. diabetes), or if they are taking medications known to affect balance (e.g. antidepressant, benzodiazepines, and neuroleptics). One older female subject who had a right shoulder rotator cuff injury that occurred 7 years ago was included after the assessment of a physical therapist; the range of motion and the manual muscle testing of the shoulder were assessed as normal. All subjects were asked to report a history of falls within the previous 1 year. None of the young subjects reported a history of falls. Three older adults reported one fall during the previous year. Each subject provided written consent and the procedures were approved by the University of Alberta Health Research Ethics Board.

Subjects walked on a treadmill at their comfortable speed (ranging 0.8-1.2 m/s for YA and 1.0-1.2 m/s for OA). Perturbations were applied during three different arm tasks: 1) arms free and swinging naturally, 2) arms folded across the chest, and 3) holding stable handles in front of the subject. The purpose of the crossing the arm task was to investigate corrective responses when the arms were constrained in assisting balance. A previous study in our laboratory demonstrated that the arms crossed task increased the level of postural instability, compared with the arms free condition (Misiaszek & Krauss, 2005). Subjects were permitted to release their arms or grasp handrails to ensure safety if necessary. Safety rails were mounted within reaching distance, approximately 75 cm in height above the treadmill belt and within 45 cm of the subjects. In addition, a spotter was ready to steady subjects to deal with any risk of falling. During the holding handles condition, subjects were asked to hold supportive handles that were securely attached to the treadmill. We hypothesized the level of postural instability would be decreased when the external supports were provided. Each task lasted approximately 15 minutes for a total duration of 45 minutes. Before data collection initiated, a training session of 5-10 minutes was provided so that subjects could become comfortable walking on the treadmill with the different arm tasks. The order of tasks was randomized across subjects and subjects were permitted to rest between tasks.

Perturbations were applied directly to the cables that were attached to the front and back of the subject's waist belt. The padded waist belt worn by the subject was connected to a drum where a handle is attached. Using this handle, the experimenter manually controlled the timing of perturbations as well as the directions. Fig. 3.1 depicts a schematic diagram of the device used for the experiments. Perturbations of 20% of body weight (BW) for YA and 10% of BW for OA groups were applied. Reduced perturbation forces were applied to ensure the safety of the older adults. Forces of this magnitude were sufficient to provide a destabilizing environment, but did not cause any older adult subjects to fall.

For each subject, the direction and timing of perturbations was randomized across the step cycle and across the tasks. Either forward or backward perturbations were delivered at four points of the step cycle (heel-strike, mid-stance, toe-off, and mid-swing). However, only backward perturbations were analyzed post-hoc, as our previous study demonstrated that the corrective responses were more pronounced, compared to forward perturbations (Misiaszek & Krauss, 2005). In addition, perturbed trials that occurred only at heel-strike and mid-stance were included in subsequent analysis, as previous studies observed the pattern of phase-dependent modulation at these specific points in the step cycle (Misiaszek, 2003; Misiaszek and Krauss, 2005). The perturbation forces were monitored using an oscilloscope so that the applied forces, as well as the timing of the force, were delivered consistently throughout the experiments. Subjects were informed that perturbations would be presented to destabilize their balance, but were not aware of either the direction or the timing of the perturbations. The perturbed trials within the range of 15-25% of the peak force for YA and 5-15% of the peak force for OA with the duration of the force pulse between 200-500 ms were screened off line for later analysis. None of the subjects fell during the experiments.

Figure 3.1: Schematic of the experimental set up. A) Subjects walked on a treadmill. B) Either backward or forward perturbations were applied to the torso during the points in the step cycle. Perturbations were delivered either forward or backward by rotating the drum controlling the cable system forward or backward. C) Subjects were asked to walk with arms swinging naturally, 2) their arms folded across the chest, and 3) holding stable handles. The handles were mounted to the front of the treadmill frame, adjusted to a height forming a 90 degree angle at the subject's elbow.



3.2.2 Recording and Data Acquisition

Electromyography (EMG) was recorded from the tibialis anterior (TA), soleus, (SOL), vastus lateralis (VL), biceps femoris (BF), anterior deltoid (AD), and posterior deltoid (PD) muscles of the right leg and arm. A pair of disposable self-adhesive electrodes was placed over the selected muscles after the skin was cleaned and shaved. EMG signals were pre-amplified and bandpass filtered at 30 Hz – 3 kHz using P511 amplifiers (Grass Instruments). Electrogoniometers (Biometrics) were placed to measure the angles of the ankle and knee joints of the right leg. Two force-sensitive sensors were placed in the sole of the subject's right shoe to determine the points of the heel-strike and toe-off within the step cycle. All signals were then digitized at 1000 Hz using a 12 bit analog-digital converter (National Instruments) and saved to a computer using custom-written software (LabView 5.1, National Instruments) for later analysis.

3.2.3 Data Analysis

For each task, approximately 70 forward and backward perturbations were applied. The backward perturbed trials were sorted offline according to the onset of perturbations within the step cycle and then divided into two bins (heel-strike and mid-stance). The timing of perturbations was determined as the time of the first visible deflection of the force trace following right heel-strike. Each bin was determined as a time window of 10% of the average control step cycle duration. Trials that did not fit within these bins were excluded from further analysis. For each selected perturbation trial, a 2s data trace starting at the right heel-strike preceding the perturbation was captured using a custom-written software program (Labview v.5). In addition, 40 unperturbed steps were captured and averaged as control trials. To avoid any influence of the perturbations, only unperturbed steps that occurred at least 2 steps following perturbations were captured. Subtracted traces were produced by subtracting the average unperturbed EMG trace from the perturbed traces. Each subtracted trace was then aligned to the onset of the perturbation and averaged. A response to the perturbation was determined for a particular muscle in a particular bin if the average trace exceeded the 95% confidence band around the unperturbed average for more than 25 continuous ms. The onset latency of the response was determined as the time that the subtracted trace began to deviate from the zero level following the onset of the perturbation. The amplitude of the response was calculated from the average amplitude of the subtracted trace within a time window of 100 ms following the onset of the response, and then normalized to the maximum EMG produced for that muscle from unperturbed arms free walking trials. The number of perturbed trials accepted for analysis ranged from 5 to 11 per bin, for each subject.

