The Role of Anticipatory Postural Adjustments in Balance Control: Effects of Age and Training

BY

NEETA SURESH KANEKAR
B.P.Th., Maharashtra University of Health Sciences, India, 2005
M.S Physical Therapy, University of Illinois at Chicago, 2008

DISSERTATION

Submitted as partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Kinesiology, Nutrition and Rehabilitation Sciences
(Rehabilitation Sciences) in the Graduate College of the
University of Illinois at Chicago, 2013

Chicago, Illinois

Defense Committee:

Alexander S. Aruin, Chair and Advisor
Ziaul Hasan
Charles B. Walter
Tanvi Bhatt, Physical Therapy
Xiaoyan Li, Rehabilitation Institute of Chicago

This thesis is dedicated to the love, passion, and joy of learning.

ACKNOWLEDGEMENTS

I would like to thank all the people who have been with me and helped me in bringing this thesis to fruition. I am deeply grateful to and wish to thank my research advisor and mentor, Dr. Alexander Aruin, for his unconditional support and guidance, his passion and enthusiasm for teaching, his belief in my abilities, and his constant encouragement. He has shaped my thinking, vision and understanding and has made this learning process an enjoyable experience. I would also like to thank my thesis committee members (Dr. Ziaul Hasan, Dr. Charles Walter, Dr. Tanvi Bhatt, and Dr. Xiaoyan Li) for their unwavering support and guidance. They consistently directed and assisted me in the preparation and execution of my research goals. I would also like to acknowledge Dr. Christina Hui-Chan, Dr. Mark Shapiro, and Dr. Mark Latash for their continuous mentorship and support in helping me accomplish my research goals.

A number of individuals from our laboratory made contributions important to the conduct of the study, and I would like to acknowledge them as well. Particularly, I would like to thank Dr. Marcio Santos, who trained me in data collection methods and helped me in my initial experiments. I would also like to thank Dr. Yun-Ju Lee, Dr. Sambit Mohapatra, Dr. Vennila Krishnan, Nilovana Panwalkar, Joseph Xaygnaraj, Maria Reyes Lopez, Bing Chen, and Ketaki Mehendale for their immense help in different aspects of data collection and completion of the study. I am grateful for their constant support, critical feedback and suggestions that helped in the successful conduct of the study.

I would also like to express my deepest gratitude to my parents, who have always given me the freedom to choose my path and for their love, encouragement and support in all that I do.

ACKNOWLEDGEMENTS (continued)

I would also like to thank my husband, Adhish, who has always believed in me and encouraged me, his love and support has been significant. I also express my gratitude to all my family members, friends, and teachers for being a part of my life and shaping it in many ways.

Above all I am ever grateful to the ALMIGHTY for giving me this opportunity.

NSK

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (continued)

<u>FIGURE</u> <u>PAGE</u>

LIST OF FIGURES (continued)

LIST OF ABBREVIATIONS

ADL	Activities of Daily Living
ANK	Ankle
ANOVA	Analysis of Variance
APAs	Anticipatory Postural Adjustments
BF	Biceps Femoris
BOS	Base of Support
CNS	Central Nervous System
COM	Center of Mass
COMy	Center of Mass displacement in the sagittal plane
COMz	Center of Mass displacement in the transverse plane
COP	Center of Pressure
CPAs	Compensatory Postural Adjustments
EMG	Electromyographic
EO	External Oblique
ES	Erector Spinae
ESL	Erector Spinae Longus
GAS	Gastrocnemius
GASL	Lateral Gastrocnemius
GASM	Medial Gastrocnemius

GM	Gluteus Medius
GMED	Gluteus Medius

LIST OF ABBREVIATIONS (continued)

HEA	Head
HIP	Hip
HSD	Honestly Significant Difference
$IEMG_{NORM}$	Normalized Integrated EMG activity
INT_{EMGi}	Integrated EMG activity
KEE	Knee
PCA	Principal Component Analysis
PCOMy	Peak Center of Mass displacement in the sagittal plane
PCOMz	Peak Center of Mass displacement in the transverse plane
PCOP	Peak Center of Pressure
PIG	Plug-In-Gait
RA	Rectus Abdominis
RF	Rectus Femoris
SOL	Soleus
SPN	Spine
ST	Semitendinosis
TA	Tibialis Anterior
TCOMy	Time of peak Center of Mass displacement in the sagittal plane
TCOMz	Time of peak Center of Mass displacement in the transverse plane

TCOP	Time of peak Center of Pressure
TOR	Thorax

LIST OF ABBREVIATIONS (continued)

VL	Vastus Lateralis
VM	Vastus Medialis
VR	Virtual Reality

SUMMARY

The first objective of this thesis was to understand how the availability of anticipatory postural adjustments (APAs) influences compensatory postural reactions and postural stability following a perturbation to balance. The second objective of the thesis was focused on understanding the changes in APAs with aging and the effect of training in improving the utilization of APAs in subsequent control of posture in the healthy young and older individuals.

The first chapter introduces the thesis by presenting a framework of viewing posture and movement as two integral components of a motor act. The chapter then elaborates the mechanisms of postural control and its significance. Particularly anticipatory/feedforward and compensatory/feedback postural strategies are discussed. Thereafter, the goal and functions of anticipatory postural control are presented. Finally, the chapter concludes by stating the research objectives of the different experiments that will be conducted in this thesis to understand the role of anticipatory postural adjustments in balance control of healthy young and older individuals and the effect of training.

Chapter two discusses the individual role of anticipatory and compensatory postural adjustments (APAs and CPAs respectively) and investigates the effect of APAs in subsequent control of posture (CPAs) in healthy young adults. Eight healthy young subjects were exposed to external predictable (eyes open) and unpredictable (eyes closed) perturbations at the shoulder level using the pendulum-impact paradigm. Electrical activity of trunk and leg muscles, center of

pressure (COP), center of mass (COM), and joint angle measurements were recorded for the anticipatory and compensatory phases. We found that when perturbations were predictable, the

muscles were activated prior to the perturbation as compared to unpredictable perturbations, where the onset of muscle activity was seen only after the disturbance ($p < 0.05$). Also, compensatory postural activity was found to be significantly larger for the unpredictable as opposed to the predictable conditions ($p < 0.05$). Moreover, maximal displacements of the COP and COM were significantly larger in unpredictable conditions (where anticipatory postural activity was absent) as compared to predictable perturbations.

Chapter three includes two experiments that examine the differences in APAs between young and older adults as well the effect of aging on the ability to use APAs in subsequent control of posture. For the first aim of this chapter, thirteen healthy young and ten healthy older adults were exposed to predictable external perturbations using the pendulum-impact paradigm. For the second aim, ten healthy older adults were exposed to predictable and unpredictable external perturbations. Electrical activity of thirteen trunk and leg muscles, COP, and COM displacements were obtained for the anticipatory and compensatory phases. We found that APAs were delayed and reduced in magnitude in older adults as compared to young adults in preparation of a predictable external perturbation ($p < 0.05$). Impaired generation of APAs was associated with larger compensatory muscle responses in older adults and greater peak displacements of COP and COM after the perturbation. We also found that in spite of age-related impairments of APAs, the older adults were able to assess the presence of APAs and utilized APAs (when available) to improve body stability.

Chapter four investigates the effect of training in enhancing the generation of anticipatory postural adjustments and their utilization in subsequent balance control in healthy young adults. Thirteen healthy young adults were exposed to predictable external perturbations before and immediately after a single training session that involved catching a medicine ball multiple times. Electrical activity of thirteen trunk and leg muscles, COP, and COM displacements were obtained for the anticipatory and compensatory phases. Training resulted in early onsets of anticipatory postural activity and larger displacements of the COP in preparation of the perturbation ($p < 0.05$) in healthy young adults. As a result, peak displacement of the COM following the perturbation was significantly smaller as compared to before training ($p < 0.05$).

Chapter five is aimed at determining whether training-related changes in anticipatory postural control could be a possible mechanism of improvement in balance control of older adults. Ten healthy older adults were exposed to predictable external perturbations before and immediately after a single training session that involved catching a medicine ball activity. Electrical activity of thirteen trunk and leg muscles, COP, and COM displacements were obtained for the anticipatory and compensatory phases. We found that following a single training session, the older adults showed early onsets of anticipatory postural activity as compared to the pre-training condition ($p < 0.05$). Increases in postural preparation were also associated with smaller peak displacements of the COP and COM after the postural disturbance.

Chapter six is the final chapter that summarizes the main outcomes of this thesis and discusses some important questions that need to be explored and suggests possible directions for further research in the area of postural control.

CHAPTER I

INTRODUCTION

Performance of a successful motor task or motor act requires an organized interaction of the two main components, namely: posture and movement (Massion 1992). Both, posture and movement influence one another and at the same time have to interact with each other in order to fulfill a motor act/task. Control of movement involves mobilization and immobilization of different body segments and movement, thus, is part of a motor task and a means to achieve it (Bouisset and Do 2008). Posture, on the other hand, is the background on which movements are organized and executed. Since the human body is not a rigid structure, but a multi-segmented structure, any movement causes a change in the body's geometry and shifts the center of gravity position. Moreover, internal muscle forces that produce the movement, themselves trigger a chain of reaction forces in the supporting segments, thereby disturbing posture (Massion 1992).

1.1 Postural Control and its Significance

Control of posture involves two aspects: postural maintenance and postural stabilization (Bouisset and Do 2008). Postural maintenance is required to maintain stance (static control) or any other position against gravitational forces and is collectively achieved through correct alignment of body segments with respect to the line of gravity, adequate joint stiffness provided by muscle tone, and constant feedback from the different visual, proprioceptive, somatosensory, and vestibular inputs. Postural stabilization is required to restore balance (dynamic control) when it is perturbed and is achieved through feedforward and feedback control mechanisms along with constant reweighing of the various sensory inputs. Another aspect of postural control involves maintaining an appropriate relationship between the body segments and between the body as a whole and the environment (Shumway-Cook A 2000). Postural control, thus serves as a frame of reference for perception and action with the external world (Massion 1992; Bouisset and Do 2008). Thus, postural control involves controlling the body’s position in space for the dual purposes of stability (static and dynamic) and orientation (Shumway-Cook A 2000).

Control of posture is essential for human mobility. A range of tasks, from maintaining a position (e.g. sitting, standing), restoring stability and orientation (e.g. slipping on icy curbs), to providing a stable background for performing movements (e.g. reaching, walking) are critical functions of postural control. Within an individual, the various systems that contribute to postural control are the sensory, neuromuscular and musculoskeletal systems with higher integration from the central nervous system (CNS), collectively referred to as the postural control system. Extensive research has demonstrated that impairments in any of these sub-systems as a result of advancing age or pathology affect control of posture. Moreover, the ability to maintain and restore balance is an important risk factor for falls in the elderly and people with neurological disorders. At the same time, it is also a predictor of functional independence and therefore a key rehabilitation goal.

1.2 Mechanisms of Postural Control

Human vertical posture is inherently unstable because it is challenged by such factors as the relatively high location of the center of mass, small support area, and multiple joints along the body axis (Massion 1992). Perturbations to balance can be classified as internal or external in origin. Internal perturbations originate from within the body such as from self-initiated movements (e.g. arm or leg lifts or trunk bends) or when a sensory input is eliminated (e.g. closing one’s eyes). External perturbations originate from the environment, for example, being pushed on a crowded street or from sudden halting while standing in a moving bus. Both types of postural perturbations create dynamic, inter-segmental forces that shift the body's center of mass (COM) closer to or outside the boundaries of the base of support (BOS), thus endangering the body's stability.

The CNS uses two control mechanisms to help maintain and restore balance when perturbations occur. The first type has been described in a groundbreaking work by Russian scientists Belen'kii, Gurfinkel, and Pal'tsev (Belen'kiĭ et al. 1967) as anticipatory postural adjustments (APAs) or feedforward postural control. Anticipatory postural adjustments (reviewed in (Massion 1992)) represent changes in the background activity of muscles *prior* to the actual postural disturbance. Anticipatory postural adjustments are based on previous experiences or anticipation and help in minimizing potential disturbances to balance due to an expected external perturbation or a forthcoming self-initiated movement (Belen'kii et al. 1967; Belenkiy et al. 1967; Bouisset and Zattara 1987a; Bouisset and Zattara 1987b; Massion 1992; Aruin and Latash 1995b). The second mechanism involves changes in the activity of postural muscles *after* a perturbation has already occurred. These adjustments serve as a means of restoration of balance and deal with the after effects of a perturbation; this mechanism is known as compensatory postural adjustments (CPAs) or feedback postural control (Nashner and Cordo 1981) (Horak and Nashner 1986). CPAs in general cannot be predicted and are triggered by sensory feedback signals in response to the perturbation (Park et al. 2004; Alexandrov et al. 2005). Accordingly there is a clear difference in the functions of APAs and CPAs: CPAs serve as a mechanism of restoration of the position of the COM after a perturbation has already occurred (Macpherson et al. 1989; Maki and McIlroy 1996; Henry et al. 1998), while the function of APAs is to reduce the effect of the forthcoming body perturbations with anticipatory adjustments

(Massion 1992; Aruin and Latash 1995b; Ito et al. 2004). Although APAs are generated in preparation of an expected/predictable perturbation, the disturbances to equilibrium cannot be counteracted by the presence of APAs only. Since they are based on approximations of the expected, not actual perturbation, they are not always completely effective, and as a result some corrective action is always needed in the form of CPAs. Compensatory muscle activity always follows the initial anticipatory adjustments in order to recover from the perturbation and restore balance. However, when the perturbations are unexpected/unpredictable, the CNS has to rely only on CPAs for recovering balance. Thus, postural control in humans is based on the effective use of anticipatory and compensatory postural mechanisms.

1.3 Functions of Anticipatory Postural Control

One of the main goals of APAs is to minimize the expected postural disturbances and maintain equilibrium. This functional role of APAs has been demonstrated in studies where perturbations were induced either by arm movements (Friedli et al. 1984; Bouisset and Zattara 1987a; Lee et al. 1987), leg movements (Nardone and Schieppati 1988), or trunk movements (Crenna et al. 1987). In order to maintain postural equilibrium, APAs are generated in the direction opposite to the direction of the expected postural disturbance. Another function of APAs involves stabilization of body segments during movement performance. This has been illustrated in studies involving bimanual load lifting tasks where, anticipatory inhibition is observed in the flexors of the forearm holding the load prior to the load being lifted by the opposite hand (details in (Massion 1992)). Such segmental stabilization by APAs is considered to be important in the manipulation and exploration of objects. While maintaining equilibrium and stabilizing body segments are independent functions fulfilled by APAs, they also a play a role in coordinating equilibrium control with postural stabilization of specific segments. For example, while lifting a leg sideways in standing, the center of gravity is shifted towards the supporting leg prior to movement initiation (to maintain equilibrium) while the head counter-rotates with respect to the trunk (to maintain vertical orientation) (reviewed in (Massion 1992). Moreover, APAs provide additional force for the movement itself. For example, APAs help accelerate the whole body COM so that transition from one posture to another is possible, such as during whole body reaching tasks from the standing position (Stapley et al. 1999). Likewise, APAs provide the postural preparation necessary for performance of movement itself. For example, in the act of rising on tip-toes from an upright standing position, the maximum shift of the COP in the backward direction co-varies significantly with the forward propulsive force in the anticipation phase (Ito et al. 2004). Thus, it can be said that the functional role played by APAs depends on the demands of the given motor act.

Majority of the previous literature has focused on the individual role played by APAs in postural control. However, since APAs are one of the mechanisms used by the CNS in control of posture, it is also important to understand how the presence of APAs influences the second mechanism of postural control, the CPAs.

1.4 **Interaction between Anticipatory and Compensatory Postural Control Mechanisms: Effects of Age and Training**

The overall objective of this thesis is to understand how the availability of anticipatory postural adjustments influences compensatory postural reactions and postural stability following a perturbation to balance. The thesis is also focused on understanding the changes in APAs with aging and the effect of training in improving the utilization of APAs in subsequent control of posture in the healthy young and older individuals.

The first experiment described in Chapter II focuses on the effect of APAs on subsequent control of posture (CPAs) in healthy young adults.

The second and third experiments described in Chapter III investigate the changes in APAs as a result of aging and examine the interaction between APAs and CPAs in healthy older adults, respectively.

The fourth experiment described in Chapter IV examines the effect of training in improving anticipatory postural control in healthy young adults.

The final and fifth experiment described in Chapter V investigates the effect of training in enhancing the utilization of APAs in subsequent control of posture in healthy older adults.

Chapter VI is the concluding chapter. It summarizes the main outcomes of this thesis and suggests the directions for future research.

CHAPTER II

THE ROLE OF ANTICIPATORY POSTURAL ADJUSTMENTS IN BALANCE CONTROL

The data presented in this chapter have been published as:

1) *Santos MJ, Kanekar N, Aruin AS (2010) The role of anticipatory postural adjustments in compensatory control of posture: 1. Electromyographic analysis. J Electromyogr Kinesiol 20(3): 388-397* (Santos et al. 2010a)
2) *Santos MJ, Kanekar N, Aruin AS (2010) The role of anticipatory postural adjustments in compensatory control of posture: 2. Biomechanical analysis. J Electromyogr Kinesiol 20(3): 398-405* (Santos et al. 2010b)

2.1 **Background**

Anticipatory (feedforward) and compensatory (feedback) postural strategies are the two main control mechanisms involved in maintaining and restoring body stability and orientation. The individual roles of APAs and CPAs in control of posture were studied extensively. Consequently, it was demonstrated that the magnitude of APAs depends on the direction (Aruin and Latash 1995a; Santos and Aruin 2008b) and magnitude of a perturbation (Aruin and Latash 1996; Bouisset et al. 2000), as well as body stability (Nouillot et al. 1992; Aruin et al. 1998; Nouillot et al. 2000). It was also shown that APAs are affected by the characteristics of a motor action used to induce a perturbation (Aruin and Latash 1995b; Aruin et al. 2003; Shiratori and Aruin 2007), body configuration (van der Fits et al. 1998; Aruin 2003), and fear of falling (Adkin et al. 2002). Previous literature reports that the CPA response depends on the direction and magnitude of the perturbation and on the dimensions of the base of support

(Horak and Nashner 1986; Henry et al. 1998; Dimitrova et al. 2004; Jones et al. 2008), predictability of perturbation characteristics (Burleigh and Horak 1996), instructions (McIlroy and Maki 1993), and involvement of a secondary task such as holding an object in the hands (Bateni et al. 2004). Moreover, distinct patterns of muscle activation called the ankle or hip strategy were described in the leg and trunk muscles in response to surface translations (Horak and Nashner 1986).

One of the roles of APAs is to minimize the effects of a forthcoming perturbation (Massion 1992); the presence of APAs does not rule out the existence of a CPA-based control of posture that involves on-line corrections (Bouisset and Zattara 1987b) and braking activities (Friedli et al. 1984; Crenna et al. 1987). While important information about the individual role of APAs and CPAs in control of posture is available in the literature, to the best of our knowledge, there are no studies investigating systematically the role of APAs in subsequent control of posture after a perturbation has occurred, i.e., during the CPA phase. Anticipatory postural adjustments could reduce the need for large CPAs resulting in better balance control. While such an association between the two components seems intuitive, it needs to be investigated further. This issue becomes all the more important since rehabilitation protocols extensively use perturbations such as throwing or catching a ball (that induce expected perturbations) in treatment of patients (Duran et al. 2001) and athletes (Cordasco et al. 1996; Blievernicht et al. 2000), as well as in exercise activities of the elderly (Barnett et al. 2003). Understanding the role of APAs in compensatory control of posture is also important because activities involving manual trunk disturbs such as pulling or pushing (that might be considered as unexpected perturbations) are commonly used by clinicians to treat individuals with orthopedic and neurologic impairments (Kisner and Colby 2007). Such perturbations are also used for balance control training or physical fitness in the elderly. However, little is known about the role of anticipatory postural adjustments, specifically, its relationship with CPAs in controlling body balance.

Electromyographic (EMG) patterns in the trunk and leg muscles during the APA and CPA intervals have been studied in experiments in which body perturbations were induced by voluntary movements and unexpected external perturbations respectively (Hughey and Fung 2005; Gage et al. 2007). Since body perturbations in these studies were triggered by either subjects' themselves or by the experimenter, it was difficult to control for the similarity of the magnitudes of disturbances applied to the body. Therefore, the observed differences in the EMG patterns during APAs and CPAs could be attributed to the differences between the two control processes, differences in the perturbation magnitudes, or a combination of both. For that reason, the primary goal of this study was to investigate further the respective contributions of the anticipatory and compensatory processes to postural control using perturbations of the same magnitudes applied at the shoulder level. Particularly, the study was focused on investigating the relationship between APAs and CPAs from a kinetic and kinematic perspective. For the experiment (Experiment 1) conducted in this study, we hypothesized that: 1) anticipatory muscle activation would reduce compensatory muscle activity resulting in smaller COM and COP displacements after the perturbation. An additional aim of this study was to examine the differences in the patterns of muscle activation between the anticipatory and compensatory periods of postural control 2) the joint angular displacements after the perturbation would be larger for the unpredictable as compared to the predictable conditions, and 3) the predictability of the perturbation would influence the relationship between COM and COP displacements.

To test these hypotheses, we used an experimental paradigm in which consistent body perturbations were induced by a pendulum released by the experimenter (pendulum-impact paradigm, details in the methods section). Throughout the experiments, the availability of information about the forthcoming perturbation was varied, as the subjects were standing with eyes open and with eyes closed while performing the same task of receiving the pendulum impact. Since APA magnitude depends on prediction of the timing and magnitude of a forthcoming perturbation, no APAs would be generated in conditions with eyes closed (when the subjects have no specific information about the timing of the pendulum impact). It is important to note here that utilization of the externally induced perturbation to study APAs is justified by the following. First, the outcome of previous studies that implemented a load catching paradigm revealed that APAs could be seen in conditions with no motor action being performed by the subjects themselves (Aruin et al. 2001; Shiratori and Latash 2001). Second, it was demonstrated experimentally that when the subjects could see the falling load, APAs were observed with patterns that are adequate for counteracting expected perturbations (Aruin et al. 2001). Third, outcome of recent studies using the pendulum impact as a source of predictable perturbations demonstrated the existence of robust APAs when the timing and magnitude of the impact was known to the subjects (Santos and Aruin 2008b; Santos and Aruin 2008a). Finally, the results of our pilot experiments confirmed that pendulum impact induces CPAs. All these facts provide sufficient support for using the pendulum paradigm to elicit both APAs and CPAs. Moreover, the paradigm allows applying the same magnitude of either predictable or unpredictable whole-body perturbation to human upright posture. As a result, the recorded EMG activity in the trunk and leg muscles could indeed be associated with respective contributions of the anticipatory and compensatory processes to postural control.

2.2 Methods

2.2.1 Subjects

Eight subjects (4 males and 4 females) without any neurological or musculoskeletal disorders participated in the experiments. The mean age of the subjects was 25 ± 2 years; mean body mass 59.1 ± 6.5 kg, and mean height 1.67 ± 0.08m. They all signed a written informed consent approved by the Institutional Review Board of the University of Illinois at Chicago.

2.2.2 Experimental Set-up and Procedure

The subjects were instructed to maintain upright stance while standing barefoot on the force platform with their feet shoulder width apart. They were positioned in front of an aluminum pendulum attached to the ceiling via ball bearings (coefficient of friction = 0.0015). A load (mass, m = 1.36 kg) was attached to the pendulum next to its distal end and a rope fastened to the pendulum was passed through a pulley system attached to the ceiling. Perturbations consisted of unidirectional forces applied to both the subjects' extended hands (mid-palmar region), using the pendulum that was pulled to a fixed distance (0.8 m) away from the subjects' hands (pendulum impact paradigm). The part of the pendulum touching the subject's hands was a round horizontal bar covered with foam and was soft to touch. Thus, when the pendulum contacted the subjects' hands, there would be no injury. The flight time was always constant (0.6 s), corresponding to the deviation of the pendulum from the vertical by 40°. All the trials of the pendulum release were implemented by the same experimenter. The subjects were required to receive each pendulum impact with their hands, while their arms, wrists, and fingers were extended at the shoulder level (Figure 1), and to maintain their balance after the perturbation. Given that the perturbation was induced in sagittal plane and applied to both the hands, it did not produce lateral or rotational body perturbations, and as such could be considered as symmetrical. Importantly, since the mass of the pendulum and the distance from which it was released remained the same for each particular subject, similar perturbations would elicit both APAs and CPAs, allowing a comparison between the two. There were two experimental conditions: 1) a

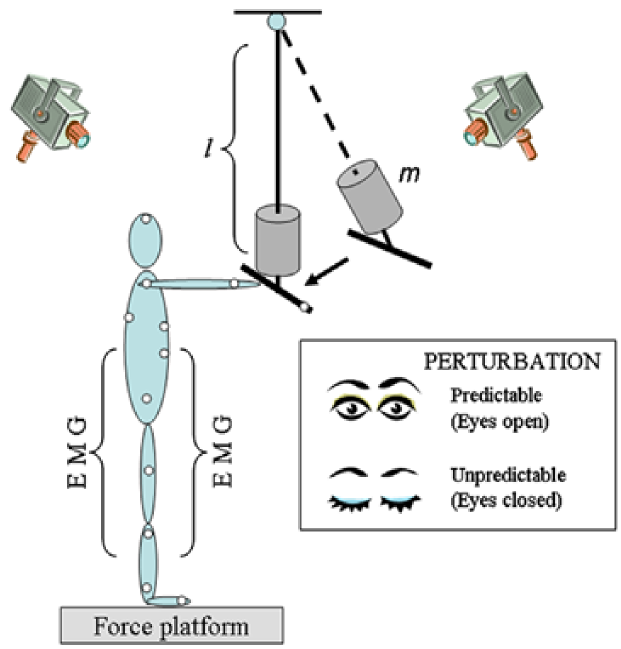

Figure 1. Schematic diagram of the experimental setup: pendulum impact paradigm. The subjects received the pendulum impact with their extended arms while standing with eyes open (predictable perturbation) or closed (unpredictable perturbation). Open circles are reflective markers, *l* is the length of the pendulum and *m* is an additional mass.

series of perturbations were applied with eyes open and as such were predictable in their timing; we call this condition "predictable perturbations" and 2) another series of perturbations were applied with eyes closed; this condition is called "unpredictable perturbations". Two to three practice trials were given prior to each experimental condition. No advance warning of the impending perturbation was provided; instead, the subjects wore earphones and listened to music delivered via a mini audio player (iPod, Apple Inc.) to prevent them from obtaining auditory information about the moment of the pendulum release. In addition, the experimenter released the pendulum at different times during the data collection, thus during the unpredictable conditions, the individuals could not predict when the pendulum would hit on their hands. For safety purposes in all the experiments, the subjects wore a harness (NeuroCom, USA) with two straps attached to the ceiling. In the case of the subject missing a pendulum impact, mechanical devices attached to the ceiling and frame would automatically stop the pendulum at approximately half a meter from the subject's upper body. As a result, the pendulum would never hit or injure the subject in any way. Five trials were performed in each experimental condition and the order of experimental conditions was randomized for each subject. All participants were allowed to have rest periods as needed. Since the mass of the pendulum and the distance from which it was released remained the same, similar perturbations were induced in both, predictable and unpredictable perturbation conditions. The magnitude of perturbation was large enough to evoke compensatory feet-in-place reactions.