3.2.4 Statistical Analysis

Statistical analysis was performed for each muscle in each age-group separately. To determine whether the amplitude of the responses was modulated according to the tasks or phases of the step cycle, a two factor repeated measures analysis of variance (ANOVA) was used. Post hoc, the Least Significant Difference test was used to evaluate the differences found. Repeated measures ANOVAs were also performed on the onset latency of the responses for each muscle. Statistical significance was determined at $p < 0.05$.

3.3 ***Results***

In this study, walking with different arm tasks following backward perturbations resulted in changes in response amplitudes of the leg muscles. In addition, early onset responses in the leg muscles, as well as arms, occurred consistently despite the various tasks being performed. These findings were comparable with previous studies with compensatory reactions in young adults (Misiaszek et al., 2000; Misiaszek, 2003; Misiaszek and Krauss, 2005). The pattern of corrective responses used in the OA group was similar to that observed in the YA group. Two pronounced findings were noted in the OA group. First, delayed onset latencies were observed in most of the leg muscles. Second, inhibition of

SOL was observed at heel strike and mid-stance rather than a co-contraction with TA.

3.3.1 Context-Dependent Modulation of Corrective Responses in Young Adults

In the YA group, the corrective responses elicited in the leg muscles were adapted to the tasks being performed. Fig. 3.2 displays the averaged, rectified, and filtered EMG and kinematic traces for one subject for the three different arm tasks obtained at heel strike; 1) arms swinging freely (left-most column), 2) arms crossed (center column), and 3) holding stable handles (right-most column). As can be seen, early onset (< 200 ms) excitatory responses in the arm and leg muscles consistently occurred regardless of the task performed. It is also apparent that the change in arm task affected the amplitude of the evoked responses. The preservation of the latencies, but the change in amplitudes can be observed more clearly from the subtracted traces depicted in Fig. 3.3. In this subject, responses elicited in all leg muscles were substantially smaller in amplitude during the holding handles condition than the other two conditions (i.e. when the arms were swinging freely and crossed).

The group averaged response amplitudes during the step cycle for three different arm tasks are depicted in Fig. 3.4. As can be seen, phase-dependent modulation was observed in TA, generating more pronounced excitatory response to perturbations applied at heel strike than the responses elicited at mid stance across conditions. This result is consistent with previous studies (Misiaszek 2003; Misiaszek & Krauss, 2005).

The response amplitudes in TA and VL evoked at heel strike (black bars) remained similar during the arms free and arms crossed conditions. In contrast, during the holding stable handles condition, significant decreases in response amplitudes of TA and VL were observed ($p < 0.05$). The response amplitude of SOL elicited at heel strike was slightly decreased when subjects crossed their arms and further decreased during the holding handles condition, compared to walking with arms free condition. The response elicited in BF at heel strike was comparable in amplitude across the arm conditions. Similar results were observed for perturbations applied at mid stance (white bars). For example, when subjects walked with their arms crossed, the amplitude of responses in TA and VL was similar to what was observed during the arms free condition. In contrast, during holding handles condition, the amplitude of the responses in TA and VL was significantly decreased, compared to the other two conditions. The amplitude of the response in BF showed a decrease in response amplitude but this was not significant.

Figure 3.2: Averaged, rectified and filtered EMG and Kinematic traces occurred at heel strike for one young representative subject following perturbations at heel strike (thick trace) and undisturbed steps (thin trace). Three different arm tasks include 1) arms free (left-most column), 2) arms crossed (center column), and 3) holding stable handles (right-most column). The vertical dashed line in each column of data is aligned to the onset of the deflection in the force trace, indicating the initial application of force to the perturbation device. Upward deflections in the kinematic traces indicate dorsiflexion for the ankle and flexion for the knee.