2.2.3 **Instrumentation**

Electrical activity of muscles was recorded from the following right lower limb and trunk muscles: lateral gastrocnemius (GAS), tibialis anterior (TA), rectus femoris (RF), biceps femoris (BF), gluteus medius (GM), external oblique (EO), rectus abdominis (RA), and erector spinae (ES). After the skin area was cleaned with alcohol wipes, disposable electrodes (Red Dot 3M) were attached to the muscle belly of each of the above muscles, based upon recommendations reported in previous literature (Basmajian 1980). After similar skin preparations, a ground electrode was attached to the anterior aspect of the leg over the tibial bone. The EMG signals were collected, filtered, and amplified (10-500 Hz, gain 2000) with a commercially available EMG system (Myopac, RUN Technologies, USA).

Ground reaction forces and moments of forces were recorded using a force platform (model OR-5, AMTI, USA). An accelerometer (Model 208CO3, PCB Piezotronics, Inc , USA) was attached to the pendulum; its signal was used to register the moment of the pendulum impact. A six-camera VICON 612 system (Oxford Metrics) was used to collect three-dimensional kinematic data. Retroreflective markers were placed over anatomical landmarks bilaterally according to the Plug-In-Gait (PIG) model (Oxford Metrics), which includes: second metatarsal head, calcaneus, lateral malleolus, lateral epicondyle of the femur, a marker on the lateral border of the leg (between the lateral malleolus and femoral epicondyle markers), anterior/posterior superior iliac spines, a marker on the lateral border of the thigh (between the femoral epicondyle and anterior superior iliac spines), second metacarpal, lateral epicondyle of the humerus, acromio-clavicular joint, and a marker on the lateral border of the arm (between the humeral epicondyle and the acromio-clavicular joint markers). Also, subjects wore head and wrists bands with 4 and 2 markers attached on them, respectively. Finally, 5 additional markers were attached over: 7^{th} cervical vertebrae, 10^{th} thoracic vertebra, inferior angle of the right scapula, between the 2 sternoclavicular joints, and xiphoid process of the sternum bone.

Kinematic data were collected at 100 Hz, while forces, moments of force, EMG, and accelerometer signals were acquired at 1000 Hz by means of the VICON 612 data station (Oxford Metrics) that controlled data collection of all signals. The synchronization was achieved by the Vicon software in a way that for one pulse of kinematic data recorded, ten pulses of analog data were recorded.

2.2.4 **Data Processing**

The data were analyzed off-line using MATLAB (MathWorks, Natick, MA) programs. All EMG signals were rectified and viewed on a computer screen and an experienced researcher aligned them according to the first visible onset rise of the accelerometer signal. The alignment time was referred to as time zero (T_0=0). Then the data was cut off 500 ms before T_0. Aligned trials within each series were averaged for each subject. Integrals of anticipatory and compensatory EMG activity were derived using average trials for each subject where as the muscle latencies were calculated using individual trials.

The muscle latency was detected in a time window from -450 ms to +200 ms in relation to T_0 by a combination of computer algorithm and visual inspection of the trials. The latency for a specific muscle was defined as the instant lasting for at least 50 ms when its EMG amplitude was greater (activation) or smaller (inhibition) than the mean of its baseline value, measured from -500 to -450 ms, plus 2 SD.

Integrals of the EMG activities ($Int_{EMG\,i}$) during both tasks were calculated for 4 different epochs, each of 150 ms duration in relation to $T_{0.}$ The time windows for the 4 epochs were: 1) from -250 ms to -100 ms (anticipatory reactions, APA1); 2) -100 ms to +50 ms (anticipatory reactions, APA2); 3) +50 ms to 200 ms (compensatory reactions, CPA1); and 4) + 200 ms to 350 ms (late compensatory reactions, CPA2). The duration of the APA windows was selected based on the literature data (Shiratori and Latash 2001), and the results of a pilot study in which onset times of the proximal and distal muscles were observed outside of the typical APA window. The CPA time window was chosen using literature data on the timing of corrective reactions observed in the trunk and leg muscles in response to external perturbations induced by a platform translation (Henry et al. 1998). The subsequent division of this interval into two sub-windows was performed to differentiate the reflex responses (CPA1) from the voluntary reactions (CPA2) (Latash 2008). The $Int_{EMG\,i}$ for each of the 4 epochs was further corrected by the EMG integral of the baseline activity from -500 ms to -450 ms in relation to T0 as described below:

$$Int_{EMG\,i} = \int_{tw_i} EMG - 3\int_{-500}^{-450} EMG \qquad (1)$$

where Int_{EMGi} is the integral of EMG activity of muscles inside each 150 ms epoch tw_i, $i=1, .., 4$, and $\int_{-500}^{-450} EMG$ is the 50 ms background muscle activity defined as the integral of EMG signal from -500 ms to -450 ms with respect to T_0 (Aruin and Latash 1995b).

The sum ($\sum Int_{EMGi}$) of the two EMG integrals representing the entire time of anticipatory postural adjustments (APA1 plus APA2) was calculated for predictable tasks. The sum ($\sum Int_{EMGi}$) of EMG integrals reflecting the entire time of compensatory adjustments (CPA1 plus CPA2) was calculated for predictable and unpredictable tasks. These $\sum Int_{EMGi}$ were calculated for each ventral and dorsal muscle.

It is known that lack of, or distorted visual information may negatively affect postural sway (Hafstrom et al. 2002; Black et al. 2008). Therefore, the generation of compensatory reactions during unpredictable conditions could be influenced by both unpredictability of the perturbation itself and a disturbance in balance control due to a lack of visual information per se. In order to eliminate the latter and attribute the results to unpredictability of the perturbation, a pilot experiment was conducted involving 3 individuals. They performed the same task of stopping the pendulum released by the experimenter with eyes closed, and with eyes open while wearing transparent glasses. In the later condition, a black tape was attached to the center of the glasses in such a way that it covered only the pendulum and its trajectory. Thus, in this second condition, while the subjects were not able to see the forthcoming pendulum, their peripheral vision remained unobstructed. The Int_{EMGi} were compared between these two conditions (eyes closed, and eyes open while wearing glasses with central vision obliterated). No significant differences were found for either variable between the two conditions - suggesting that closing the eyes in itself did not interfere with the ability of a subject to control balance after unpredictable perturbations. Therefore, the responses obtained in this study with eyes closed were exclusively associated with the unpredictability of the perturbation.

Kinematic and kinetic data were recorded and stored on a computer for further analysis. The kinematic data were first processed using the Vicon and BodyBuilder 3D modeling software. The joint angles were derived from the Plug-in-Gait (PIG) model (Oxford Metrics). The PIG model consisted of fifteen body segments, including pelvis, femur (2), tibia (2), feet (2), humerus (2), radius (2), hands (2), thorax, and head. Body mass and height, 7 anthropometrical measures such as leg length, knee, ankle, elbow, and wrist width and shoulder offset and hand thickness for each subject were entered in the PIG model. These measures together with the kinematic data were used to calculate body's COM position. All signals were then analyzed using Matlab programs. Individual trials were viewed on a computer screen and aligned according to the first visible onset rise of the accelerometer signal. The alignment time was referred to as time zero (T_0=0). Aligned trials within each series were averaged for each subject.

Displacements of the center of pressure (COP) in the anterior-posterior direction were calculated using the following equation (Winter et al. 1996):

$$COP = \frac{Mx - (Fy * dz)}{F_Z} \qquad (2)$$

where Mx is the moment in sagittal plane, Fz and Fy are the vertical and the anterior-posterior components of the ground reaction force, and dz is the distance from the origin of the platform to the surface (0.038 m). The average magnitude of the COP displacement for each of the four 150 ms epochs was calculated and corrected by its respective baseline (see below). The kinematic data were low-pass filtered at 8 Hz and angular displacements of the ankle (ANK), knee (KEE), hip (HIP), spine (SPN), thorax (TOR), and head (HEA) and COM displacements in the sagittal (COMy) and transverse planes (COMz) in the tridimensional planes were obtained. The mean displacements of the ANK, KEE, HIP, SPN, TOR, and HEA angles, COMy, COMz, and COP were calculated for each of the 4 epochs of 150 ms duration. Thus, the following epochs were utilized: 1) -200ms to -50 ms (APA1), 2) -50ms to +100ms (APA2), 3) +100ms to 250 ms (CPA1), and 4) +250ms to 400 ms (CPA2). Note that the duration of each of four epochs was the same (150 ms) as the duration of the epochs used to analyze the EMG signals, however, the starting point of each epoch was shifted 50 ms towards T_0 to account for the electromechanical delay (Cavanagh and Komi 1979; Vint et al. 2001; Georgoulis et al. 2005; Rocchi et al. 2006). This shift was applied to account for the kinetic and kinematic changes produced by the muscular activity that occurred before the pendulum impact (APAs). For example, the mechanical event of the first epoch (-200 to -50ms) corresponded to the muscular activation that occurred at (-250 to -100ms). The baseline for each kinetic and kinematic variable was calculated as well in the interval from -500 ms to -450 ms. The baseline measure for each variable was multiplied by 3 to account for 3 times difference in the duration of the baseline window and the four epochs. This baseline measure was then subtracted from each of the respective kinetic and kinematic variables. For ANK, KEE, and HIP, the angles were calculated for both the right and left body sides. As the perturbations were symmetrical, only the right ANK, KEE, and HIP angles were used for statistical analysis. For ANK, KEE, HIP, SPN, and HEA in the sagittal plane, the positive sign corresponds to flexion and the negative to extension.

Since the perturbations were induced symmetrically, they were associated with anterior-posterior displacements of the COM and COP and negligible COM and COP displacements in medial-lateral directions. Hence, data on COM and COP displacements in medial-lateral directions were not used for analysis purposes and will not be further presented. Only COM and COP displacements in the anterior-posterior direction (Y-axis according to our experimental set up) will be reported. The onset of COMy, COMz and COP displacements were determined visually by a trained researcher. The peak displacements for COMy (PCOMy), COMz (PCOMz) and COP (PCOP) and their respective times (TCOMy, TCOMz, and TCOP) were also calculated. These measures indicated the individuals' balance control ability after the perturbations.

Principal component analysis (PCA) was used to better understand the segmental coordination during the APA and CPA phases. Each of these principal components is a linear combination of the original variables. As they are orthogonal to each other, there is no redundant information. This approach has been utilized in the past to interpret EMG activities (Wang et al. 2006) and movements of the body segments (Hughey and Fung 2005; Li and Aruin 2008) associated with self-induced or external body perturbations. The data included the mean raw angles of ANK, KEE, HIP, SPN, TOR, and HEA for each subject in the sagittal plane. Thus, for predictable conditions, the principal components were computed from 4 data matrices of 15 x 6, i.e., 15 samples accounting for 150 ms and 6 angles. For unpredictable conditions, only two data matrices of 15 x 6 were used to calculate the principal components, which corresponded to the two 150 ms CPA time windows. Also, combined PCA values were calculated for each of the APA (APA1 and APA2) and CPA (CPA1 and CPA2) phases. As a result, for predictable conditions, the principal components were computed from 2 data matrices of 30 x 6, i.e., 30 samples accounting for 300 ms and 6 angles. These 300 ms corresponded to the sum of the two

150 ms time windows of APA and CPA. For unpredictable conditions, only one data matrix of 30 x 6 was used to calculate the principal components, which corresponded to the two 150 ms CPA time windows. The percent of total variability explained by each principal component was also calculated for both time windows as well. The mean PCA values of all subjects are presented in absolute values.

2.2.5 **Statistical Analysis**

Multiple repeated measures ANOVAs with two within-subjects factors (2 conditions - predictable, unpredictable and 4 epochs – APA1, APA2, CPA1, CPA2) were used to compare the Int_{EMGi} for each muscle, mean displacement for each joint angle (ANK, KEE, HIP, SPN, TOR, HEA), and COM and COP mean displacements. A post hoc analysis was used for further comparisons within the 4 epochs. Repeated measures ANOVA with two within-subjects factors [condition (2) and time windows (2)] were also used to compare the 4 PCA values. A paired t-test was used for the comparison of muscular latencies (muscle onsets) and the CPA $\sum Int_{EMGi}$ for ventral and dorsal muscles between predictable and unpredictable conditions. Paired t-test was also used to compare PCOMy, PCOMz, PCOPy as well as TCOMy, TCOMz, and TCOP, between conditions (predictable and unpredictable). For all tests, the statistical significance was set at $p < 0.05$.

2.3 **Results**

2.3.1 **Profiles of Electromyographic Activity**

Figure 2 displays EMG traces obtained from the ventral, dorsal, and lateral muscles of a representative subject during performance of the task involving predictable and unpredictable perturbations. Anticipatory activity was seen in most of the muscles in the predictable conditions as an increase (rise/activation) or cessation (inhibition) of the background EMG activity. Notice a reciprocal pattern of anticipatory activity of the trunk and leg muscles seen as activation of the ventral muscles (TA, RF, and RA) and inhibition of the dorsal muscles (GAS, BF, ES) in conditions with the predictable perturbations induced by the pendulum impact. In contrast, no APAs were observed in the experiments with unpredictable body perturbations; instead, a large compensatory EMG activity was seen in most of the trunk and leg muscles after the pendulum impact.

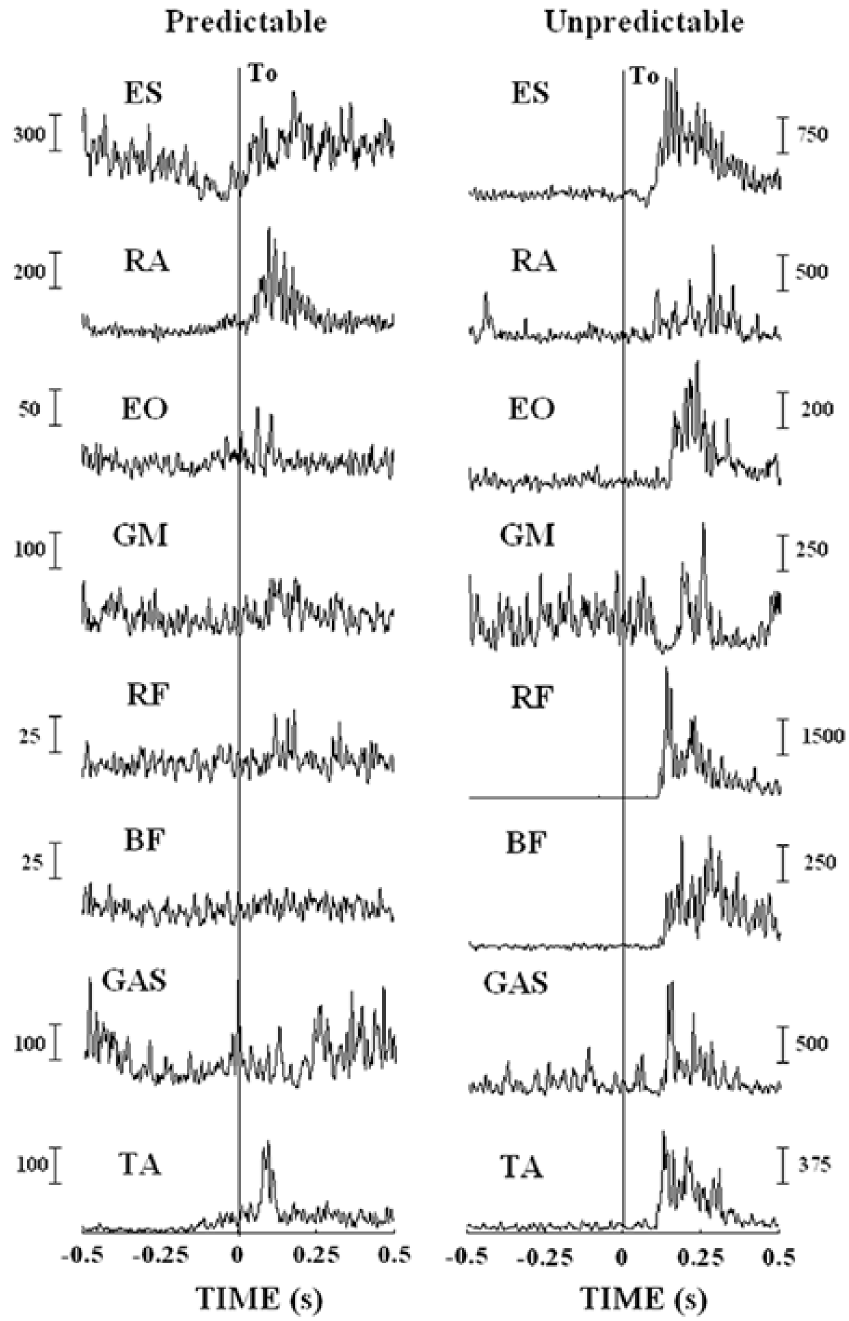

Figure 2. A typical EMG pattern (averages of six trials for a representative subject) of the ventral (TA, RF, and RA), dorsal (GAS, BF, and ES), and lateral (EO and GM) muscles recorded in conditions with predictable and unpredictable perturbations. The vertical lines show the moment of body perturbation (T_0). Time scales are in seconds and EMG scales are in arbitrary units. Muscles abbreviations: TA- tibialis anterior, GAS -gastrocnemius, BF- biceps femoris, RF- rectus femoris, GM- gluteus medius, EO- external obliques, RA- rectus abdominis, and ES- erector spine.

2.3.2 Onset of Muscle Activity (Muscle Latency)

In conditions with the predictable perturbations, onset of EMG activity was seen before the pendulum impact in all the studied muscles (Figure 3). Gastrocnemius was the first muscle showing inhibition in the EMG background activity at -215 ± 44 ms followed by the inhibition of other dorsal muscles, BF at -178 ± 79 ms and ES at -168 ± 15 ms before the pendulum impact (T_0). Early activation was seen in TA, RF, and RA with latencies at -160 ± 32 ms, -181 ± 56 ms, and -166 ± 95 ms before the impact, respectively. Bursts of EMG activity were observed in lateral muscles as well with latencies of -164 ± 65 ms for GM and -168 ± 95 ms for EO before the impact. The order of activation of muscles in the predictable conditions was from distal to proximal.

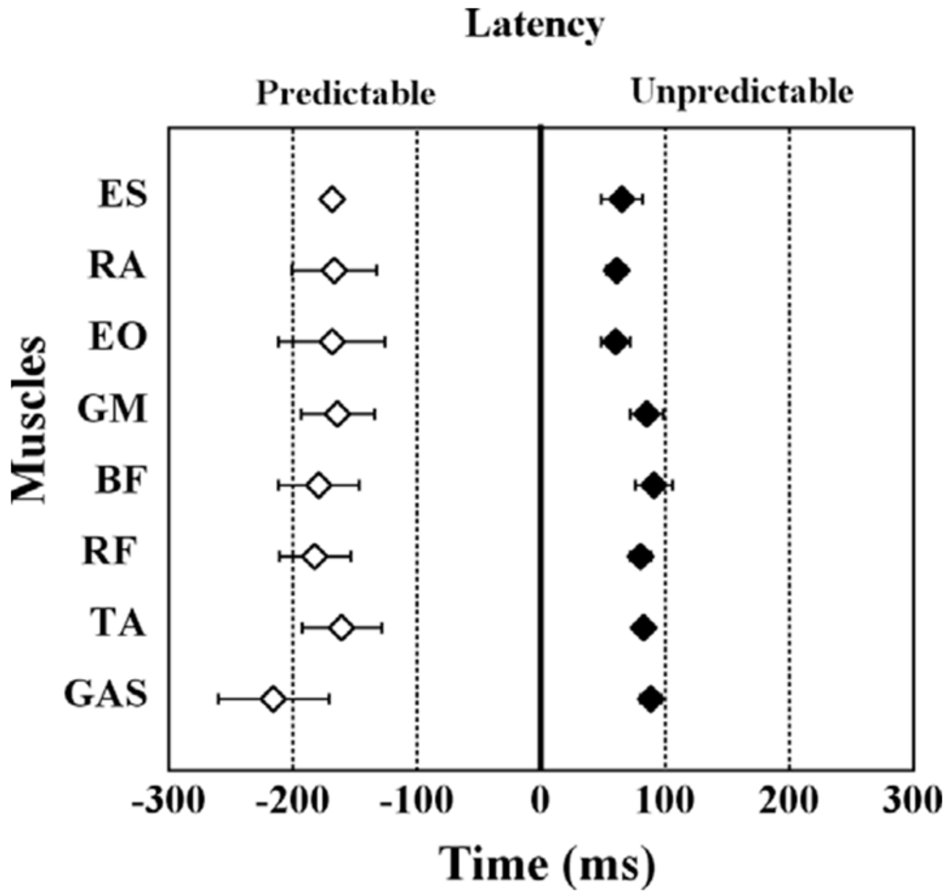

Figure 3. Muscle activity onsets. Note that for predictable perturbations the onset of muscle activity occurred prior the perturbation and the order of activation of muscles is from distal to proximal. In case of unpredictable perturbations, the muscle onsets occurred after the perturbation (T_0) and the order of activation is from proximal to distal. Muscles abbreviations are the same as shown in Figure 2.

None of the eight studied muscles showed changes in their background activity before the pendulum impact during the series with the unpredictable perturbations; instead, all the muscles became active after the perturbation impact. The EO, RA, and ES were the first muscles to be activated with latencies at 60 ± 25 ms, 61 ± 21 ms and 65 ± 40 ms after the perturbation, respectively. The onsets of these muscles were followed by the onsets of the RF at 80 ± 16 ms, TA at 82 ± 11 ms, GM at 85 ± 29 ms, GAS at 88 ± 14 ms, and BF at 91 ± 36 ms. The sequence of activation of muscles was from proximal to distal and it was different than the sequence observed for predictable conditions.

The differences in the latencies of muscles between predictable and unpredictable conditions were statistically significant for all studied muscles ($p < 0.05$).

2.3.3 **Integrated Electromyographic Activity**

A. ***Electromyographic Integrals in Ventral Muscles***

In the series with unpredictable perturbations, $Int_{EMG\,i}$ in the ventral muscles (TA, RF, and RA) observed prior to the perturbation onset during both the APA1 and APA2 epochs were negligible. Instead, large $Int_{EMG\,i}$ could be seen after the pendulum impact. Figure 4 shows the temporal evaluations of the $Int_{EMG\,i}$ during performance of the tasks with predictable and unpredictable perturbations; $Int_{EMG\,i}$ for each of the four epochs are broken into 50 ms blocks for better visualization. Similar representation will be used below in Figures 5 and 6. The results of statistical analysis of differences in Int_{EMG} between conditions and epochs as well as interactions for each individual ventral muscle are presented in TABLE I. Tibialis anterior, RF, and RA Int_{EMG} were significantly different between the conditions and epochs. The post hoc analysis demonstrated that for the predictable conditions the RF Int_{EMG} APA1 epoch was significantly smaller than the CPA1 and CPA2 epochs. For unpredictable perturbations TA, RF, and RA Int_{EMG} during the CPA1 epoch were significantly greater than Int_{EMG} calculated for the CPA2 epoch.