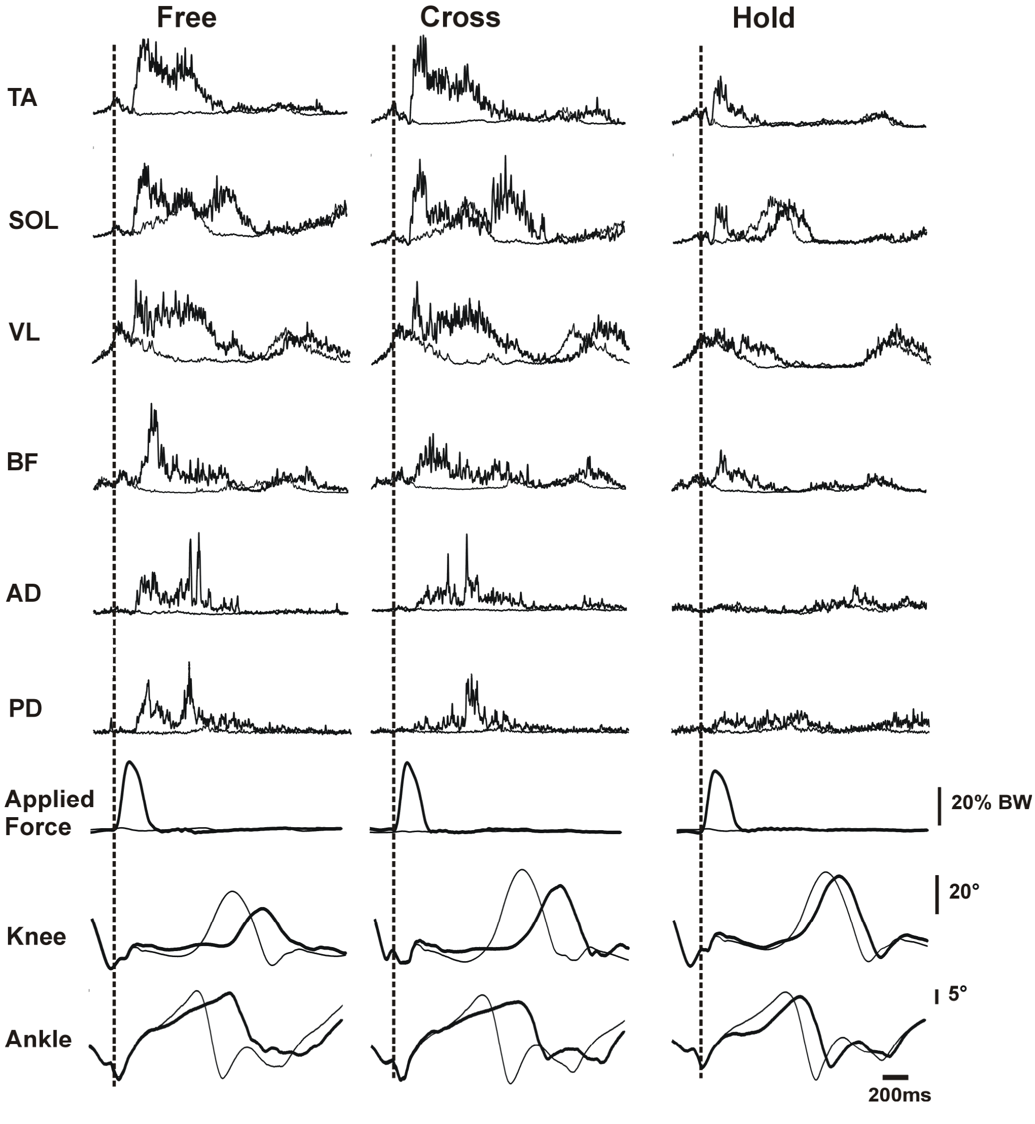


Figure 3.3: Averaged subtracted EMG and kinematic traces from one young subject following perturbations applied at heel strike. The black thick line represents the subtracted trace from the trials with arms swinging freely. The grey line presents the subtracted trace from the trials with arms crossed. The dotted line represents the subtracted trace from the trials with holding handles. The two thin lines of each set of traces represent the 95% confidence band around the average undisturbed trace. Each trace begins at the onset of the perturbing force. Scale bars for the EMG traces are expressed as percent of the maximum EMG amplitude of the undisturbed steps for each muscle (*TA* tibialis anterior, *SOL* soleus, *VL* vastus lateralis, *BF* biceps femoris, *AD* anterior deltoid, *PD* posterior deltoid)

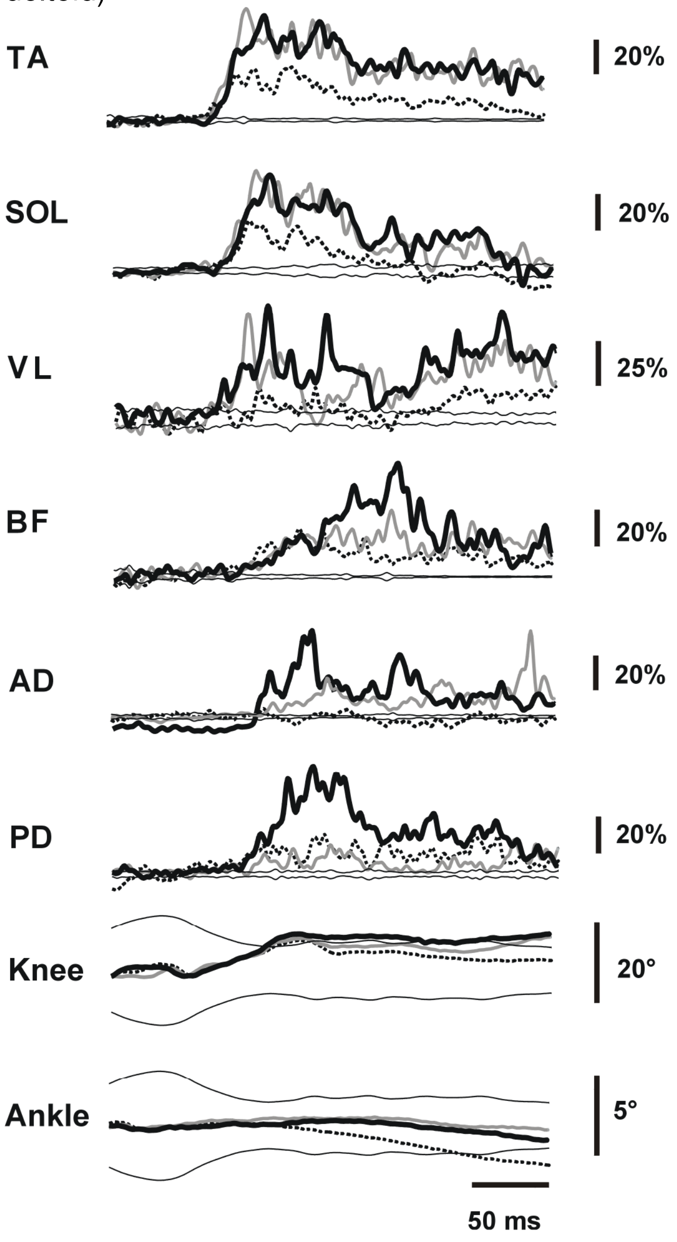
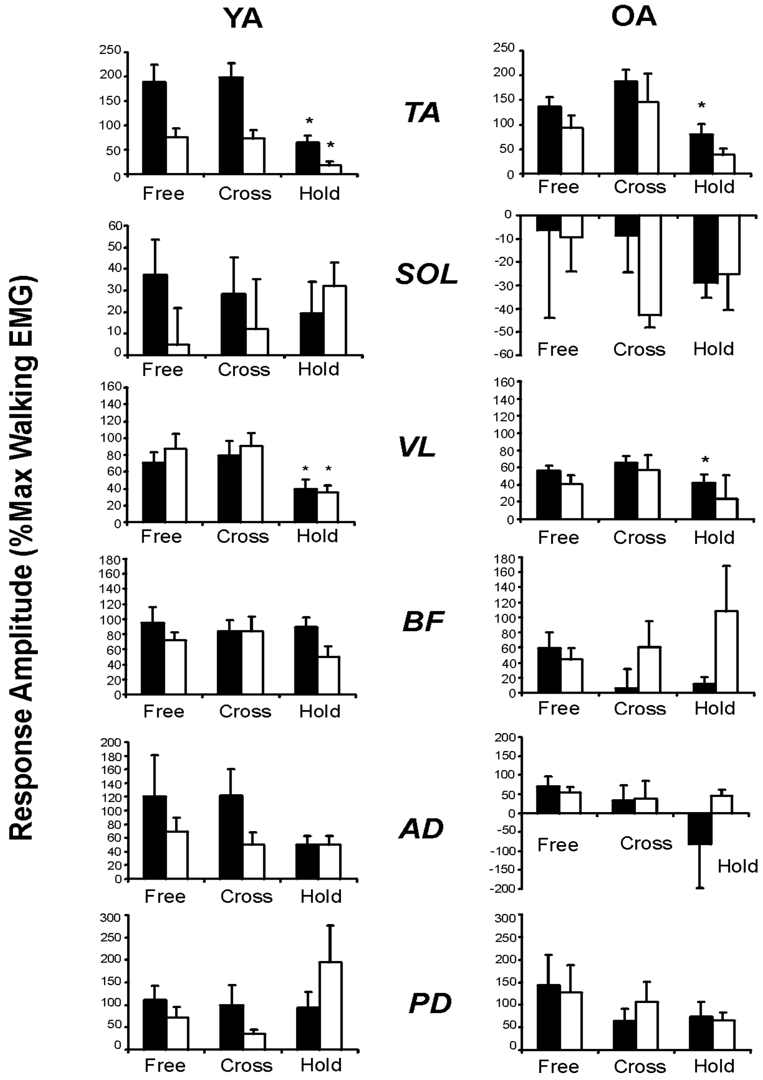