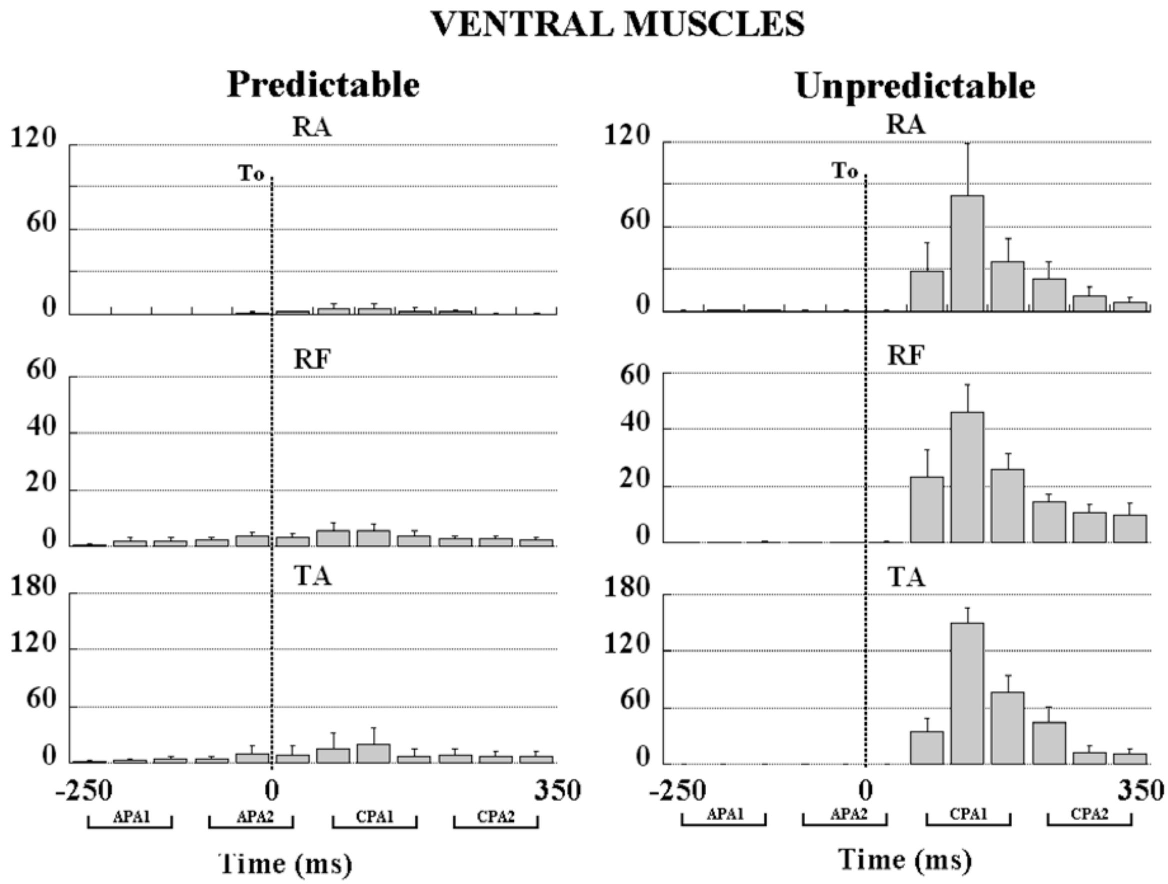

Figure 4. Temporal evaluation (from -250 ms to +350 ms in relation to T0) of the EMG activities of the ventral muscles during predictable and unpredictable conditions. Each point represents the averaged in 50 ms intervals and its standard error across 8 subjects. The 4 time epochs of 150 ms used for the analysis are represented by the brackets on the bottom (APA1, APA2, CPA1, and CPA2). The vertical lines show the moment of body perturbation (T0).

TABLE I

ANOVA RESULTS FOR INT_{EMG} BETWEEN CONDITIONS AND EPOCHS AS WELL AS CONDITION*EPOCH INTERACTIONS FOR EACH MUSCLE

Muscles	Condition (C)		Epochs (E)		Interaction (C*E)	
	F (1, 7)	*p*	F (3, 21)	*p*	F (3, 21)	*p*
ES	1.9	0.22	1.77	0.19	0.96	0.43
RA	5.7	0.04*	4.9	0.01**	3.6	0.02*
EO	8.4	0.02*	6	<0.01**	6.3	<0.01**
GM	29	<0.01**	15.5	<0.01**	15	<0.01**
BF	57.5	<0.01**	1.3	0.30	0.9	0.44
RF	8.7	0.02*	34.4	<0.01**	18.8	<0.01**
TA	102.6	<0.01**	53.7	<0.01**	30.3	<0.01**
GAS	55.5	<0.01**	18.7	<0.01**	14.4	<0.01**

* $p < 0.05$.

** $p < 0.01$.

B. ***Electromyographic Integrals in Dorsal Muscles***

In the experiments with the predictable conditions, $Int_{EMG\,i}$ in the dorsal muscles (GAS, BF, and ES) were mostly negative suggesting that dorsal muscles were inhibited during both the anticipatory and compensatory phases of postural control. In contrast, in conditions with the unpredictable perturbations, small $Int_{EMG\,i}$ in dorsal muscles during the APA1 and APA2 phases (as compared to predictable conditions) were accompanied by large $Int_{EMG\,i}$ .after the perturbation onset (best of all seen in GAS) (Figure 5). The effect of condition was significant in GAS and BF (TABLE I); in addition, analysis of GAS $Int_{EMG\,i}$ revealed statistically significant difference among the epochs and interaction between conditions and epochs. The post hoc analysis demonstrated that GAS $Int_{EMG\,i}$ calculated for CPA1 was significantly greater than the CPA2.

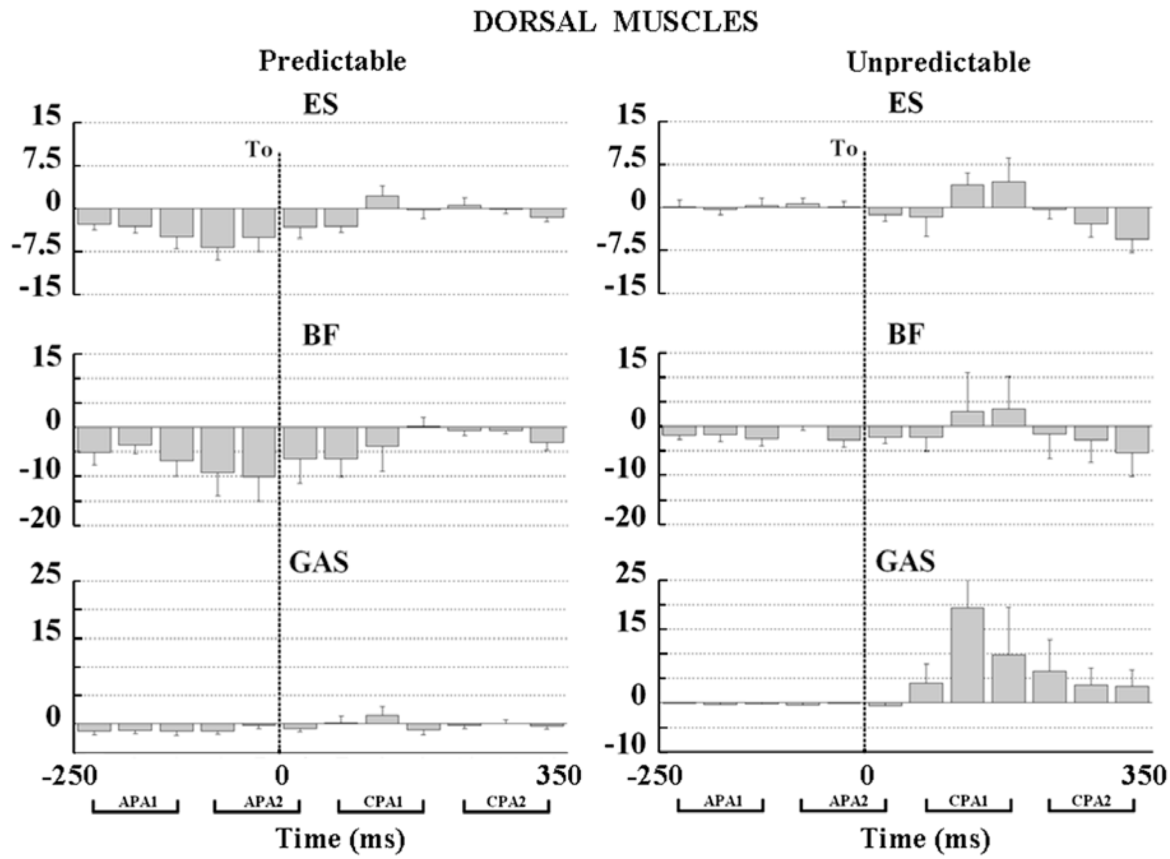

Figure 5. Temporal evaluation (from -250 ms to +350 ms in relation to To) of the EMG activities of the dorsal muscles during predictable and unpredictable conditions. Each point represents the averaged in 50 ms intervals and its standard error across 8 subjects. The 4 time epochs of 150 ms used for the analysis are represented by the brackets on the bottom (APA1, APA2, CPA1, and CPA2). The vertical lines show the moment of body perturbation (T0).

C. ***<u>Electromyographic Integrals in Lateral Muscles</u>***

Significant differences in the Int_{EMG} between the conditions, epochs, as well as conditions-epoch interactions were found in both GM and EO muscles (Figure 6, TABLE I). The post hoc analysis revealed that in the unpredictable condition, the GM and EO Int_{EMG} during the CPA1 and CPA2 epochs were significantly larger than APA1 and APA2 epochs.

Moreover, GM and EO Int_{EMG} during the CPA1 epoch were significantly greater than Int_{EMG} calculated for the CPA2 epoch.

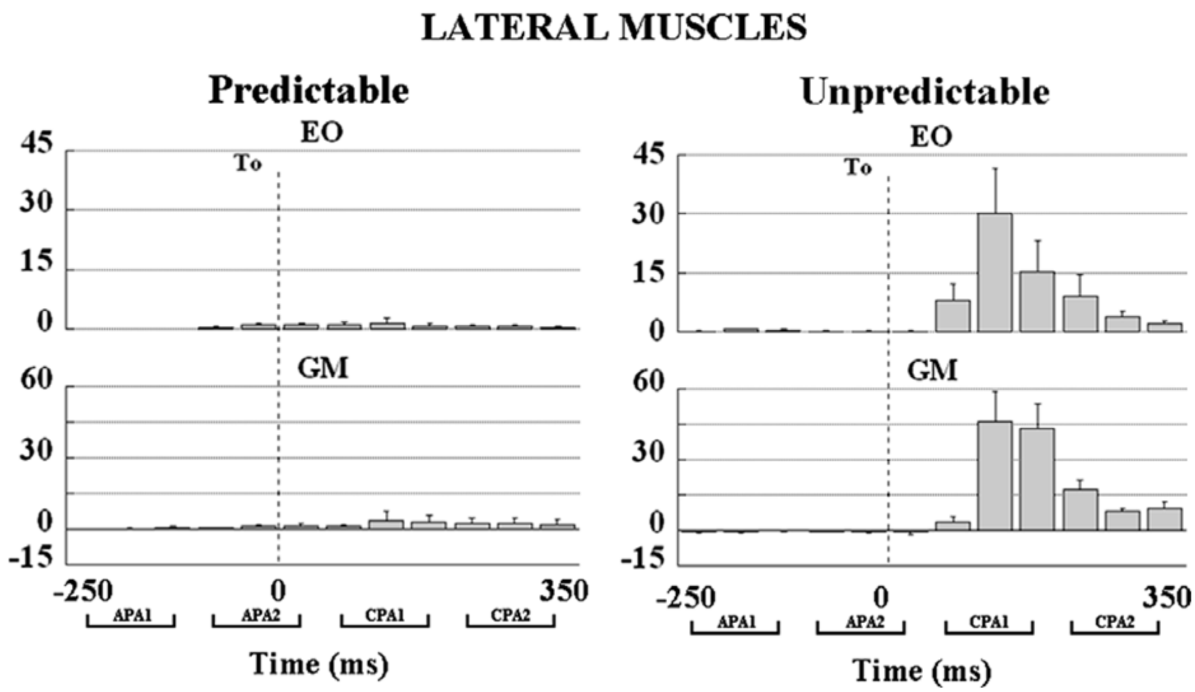

Figure 6. Temporal evaluation (from -250 ms to +350 ms in relation to To) of the EMG activities of the lateral muscles during predictable and unpredictable conditions. Each point represents the averaged in 50 ms intervals and its standard error across 8 subjects. The 4 time epochs of 150 ms used for the analysis are represented by the brackets on the bottom (APA1, APA2, CPA1, and CPA2). The vertical lines show the moment of body perturbation (T0).

D. ***Difference between Predictable and Unpredictable Conditions***

Figure 7 depicts the sum of Int_{EMG} of the ventral and dorsal muscles calculated during the anticipatory (APA) and compensatory (CPA) postural adjustments in conditions with predictable and unpredictable perturbations. Notice a considerable inhibition of the dorsal muscles (represented by negative values of the $\sum Int_{EMGi}$) during the APA phase in conditions with predictable perturbations. Also notice that $\sum Int_{EMGi}$ calculated for each ventral muscle during the CPA phase in the unpredictable conditions were several times larger than $\sum Int_{EMGi}$ calculated during the CPA phase in the predictable conditions. The TA, RF, and RA $\sum Int_{EMG}$ during the CPA phase were significantly greater for unpredictable than predictable conditions ($p<0.05$). In contrast, when $\sum Int_{EMG}$ of the dorsal muscles calculated during CPA phase for predictable and unpredictable conditions were compared, the only muscle showing statistically significant difference between the conditions was GAS ($p<0.01$).