Figure 3.4: Means and standard errors of the response amplitudes for each of the recorded leg and arm muscles across the step cycle for three arm tasks. The data were standardized to the maximum EMG amplitude observed during normal undisturbed walking for that muscle, for each subject, prior to averaging. Solid histograms depict the data from the perturbed trials at heel strike. Empty histograms depict the data from the perturbed trials at mid-stance. The asterisks indicate average response amplitudes that are significantly different from the response amplitude for walking with the arms freely swinging for that point in the step cycle. (Free: arms swinging freely, Cross: arms crossed, Hold: holding handles)



Early corrective responses in the arm muscles were also observed, with comparable onset latencies elicited in the leg muscles. In particular, the response elicited in AD occurred simultaneously with the response evoked in TA in all conditions. For example, the average onset latencies elicited in AD at heel strike during the arms free, arms crossed, and holding handles conditions were 123.5±8.2 ms, 130.4±10.3 ms, and 119.6±11.1 ms, respectively while the onset latencies of the evoked response in TA were 124.9±6.4 ms, 131.1±4.8 ms, and 118.3±7.5 ms. During holding handle condition, the amplitude of the response in AD was decreased following perturbations applied at heel strike, compared to the other two conditions (i.e. arms free and arms crossed). However, this decrease did not reach significance (Fig 3.4). The amplitude of the response in PD at mid stance appeared to be more responsive, compared with the responses occurred at heel strike, but this was not significant.

Backward perturbations during walking resulted in increased deviations of the knee joint during the step cycle. The average deviations of the knee flexion were 5.76° and 5.87° for arms free and arms crossed conditions following perturbations applied at heel strike during the first 400 ms of the response (Fig 3.3). No noticeable change in knee trajectory was observed during holding handles condition. The average onset latencies of the knee flexion at heel strike were 115±14.49 ms, 95±17.02 ms, and 93±21.35 ms for arms free, crossed and holding handle conditions. Similar onsets of deviation of the knee joint at mid stance were observed but the amplitude of the knee flexion occurred with slightly larger deviations than those observed at heel strike. Averaged deviations of the knee joint were 9.33°, 7.80°, and 6.37° during arms free, crossed, and holding handle conditions, respectively. The average onset of ankle dorsiflexion was 31.75±2.65 ms with very small deviations of the ankle joint ranging between 1-2° following perturbations applied at heel strike during the first 400 ms of the response.

3.3.2 Context-Dependent Modulation of Corrective Responses in Older Adults

Averaged, rectified, and filtered EMG and kinematic traces and subtracted traces for one older subject are presented in Fig 3.5 and Fig 3.6, respectively. Compared to the YA group, the corrective reactions in older adults elicited following backward perturbations were delayed in most of the leg muscles. Particularly, the onset of the evoked response elicited in TA at heel strike was significantly delayed in older adults, with onset latencies of 124.9±6.41 ms and 156.5±9.06 ms in YA and OA groups, respectively.

Shown in Fig. 3.4 is the group averaged response amplitudes elicited in the leg and arm muscles during the step cycle in the OA group. The phase-dependent modulation in response amplitudes across the step cycle was observed in TA muscle only during holding handle conditions.

As we previously observed in young adults, walking with holding handles resulted in significant decreases in the response amplitudes in TA and VL at heel strike in all older subjects that responded ($p < 0.05$). The burst amplitude of TA appeared to increase when the arms were crossed to perturbations at heel strike but this did not reach significance. The burst amplitude in BF tended to be decreased during walking with arms crossed and holding handles conditions, compared to the burst generated when the arms were free. Following perturbations applied at mid-stance, the response in the TA muscle appeared to be decreased in amplitude during the holding handle condition, compared with the arms free and arms crossed conditions. However, this decrease was not statistically significant. The change in response amplitude for VL was comparable across conditions. A response in BF tended to be larger when subjects held handles, compared to the other two tasks. However, no significant difference was identified.

Figure 3.5: Averaged, rectified and filtered EMG and kinematic traces occurred at heel strike for one older representative subject following perturbations at heel strike (thick trace) and undisturbed steps (thin trace). Three different arm tasks include 1) arms free (left-most column), 2) arms crossed (center column), and 3) holding stable handles (right-most column). The vertical dashed line in each column of data is aligned to the onset of the deflection in the force trace, indicating the initial application of force to the perturbation device. Upward deflections in the kinematic traces indicate dorsiflexion for the ankle and flexion for the knee.

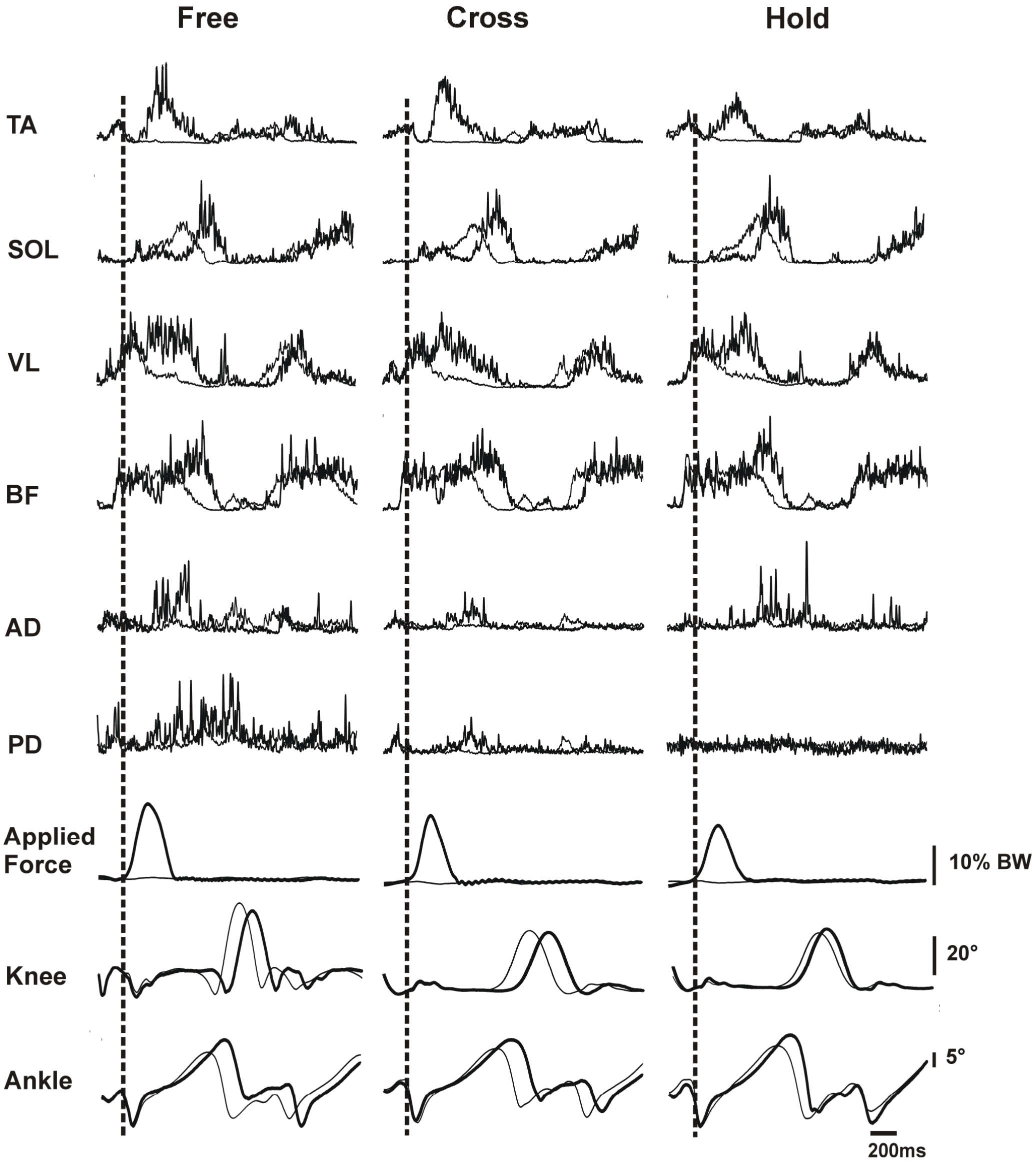
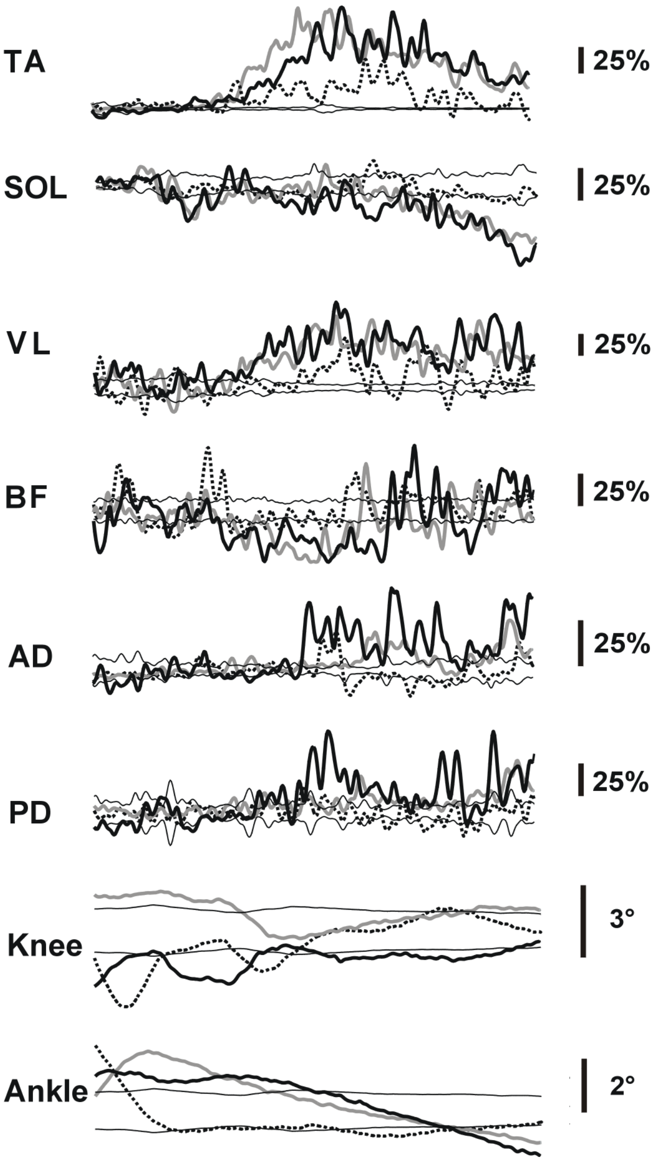


Figure 3.6: Averaged subtracted EMG and kinematic traces from one older subject following perturbations applied at heel strike. The black thick line represents the subtracted trace from the trials with arms swinging freely. The grey line presents the subtracted trace from the trials with arms crossed. The dotted line represents the subtracted trace from the trials with holding handles. The two lines of each set of traces represent the 95%confidence band around the average undisturbed trace. Each trace begins at the onset of the perturbing force. Scale bars for the EMG traces are expressed as percent of the maximum EMG amplitude of the undisturbed steps for each muscle (*TA* tibialis anterior, *SOL* soleus, *VL* vastus lateralis, *BF* biceps femoris, *AD* anterior deltoid, *PD* posterior deltoid)