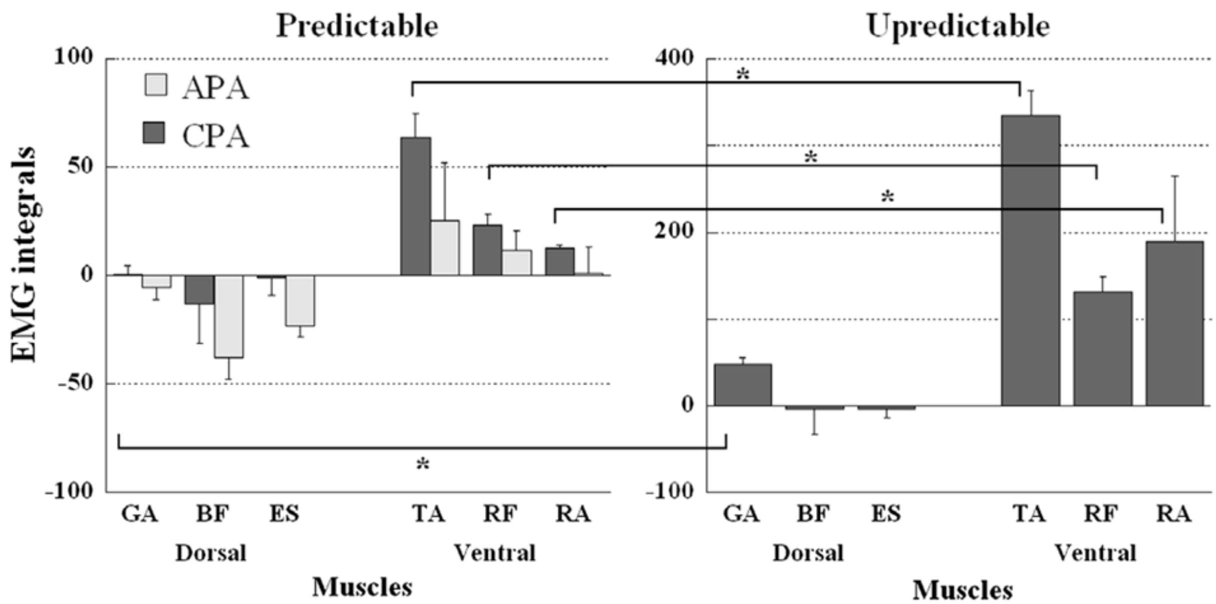

Figure 7. Muscular synergies involving ventral and dorsal muscles represented by the sum of APAs and CPAs for predictable tasks and the sum of CPAs for unpredictable conditions. * denotes significant differences in $\sum Int_{EMGi}$ between predictable and unpredictable conditions ($p<0.05$).

2.3.4 **Angular Displacements**

Changes in the angular position of the ankle, knee, hip, spine, thorax, and head are shown in Figure 8. Note that the angular position was calculated during the interval from -200 ms to +400 ms in relation to T_0, each point represents the average of 50 ms time window and their respective standard errors, and the four 150 ms epochs are shown. There were no anticipatory displacements in the ankle, knee, and hip joints while small anticipatory displacements could be seen in the spine, thorax, and head angles prior to the perturbation (T_0). The observed anticipatory displacements however were not significantly different between predictable and unpredictable conditions. In contrast, during the CPA phases, the displacement of the ankle, knee and hip joints were markedly greater during unpredictable compared to predictable conditions with the largest displacement occurring in the knee and ankle joints. The difference in the angular displacement in each of these two joints between the predictable and unpredictable conditions was statistically significant (ankle, $p=0.01$ and knee, $p<0.01$). Also, a significant interaction effect between conditions and epochs was observed for the angular displacements in the ankle, knee, and hip joints [($p<0.01$, $p<0.01$, and $p<0.01$) for all comparisons]. No significant differences were observed between conditions (expected and unexpected perturbations) for spine, thorax and head displacements. Overall, the within comparison of the four epochs for the angular displacements showed significant differences for all joints across the time windows. Usually, the angular displacements during the epochs APA1 and APA2 were close to zero and increased (ankle, knee, hip, and spine) or decreased (head and thorax) significantly after the impact (CPA1, CPA2) (Figure 8).

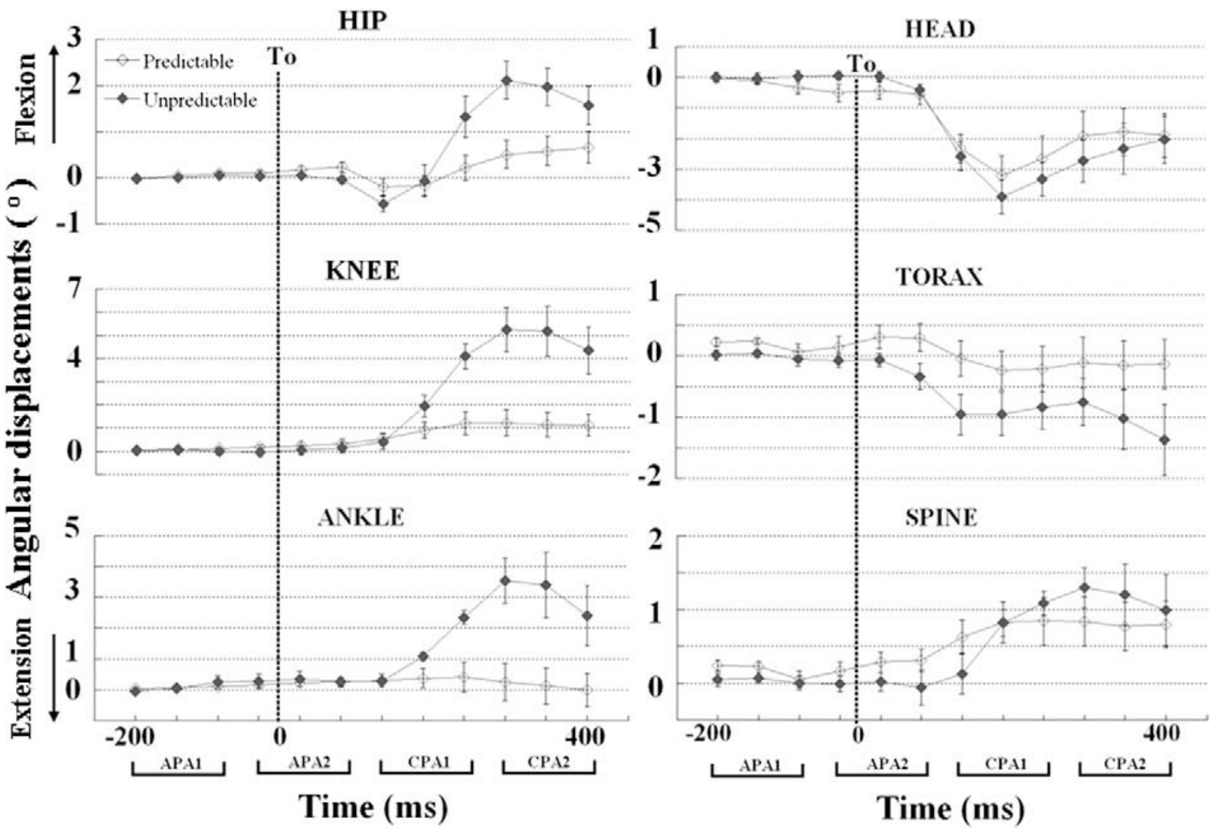

Figure 8. Temporal evaluation (from -200 ms to + 400 ms in relation to T_0) of the ankle, knee, hip, spine, thorax, and head displacements during predictable and unpredictable conditions. Each point represents the angular displacements in the sagittal plane (flexion (+) and extension (-) of these variables averaged over a 50 ms interval (-201 to -150 ms, -151 to -100, and so on) and its standard error. The 4 time epochs of 150 ms used for the analysis are represented by the brackets on the bottom (APA1, APA2, CPA1, and CPA2). The dotted vertical line shows the moment of body perturbation (T_0).

Since there were no significant differences in PCA values between the two APA (APA1 and APA2) phases or between the two CPA phases (CPA1 and CPA2), only the combined CPAs were further analyzed. The analysis of the combined PCAs demonstrated that the first two principal components accounted for approximately 96% of the variance of the six angles for predictable (APA and CPA) and unpredictable (CPA) conditions. TABLE II lists the averaged loading of the two principal components and their percentage of variance. The first principal component during predictable conditions accounted for 79% and 77% of the variance for APA and CPA phases, respectively. Similarly, the principal component during unpredictable conditions (CPA) was responsible for 79% of the variance as well.

TABLE II

TWO PRINCIPAL COMPONENTS (MEAN AND STANDARD DEVIATION) AND THEIR CORRESPONDING PERCENTAGE VARIANCE

Joints	Predictable								Unpredictable			
	APA				CPA				CPA			
	pc1	sd	pc2	sd	pc1	sd	pc2	sd	pc1	sd	pc2	sd
Head	0.57	±0.31	0.49	±0.26	0.70	±0.27	0.47	±0.37	0.28	±0.17	0.74	±0.19
Thorax	0.43	±0.18	0.36	±0.25	0.27	±0.16	0.25	±0.18	0.15	±0.09	0.30	±0.26
Spine	0.31	±0.13	0.40	±0.26	0.14	±0.12	0.28	±0.34	0.19	±0.18	0.19	±0.13
Hip	0.19	±0.15	0.23	±0.22	0.29	±0.21	0.41	±0.29	0.42	±0.11	0.23	±0.16
Knee	0.28	±0.24	0.27	±0.17	0.24	±0.25	0.19	±0.11	0.67	±0.10	0.25	±0.11
Ankle	0.18	±0.24	0.21	±0.27	0.22	±0.19	0.25	±0.23	0.36	±0.18	0.23	±0.19
% of variance	78.78	±13.11	16.78	±12.17	76.97	±13.10	19.12	±11.96	79.48	±12.48	16.69	±11.48

In addition, according to the PCA loadings, the proximal joints (head and thorax) were the principal joints to change the angular position in the APA phase during predictable conditions. In the experiments with the predictable perturbations, head and hip joint were the most responsible for the movements in the CPA phase. In contrast, for unpredictable conditions, the knee followed by the hip joint accounted for the principal angular changes in the CPA phase (TABLE II).

2.3.5 **Center of Mass and Center of Pressure Displacements**

For the predictable conditions, the COP was the first to move at -306 ± 77 ms followed by COMz at -226 ± 98 ms and COMy at -153 ± 39 ms before T_0. For unpredictable conditions the COMy was the first to move: the onset time for COMy was 42 ± 16 ms followed by COMz and COP at 46 ± 28 ms and 48 ± 27 ms after To, respectively.

Figure 9 depicts the mean displacements of COM in the anterior-posterior and vertical directions and COP displacement in the anterior-posterior direction for both predictable and unpredictable conditions. During the APA phase small displacements of COMy in the anterior direction and COMz displacements in the downwards direction, were observed during the predictable conditions. In addition, the COP excursion in the posterior direction prior to the perturbation was observed when the perturbation was predictable. In contrast, for unpredictable conditions no displacements were seen for COMz and COP during anticipatory phase. At the same time, small displacements were observed for COMy in the posterior direction (Figure 9). After the perturbations, displacements of COMy and COP in the posterior direction and COMz in the downward direction were seen in predictable and unpredictable conditions as well. However, the magnitudes of COMy, COMz, and COP displacements were substantially larger in conditions with unpredictable perturbations compared to predictable perturbations.