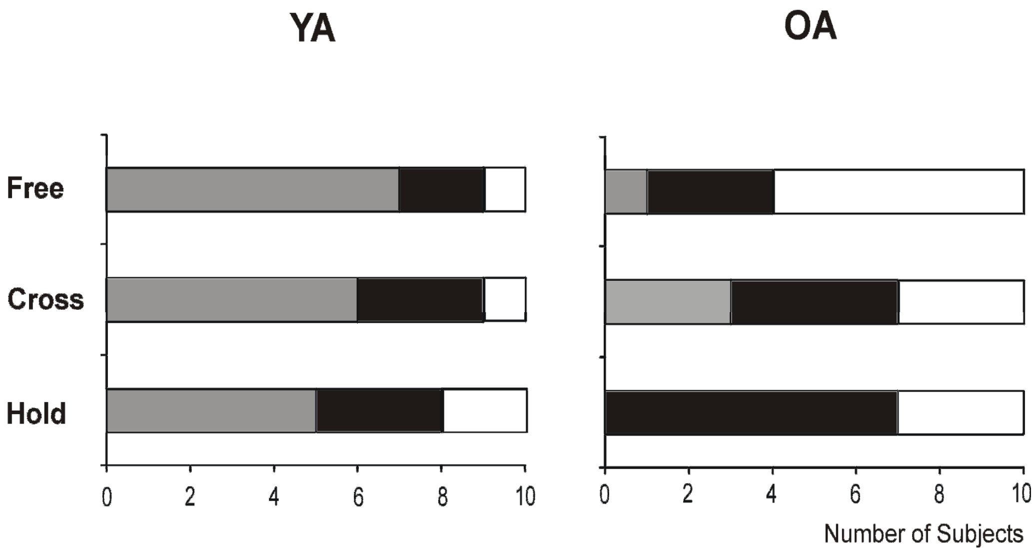
One of the distinctive responses observed in older adults was an inhibition of SOL following perturbations applied during the step cycle. Fig. 3.7 depicts the frequency of activation elicited in SOL. As seen in this figure, perturbations applied at heel strike typically resulted in co-contraction of SOL with TA in young adults. In contrast, inhibition of SOL was frequently observed in older adults following perturbations at heel strike and mid-stance rather than a co-contraction with TA. In particular, this inhibitory response was observed in all older subjects that displayed measurable responses during holding handles condition.

Early responses in the arm muscles were consistently observed across the conditions, with comparable onset latencies elicited in the leg muscles. The averaged onset latencies evoked in AD and PD were 135.5±11.04 ms and 148.57±5.63 ms. No significant difference was observed in response amplitudes elicited in muscles of the arm across the conditions in older adults.

The average onset for changes in knee flexion following perturbations at heel strike was very similar to that observed at mid stance (114.67±35.79 ms and 111.00±16.97 ms, respectively). The amplitudes of the deviations observed in knee joint were similar across the step cycle and conditions, ranging between 2.1°-3.7° for the first 400 ms of the response. Changes occurred in amplitudes of the ankle trajectory at heel strike were

2.26±2.41°, 3.46±3.57°, and 3.2±0.76° during arms free, crossed, and holding handle conditions with the average response latencies of 28.67±18.58 ms, 31.0±24.04 ms, and 28.5±17.68 ms, respectively during the first 400 ms of the response. No visible deviations of the ankle joint at mid-stance were observed in almost all of older subjects.

Figure 3.7: Frequency of occurrence of SOL responses in three different arm tasks following perturbations at heel strike. The grey bar represents excitatory responses in SOL, the black bar represents inhibitory responses in SOL, and the white bar represents no measurable responses in SOL.



3.4 Discussion

The purpose of this study was to investigate balance strategies following unexpected postural disturbances during walking with different arm tasks in young and older adults. In particular, we were interested in whether corrective responses in older adults would modulate in a similar way to that observed in young adults. The main findings of the study were 1) there was regulation of corrective responses in a context dependent manner and 2) there was a similar pattern of modulation in response amplitudes to the tasks between age groups.

3.4.1 Context-dependent modulation in corrective responses in young and older adults

Perturbations applied to the waist while walking with different tasks resulted in compensatory reactions for both age groups. In this study, the level of postural threat was increased or decreased by asking subjects to cross their arms or hold external supports. Corrective responses in the leg muscles were adapted to the arm tasks. The pattern of modulation to the tasks we observed was comparable with previous findings (Misiaszek et al. 2000; Misiaszek and Krauss, 2005). In older adults, early compensatory reactions were well preserved regardless of the tasks being performed following perturbations during walking. In addition, older adults were capable of regulating corrective responses in a context dependent manner, similar to that observed in young adults. Increasing or decreasing response amplitudes in the leg muscles were observed according to the demands of the tasks.

3.4.2 Inhibitory Response in Soleus (SOL) in Older Adults

In this study, whereas co-contraction strategies between TA and SOL were normally used in young adults, an inhibitory SOL response was typically observed in older adults regardless of the tasks. Rather than stiffening the ankle joint, as observed in young adults, strong and robust activation of TA with inhibition of SOL (i.e. reciprocal inhibition) was used to compensate for postural disturbances in older adults. This inhibitory response of SOL was consistently observed during the step cycle in older adults (Fig 3.4). Thus, unexpected perturbations during walking resulted in the excitation of TA and associated reciprocal inhibition in older adults. This may also explain the augmented responses elicited in TA observed in older adults to ensure balance to perturbations. Similar results were reported following perturbations applied to the torso at the end of stance phase (Misiaszek et al. 2000) and the early and mid-portions of the stance phase (Misiaszek, 2003). When subjects were asked to walk on a treadmill with the arms swinging freely, excitation of TA with reciprocal inhibition of SOL was also observed to correct balance following perturbations.

3.4.3 Limitations

In this study, there was a delay in onset latencies of the corrective responses in the leg muscles among older adults. The differences in the response latencies we observed between groups can be attributed to changes with aging. Similar results were also found in studies of balance control between young and older adults. For example, age-related differences in onset latencies of postural responses were observed in response to forward slip-like perturbations at heel strike during walking (Tang and Woollacott, 1998; 1999) and platform translations during standing (McIlroy and Maki, 1996). However, we cannot rule out the small amount of force perturbation that was applied to older adults (i.e. 10% of body weight for OA and 20% of body weight for YA). It is probable that the corrective responses elicited in the leg muscles would be affected by the small amount of perturbation in older adults, such as delayed onset of muscle activities.

3.4.4 Functional relevance

In this study, we were interested in whether the older adults would be capable of generating appropriate corrective responses while walking with different arm tasks as that observed in young adults. In the OA group, the response amplitude of these responses was largely increased while walking with the arms crossed, as compared with walking with the arms swinging freely. These increased corrective reactions in the leg muscles would serve to meet the functional needs of walking balance when the use of the arms is restricted. For example, when the arms are engaged in tasks such as carrying groceries, the increase in response amplitudes evoked in the leg muscles would assist in coordinating corrective reactions when balance is challenged. This increase in response amplitudes evoked in the leg muscles was comparable to what we have observed in young adults. However, when the level of postural threat was decreased by holding stable handles, the response amplitudes evoked in the leg muscles were decreased in older adults, compared to walking with the arms free condition. This may suggest that balance reactions in older adults are affected by changes in the tasks. Overall, the modulation in response amplitudes according to the tasks observed in older adults was similar to that observed in young adults.

The implication is that the healthy older adults are capable of modifying corrective reactions according to the needs of the task. In the OA group, corrective reactions in the leg muscles were largely increased when postural threats were increased by crossing subjects' arms. However, the response in the legs was reduced when the postural threats were decreased by providing external supports. This would have important implications for balance-impaired older adults such as older adults who use walkers or canes as a balance aid. Holding onto handles during standing can limit the functional role of the arm reactions in correcting balance, as shown in previous studies (Bateni et al. 2004a; Bateni et al. 2004b). Whether using mobility aids during walking would result in adaptive balance reactions in this older population needs further investigation in the future.

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Chapter 4 – General Discussion

The purpose of the thesis was to investigate two main aspects of balance control when balance was destabilized during standing and walking among older adults. Firstly, anticipatory control was assessed to investigate whether responses elicited in the postural muscles prior to self-initiated perturbations during standing can be adapted as a result of training. Secondly, reactive control was investigated to identify context-dependent modulation of corrective responses to external perturbations during walking.

4.1 Balance strategies of older adults

Studies on APAs reported adaptability of postural strategies in gymnasts during backward upper trunk movements (Pedotti et al. 1989) and in dancers during head-trunk stabilization (Mouchnino et al. 1992). Those anticipatory adaptations occurred as a result of training to counterbalance destabilization of the body in an efficient manner. To investigate whether similar changes in APAs would occur after training in an older population, we chose Tai Chi as it has been shown to be effective in enhancing balance among older adults. Recently, several studies suggested positive effects of Tai Chi in controlling reactive balance to perturbations during standing (Fong and Ng, 2006; Tsang and Hui-Chan, 2005) and walking (Gatts and Woollacott, 2006; 2007). Results from these studies indicated enhanced corrective reactions when balance was disturbed in older adults who practiced Tai Chi, compared to non-Tai Chi practitioners. In Chapter 2, I investigated whether Tai Chi training would yield similar changes in the organization of APAs. The main findings of the study were 1) long-term Tai Chi practitioners utilized a modified anticipatory postural strategy by initiating the postural adjustments earlier than young adults, relative to the movements of the arms, and 2) older adults who practiced Tai Chi did not sway any more than young adults. In contrast, performing the same task, OA group swayed more than the other three groups for both self-paced and reaction time conditions. Taken together, longer preparatory adjustments observed in long-term Tai Chi practitioners likely lead to minimize displacement induced by voluntary arm elevation. Thus, Tai Chi presumably offers adaptive changes in the performance of anticipatory balance control.

In Chapter 3, corrective responses evoked in the leg muscles to adapt to the needs of different tasks during walking were investigated. The main result of the study was that older adults were capable of regulating corrective responses in a context-dependent manner, similar to that observed in young adults (Misiaszek & Krauss, 2005). Compared to walking with the arms swinging freely, the amplitude of evoked responses in the leg muscles were increased when subjects were pulled backward while walking with the arms crossed. In contrast, when holding handles, leg muscle activity was decreased. Taken together, the results of the present study suggested that the corrective reactions were retained in older adults, and that the amplitudes of corrective reactions were modulated to meet the demands of the tasks.

Another difference we observed in the study was inhibitory responses in SOL among older adults. Whereas the EMG responses observed in young adults consisted of increased EMG activity in both TA and SOL, inhibitory SOL response was typically observed in older adults regardless of the tasks being performed. In older adults, the contraction of TA appeared to be mainly responsible for ensuring stability to perturbations during walking.

4.2 Functional relevance of balance strategies

In this thesis, I investigated both anticipatory and reactive balance control of older adults when their balance was destabilized. In Chapter 2, the results of the study demonstrated the difference in anticipatory control between Tai Chi and non-Tai Chi older adults. That is, long-term Tai Chi practitioners performed voluntary movements through a modified anticipatory control, preparing postural adjustments earlier relative to the onsets of the arm movements. As a consequence, Tai Chi older adults did not sway any more than young adults, suggesting functional significance of modified anticipatory control.

The temporal adaptation of APAs in Tai Chi older adults was consistent with other studies that have suggested improved reactive balance control following Tai Chi training (Fong and Ng, 2006; Gatts and Woollacott 2006, 2007; Tsang and Hui-Chan, 2005). Observations from other Tai Chi studies showed that Tai Chi older adults were capable of regulating balance reactions effectively when perturbations were applied during standing (Fong and Ng, 2006; Tsang and Hui-Chan, 2005) and walking (Gatts and Woollacott 2006, 2007). Gatts and Woollacotts (2006) showed that corrective responses elicited in TA following slip-like perturbations among Tai Chi older adults were faster by 50.25 ms after training. Fong and Ng (2006) demonstrated earlier onsets of EMG activity in the leg muscles in response to perturbations of the torso in the long-term Tai Chi group (1-3 years) than the short-term and non-Tai Chi older adults. Similar to differences observed in our long-term Tai Chi older adults, favorable effects of practicing Tai Chi in long-term were also noted in previous studies. Compared to non-Tai Chi older adults, less sway was observed following anterior-posterior platform perturbations in older adults with average Tai Chi experience of 8.5± 7.6years (Tsang and Hui-Chan, 2005). A similar result was reported by Hong et al. (2000), who showed higher score in one leg standing with eyes closed in older adults with 13.2 years of Tai Chi experience, compared to non-Tai Chi older adults.