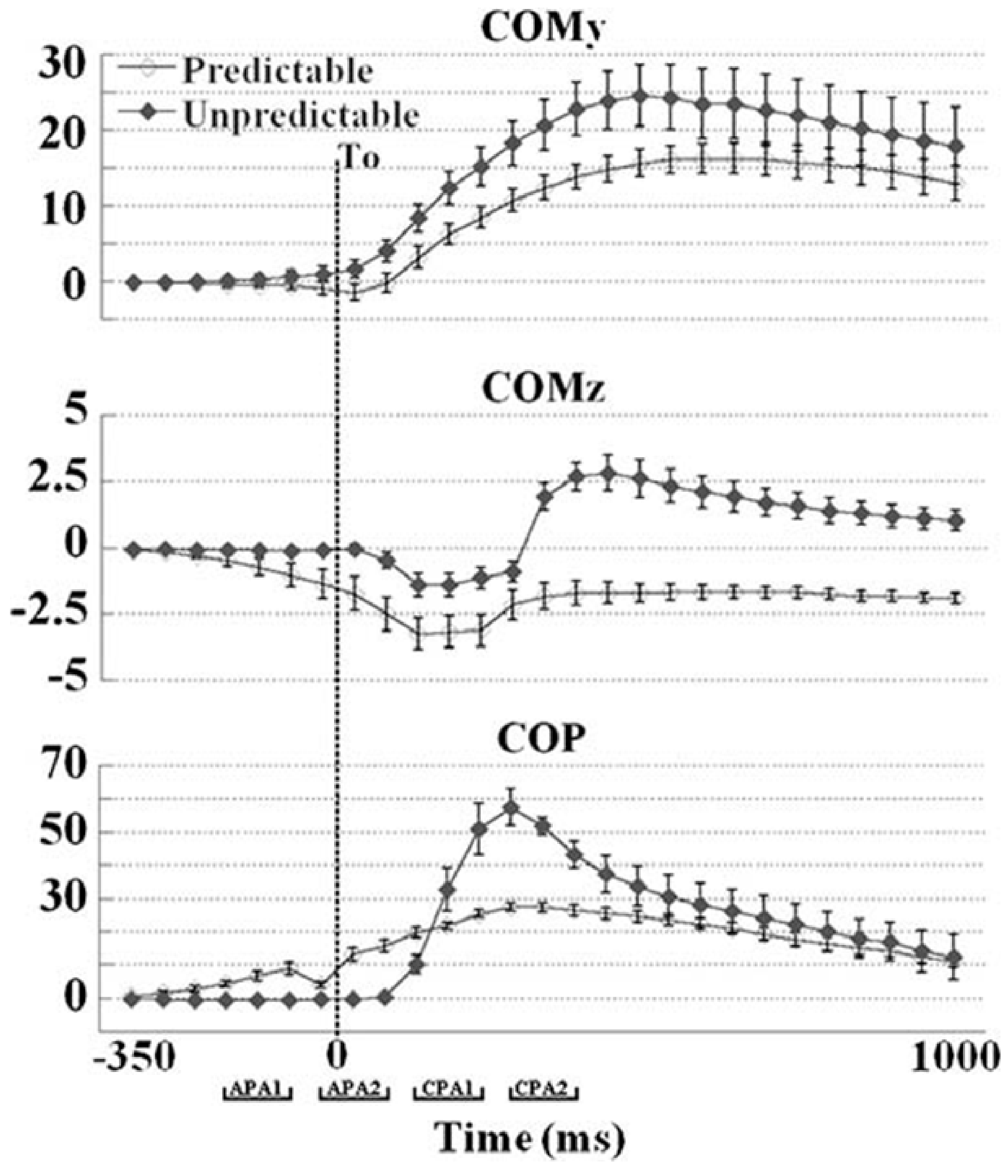

Figure 9. Temporal evaluation (from -350 ms to +1000 ms in relation to T_0) of the COMy, COMz, and COP displacements during predictable and unpredictable conditions. Each point represents the mean COMy and COP displacements in anterior (-) and posterior (+) directions and COMz displacements towards downward (-) and upward (+) directions averaged over a 50 ms intervals (-351 to -300 ms, -301 to -250, and so on) and its standard error across 8 subjects. The dotted vertical line shows the moment of body perturbation (T_0).

The displacements of the COP in the anterior-posterior direction are shown in Figure 10. In general, the COP displacements were significantly larger when perturbations were unpredictable compared to predictable conditions ($p<0.01$). For the time period prior to the pendulum impact (APA1 and APA2), considerable displacements in COP were observed when the perturbations were predictable; when they were unpredictable, the COP displacements were negligible. The post hoc tests detected that all COP epochs were significantly different from each other during the predictable condition and that the COP displacement in these epochs increased gradually and significantly from APA1 epoch to CPA2. For unpredictable conditions, the APA1 and APA2 epochs were not significantly different from each other. However, the APA1 and APA2 epochs were significantly smaller than the CPA1 and CPA2 epochs ($p<0.01$, $p=0.01$, $p<0.01$, and $p<0.01$). Moreover, CPA2 was significantly greater than CPA1 epoch ($p<0.01$). Importantly, during the compensatory phases (CPA1 and CPA2), the COP displacement for the unpredictable condition was significantly greater as compared to the predictable condition ($p<0.01$).

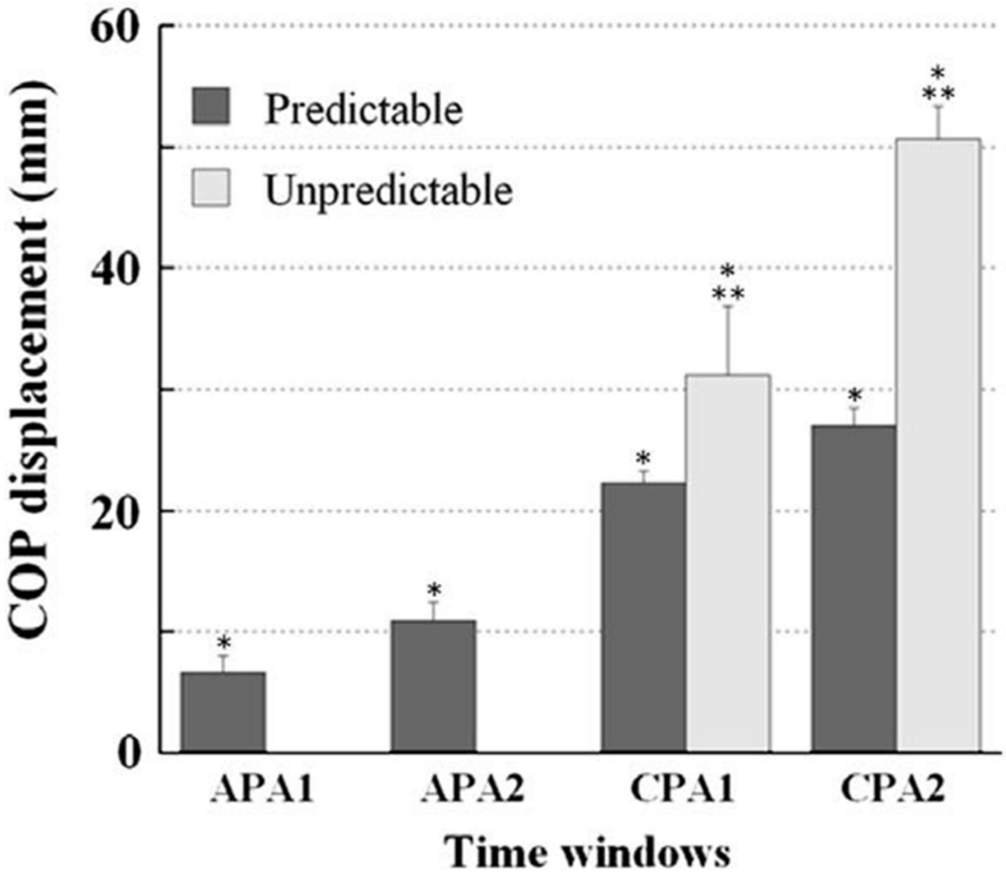

Figure 10. COP displacement (mm) for predictable and unpredictable conditions. Positive values correspond to the displacements of the COP backwards. * indicates significant differences among the epochs (APA1, APA2, CPA1, and CPA2) and ** represents significant differences between conditions (unpredictable and predictable).

The peak COMy, COMz, and COP displacements calculated after T_0 are shown in Figure 11. The peak of COP displacement (PCOP) was 28 ± 3.6 mm for predictable condition and 60 ± 14 mm for unpredictable condition, in the posterior direction. The peak of COMz displacement (PCOMz) in downward direction was 3.6 ± 0.6 mm for predictable and 1.7 ± 0.4 mm for unpredictable conditions. The COMy peak in the posterior direction reached 17 ± 5.5 mm in experiments with predictable perturbations while for unpredictable task it reached 28 ± 9.6 mm. All the three maximal displacements were significantly different between predictable and unpredictable conditions (*p*<0.01, *p*=0.01, *p*<0.01, respectively).

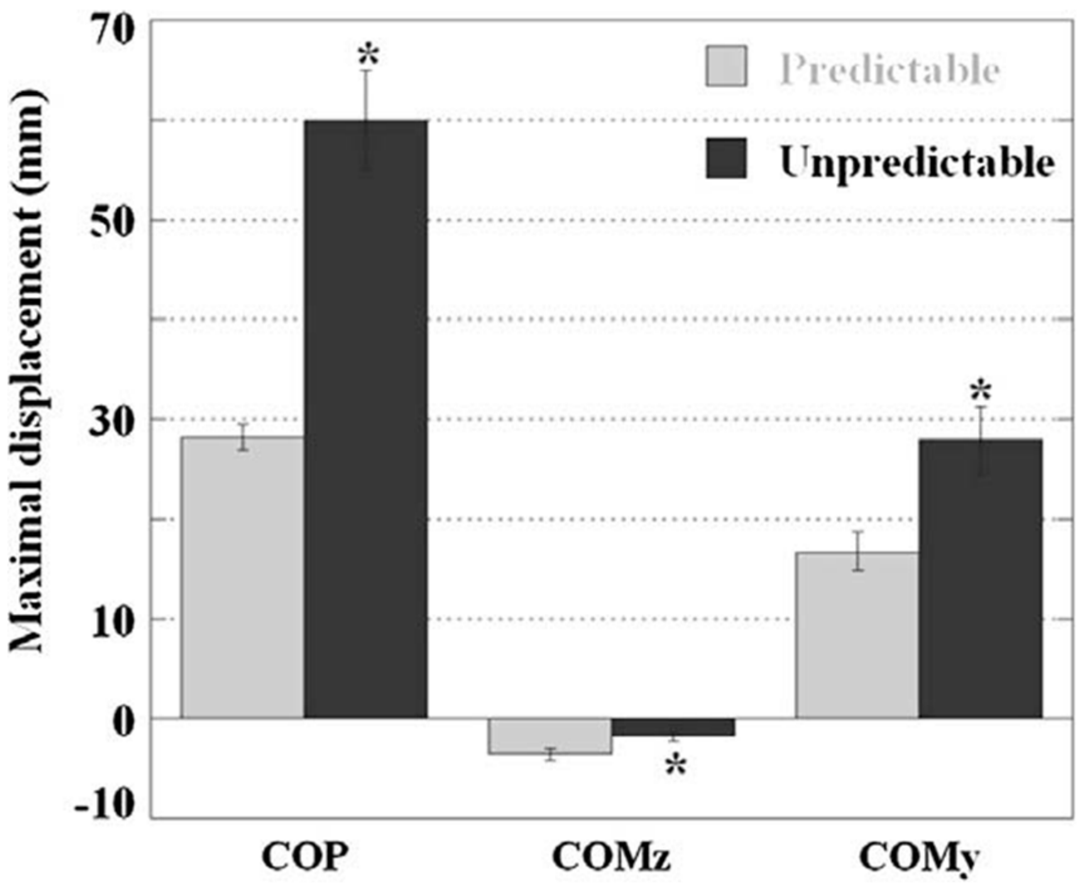

Figure 11. Differences between predictable and unpredictable conditions in the maximal/peak COMy, COMz, and COP displacements (mean and standard error) after the perturbation. * denotes significant difference at alpha level of 0.05.

The COMz was the first to reach its peak in both predictable and unpredictable conditions: the times of the TCOMz peaks were 146 ± 10 ms and 145 ± 5 ms after T_0, respectively. The COP reached its peak after COMz, its times (TCOP) were 323 ± 98 ms and 332 ± 142ms after the T_0 for predictable and unpredictable conditions, respectively (Figure 12). The COMy reached its peak last: during predictable conditions TCOMy was at 646 ± 112 ms after the perturbation impact while for unpredictable conditions TCOMy was observed at 573 ± 112 ms after T_0. The time when each of the COMy, COMz and COP variables reached their peaks was not significantly different between the predictable and unpredictable conditions.