Benefits of practicing Tai Chi were also closely related to the reduced occurrence of falling as suggested elsewhere (Gatts and Woollacott, 2007; Wolf et al. 1996). Studies on Tai Chi reported that 3-15 weeks of Tai Chi training reduced the incidence of falling (Gatts and Woollacott, 2007; Wolf et al. 1996). A community-based group exercise program involved modified Tai Chi forms, functional activity exercises such as reaching or weight shifting, muscle strengthening, and fast walking reduced the incidence of falls by 40% (Barnett et al. 2003). Results from these Tai Chi studies may have implications for clinical intervention as it suggested that increased balance capacity is possible when older adults were trained.

As stated above, Tai Chi as a potential approach to enhance balance control was further supported by the observation that Tai Chi older adults were capable of modifying anticipatory control. Postural adjustments associated with voluntary movements through prior learning experience are thought to be an example of an internal model based on feedback for error correction in the CNS (Frank and Earl, 1990; Shamehr and Wise, 2005). This internal model, estimating forces and torques that are required to perform the desired limb displacement, addressed how CNS controls regulation of standing balance during voluntary movements. The benefit of this model is that previously learned skills are transferred to another similar task (i.e. generalization) (Schmidt and Wrisberg, 2004). In this study, repetition of Tai Chi forms likely lead modified anticipatory balance strategies whereby the movements occur in a way that is adapted in temporal organization of APAs. Thus, the timing of APAs was adapted when voluntary arm movements were executed by Tai Chi older adults. Taken together, the ability to control anticipatory adjustments were preserved for all older adults tested, but the components of APAs in Tai Chi practitioners were modified.

Based on observations from this study, I suggest that the differences observed in long-term Tai Chi practitioners would serve them better during daily tasks that require counterbalancing of forthcoming perturbations. Without these postural adjustments, functional daily activities, such as pulling on a heavy door or bending to pick up newspapers, may lead to loss of balance. Therefore, therapeutic interventions aimed at improving balance control should include the specific components of anticipatory control. In addition, the findings suggest that balance measurements should include a combination of anticipatory and reactive balance control to identify older adults with poor balance successfully. As well, unlike laboratory settings, electromyography and force plates are expensive and not necessary in the clinical settings. Thus, a brief balance measurement may benefit in assessing balance in clinical settings. Such an assessment will help clinicians and practitioners to identify older adults who should be referred for balance training programs. As Tai Chi is a gentle and slow form of exercise, I also suggest that enhanced patterns of postural strategies observed in Tai Chi practitioners would likely benefit other older populations such as the frail elderly. It appears that the incorporation of Tai Chi forms into balance training programs may have potential to offer favorable results in older adults with poor functional balance and impaired mobility. A recent review also suggested Tai Chi as an example of whole-body coordination training (Marigold and Misiaszek, 2009). Future research is needed to identity whether APAs can be modified with training in older adults who are frail.

Further evidence of adaptations in balance reactions from the whole-body was presented in Chapter 3. Perturbations applied to the torso during walking resulted in early compensatory reactions (<200 ms) in the muscles of the legs in older adults, similar to the previous results utilizing support surface perturbations (Gatts and Woollacott, 2006; Tang and Woollacott, 1998; 1999). The new finding of the study was that older adults were capable of generating corrective reactions in the leg and arm muscles to meet the demands of task constraints. For example, the amplitude of the responses evoked in the leg muscles increased when the postural threats were increased but decreased when the postural threats were decreased by providing external supports, as compared with the arms free walking. Overall, corrective reactions in the leg muscles were increased or decreased as the level of postural threats were increased or decreased, consistent with a previous study in young adults (Misiaszek and Krauss, 2005). Results from the study suggested that balance corrective reactions in older adults were also able to be modulated in a context-dependent manner, similar to young adults.

Whether similar scaling of balance reactions would occur in other older populations, particularly for those older adults who rely on mobility aids need to be addressed in the future (Bateni et al. 2004a; Bateni et al. 2004b; Bateni and Maki, 2005; Marigold and Misiaszek, 2009). Presumably, frail older adults who use mobility aids may further restricted in their available balance strategies. Older adults who are more reliant on mobility aids may compensate for the balance impairment by using the sensory information from light touch on a cane or walker. Prolonged practice of holding onto handles as a source of stabilization could negatively influence the balance capacity in this population. This postural compensation should also be taken into consideration when designing balance treatment programs for this population.

The use of mobility aids, such as canes or walkers, is controversial. Some research suggested that using mobility aids can increase the older adults' confidence and assist in improving their mobility skills (Health Canada/Veterans Affairs Canada Falls Prevention Initiative, 2001; Public Health Agency of Canada, 2006). Other researchers showed using mobility aids interfering prompt responses and adversely affect correcting balance (Bateni et al. 2004a; Bateni and Maki, 2005; Charron et al. 1995). Frequent collisions of legs on mobility aids and over-dependence on canes when fixed supports are available during balance recovery were reported, indicating a high possibility of falls and fall related injuries (Bateni et al. 2004a; Bateni et al. 2004b). Futures studies on the influence of mobility aids need to address whether those older adults also display the adaptive balance reactions when their arms are constrained in weight support.

An exercise-based approach in enhancing balance and reducing the incidence of falls has been widely used in current fall prevention programs. Recently, Tai Chi has become a popular exercise and recommended as one of fall prevention exercises (Gillespie et al. 2009). The result of the Tai Chi study implies that balance strategies are modifiable in Tai Chi trained older adults. It is probable that training programs targeting corrective reactions will likely yield increases in the balance capacity of older adults. Older adults may benefit from interventions aimed at improving capacity of reactive balance. A recent randomized controlled study, which is now in progress by Mansfield et al. (2007) showed a perturbation-based training program focusing on compensatory reactions in older adults. Using unexpected platform perturbations in diverse directions to promote stepping and grasping balance reactions can be a potential approach to enhance balance. As such, training approaches that include coordination of the arms and legs would optimize the benefits to improve balance reactions in older adults. As shown in the study of context-dependent modulation among healthy older adults, balance tasks that utilize whole-body responses would improve available balance strategies of older adults (Marigold and Misiaszek, 2009). The implication for rehabilitation is that learning to coordinate the muscles of the whole body through training programs may have the advantage of enhancing balance.

Overall, this thesis provides a foundation for future studies on whole-body balance reactions among older adults. Results of the study highlight the need to include tasks involving whole-body coordination, when training balance in older adults. Developing exercise or treatment programs focusing on whole body coordination may lead to benefits for an older adult population who is at higher risk of falling.

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