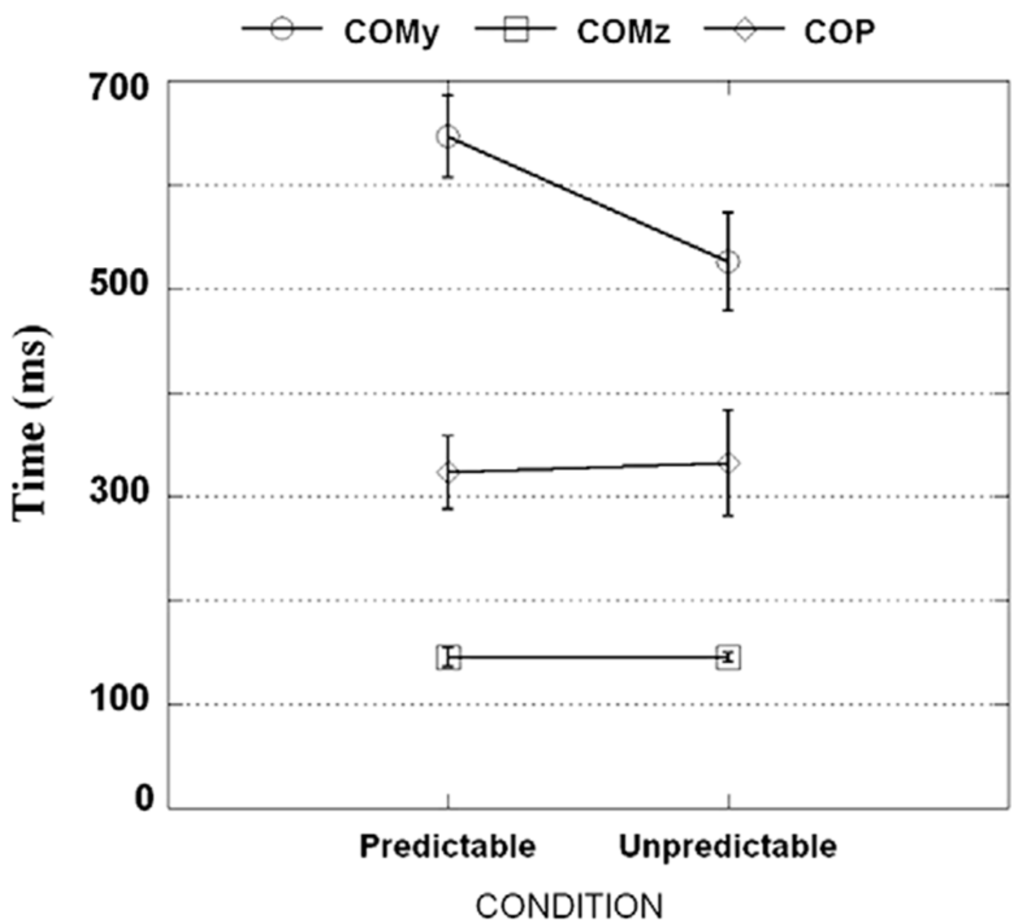

Figure 12. Times at which COMy (TCOMy), COMz (TCOMz), and COP (TCOP) reached their maximal/peak displacements (mean and standard error) after the perturbations for predictable and unpredictable conditions.

2.4 **Discussion**

In this study, we analyzed the anticipatory and compensatory postural adjustments triggered by external predictable and unpredictable perturbations of the same magnitude applied at the shoulder level of standing subjects. There were several principal findings. First, the hypothesis that the amount of compensatory muscle activation depends on the availability of anticipatory EMG activity was supported. Second, the patterns and magnitudes of joint angular displacements differed between the predictable and unpredictable conditions. Thus, small changes in the lower extremities joint angular positions were seen after the predictable pendulum impact. In contrast, large changes in the ankle, knee, and hip angular positions were observed after the unpredictable perturbations. Second, the COP and COM onset sequence changed between predictable and unpredictable perturbations. Third, when APAs were utilized (predictable perturbations), small COP and COM excursions were seen during the CPA phase. In contrast, when the perturbation was unpredictable, large COM and COP displacements were observed during the recovery of body balance. Finally, the timings of the peak of COM and COP displacements were similar for the predictable and unpredictable conditions whereas the magnitudes of the peak displacements were significantly different between the two conditions. These main differences in the EMG activity of muscles across the postural responses between predictable and unpredictable perturbations and the COM-COP interplay are discussed in details below.

2.4.1 Effect of Anticipatory Muscle Activity on Compensatory Reactions

Larger compensatory reactions were seen during the unpredictable perturbations because these conditions were not associated with any anticipatory activity. However, when the perturbations were predictable, so that the subjects knew the timing of the perturbation, they generated strong APAs: this resulted in significantly smaller compensatory reactions. The observed changes in the electrical activity of muscles suggest that the CNS assesses the effect of involvement of the APAs and generates or scales down CPAs accordingly. Such assessment and utilization of anticipatory activity resulting in reduced compensatory corrections following a perturbation have also been reported in tasks involving precision grip maintenance in sitting (Kourtis et al. 2008). Thus, it can be suggested that while dealing with perturbations, the general rule applied by the CNS is to optimally use anticipatory activity if and when possible, resulting in appropriate scaling down of compensatory activity. It is important to note that, the way anticipatory and compensatory corrections were used does not resemble “all or nothing” strategy since implementation of APAs prior to the pendulum impact while dealing with predictable perturbations did not completely exclude the generation of CPAs after the perturbations occurred. Moreover, the “all or nothing” strategy is rather a theoretical approach since in real life there is always some type of compensatory EMG activity used in control of vertical posture. This suggestion could be supported by several observations. First, involvement of EMG activity in the trunk and leg muscles during the CPA phase could be associated with insufficiency of the APAs that was reported in young children (van der Heide et al. 2003; Hadders-Algra 2005) and in individuals with neurological disorders (Bazalgette et al. 1987). Second, it was reported that APAs are attenuated in conditions of body instability (Aruin et al. 1998). In such a case, sufficient compensatory muscle activity would be needed to preserve balance. Finally, the existence of continuous muscular activity across both APA through CPA phases during predictable (self-initiated) and unpredictable (externally induced) perturbations has been described in the literature (Hughey and Fung 2005).

2.4.2 **Differences in Muscle Activation Patterns between Predictable and Unpredictable Perturbations**

The EMG patterns observed in the current study have several important features. First, in the case of predictable perturbations, APAs were present during both, APA1 and APA2 epochs. However, the largest anticipatory responses occurred during the APA2 epoch (between -100 ms to +50 ms in relation to T_0). The existence of the robust anticipatory adjustments inside this time window are consistent with the APA literature involving self-initiated (Belen'kiĭ et al.

1967; Cordo and Nashner 1982; Zattara and Bouisset 1988; Kanekar et al. 2008) or external predictable perturbations (Aruin et al. 2001; Shiratori and Latash 2001; Santos and Aruin 2008b). Hence, the observation of largest APAs during the APA2 epoch suggests that the CNS is capable of generating APAs in a time frame that is close to the moment of the perturbation. However, in case the forthcoming perturbations and/or current balance status are more challenging, the CNS might choose generating APAs earlier. The existence of early APAs (between -250 and -100 ms) was described in the experiments involving pointing movements to targets of different size (Bonnetblanc et al. 2004) and the arm-raising task after fatigue (Allison and Henry 2002).

Second, when no anticipatory activity was generated (as it happened in the unpredictable conditions), larger EMG responses were seen during the first compensatory phase (CPA1, from 50 ms to 150 ms after the perturbation onset) in almost all studied muscles (TA, RF, GA, GM, and EO) when compared with the second compensatory (CPA2) phase. It suggests that the body perturbations were relatively successfully minimized with the muscular responses generated right after the perturbation that could be attributed to the stretch reflex (Cordo and Nashner 1982; Bloem et al. 2002; Granata et al. 2004). As a result, a significantly smaller compensatory muscular activity was needed during the second stabilization (CPA2) phase of the compensatory control of posture. This suggestion is supported by the decreased Int_{EMG} during the CPA2 phase seen in the TA, RF, GA, GM, and EO muscles. On the other hand, large CPAs observed right after the perturbation onset (CPA1) might generate “too much” compensation which needs to be corrected during the following compensatory activity and such corrections are represented by the EMG activity seen later inside the second (CPA2) epoch.

Third, during predictable perturbations a reciprocal pattern of activation was seen both, before and after T_0; dorsal muscles were inhibited whereas ventral and lateral muscles were activated. On the other hand, during unpredictable perturbations a co-activation of the distal leg muscle pair during the second phase of compensatory activity was observed. Co-activation of leg and trunk muscles to increase the stiffness of the joints has been described in the literature during both, the anticipatory (Aruin and Almeida 1997; Slijper and Latash 2000; Danna-Dos-Santos et al. 2007; Li and Aruin 2007) and compensatory (Allum et al. 1989; Berger et al. 1992; Dimitrova et al. 2004) phases of postural control. However, it is important to note that the co-activation of TA-GAS muscles, seen in the current study 200 ms after the perturbation, was accompanied by a reciprocal pattern of muscle activation of the proximal muscles (RA and BF activation and ES and RF inhibition). It appears that by co-activating the distal leg muscle pair the subjects of the current experiment opted to increase the stiffness of the ankle joints in order to generate forces needed for foot-in-place responses. At the same time, in order to restore the upper body position a reciprocal control strategy was used. The fact that the two strategies are used simultaneously suggests that the CNS is capable of implementing multiple strategies while controlling the body position in space.

Finally, a distal to proximal order of anticipatory muscle activation has been observed in experiments with self-initiated elbow flexions (Cordo and Nashner 1982; Friedli et al. 1984). Similar order of early muscle activation (distal to proximal) was seen in the current study even though the perturbations were induced externally but their timing and magnitude was known to the subjects. It was advocated previously that distal to proximal sequence of muscle activation relates to the self-initiated perturbation itself as well as to postural requirements or “postural set” (as coined by (Cordo and Nashner 1982). As such it is employed “to modify the subjects’ balance sway”, making it easy for them to counteract the imminent forces generated by the perturbations to the body (Cordo and Nashner 1982). However, when the subjects were exposed to unpredictable perturbations as in the current experiment, the sequence of compensatory activation of the muscles was proximal to distal. Similar order of muscle activation starting with the biceps brachii, followed by thoracic muscle and then followed by the low back muscles was observed in experiments with unpredictable external perturbations applied through the upper limbs of standing individuals (Hodges 2001; Moseley et al. 2003). In the present experiment, the subjects used different strategies to restore the equilibrium according to the perturbation predictability. It appears that when information about the forthcoming perturbation is unavailable, the CNS uses a proximal to distal approach of muscle activation so as to initially restore the upper body position and maintain the body’s vertical orientation. When the perturbation is predictable, the CNS uses distal to proximal order of muscle activation which first and foremost allows applying forces to the ground thus counteracting the perturbation effect, and after that helps restore the upper body position.

The patterns of EMG activity observed in the current study provide evidence that there is a relationship between the anticipatory and compensatory components of postural control. In addition, this study provides evidence that the CNS is able to use the anticipatory activation of muscles to prevent further destabilization of balance and as a result, it does not need to call in place large compensatory muscle activity. Also, once body stability is achieved (or at least it is improved to a certain degree), the CNS employs a strategy that involves (1) decreasing globally the activity of postural muscles, and (2) utilizing a reciprocal and co-activation pattern of activation in combination, which was seen for example in RA-ES, RF-BF, and TA-GAS muscle pairs during the CPA2 phase, respectively.

2.4.3 **<u>Postural Control during Predictable and Unpredictable Perturbations</u>**

As described above, the patterns and sequence of activation of muscles used in postural control change depending on the availability of information about the forthcoming perturbation. When the perturbation was predictable, a distal-to-proximal sequence of anticipatory activation of leg and trunk muscles was observed prior to the pendulum impact. This pattern of activation, however, might not be associated with large movements in the lower limb and the upper body joints prior to the pendulum impact as is shown in the current study (Figure 8). Notice that these displacements were similar to those during unpredictable perturbations, in which no anticipatory muscular activity occurred prior to the pendulum impact. Interestingly, during predictable conditions, small amount of anticipatory EMG activity was associated with smaller joint angular displacements after the perturbations. Quite opposite, during unpredictable conditions, higher compensatory EMG activity with a proximal to distal sequence of activation was associated with larger angular displacements, especially of lower limb joints after the perturbations (Figure 8).

Although the ankle, knee, and hip angular positions as well as COM and COP excursions were greater during unpredictable perturbations, the movements of the upper part of the body, especially in the CPA phase, were smaller and similar between the two experimental conditions. The small changes in the angular position of the upper body seen as a combination of head extension and the flexion of the thorax, spine, and hip during the APA phase (confirmed by the PCA analysis, TABLE II) could be responsible for the anterior and downward displacement of the COM in anticipation to the pendulum impact. Similar small trunk movements and relatively large hip and ankle joint displacements were reported in subjects exposed to multidirectional surface perturbations (Henry et al. 2001). The outcomes of both studies suggest that the changes in the angular position of the lower limb joints play an important role in minimizing the trunk displacement after unpredictable perturbations in standing individuals. In fact, when the lower limbs are not utilized to counteract the perturbation, for example while the seated subjects are exposed to horizontal surface translations, the COM displacements and changes in the angular position of the head, trunk and arms are larger compared to ones recorded in standing subjects (Preuss and Fung 2008). Therefore, the results of the current study taken together with the literature data suggest that regardless of the level at which the unpredictable perturbation is induced to a standing individual (via the surface on which the subjects stand or at the shoulder level), movements of the lower limbs are used to minimize the trunk and head movements. This in turn allows preserving the upper body vertical orientation, especially its orientation in the sagittal plane.

Moreover, the lower limb joint excursions described in the present study seem to be primarily responsible for differences found in COM and COP displacements between the conditions with predictable and unpredictable perturbations. It appears that during predictable perturbations, the CNS strategy was to better arrange the body segments, especially the proximal ones, and as a result, smaller changes in the angular position of the lower limb joints were seen after the perturbation. In contrast, to recover the equilibrium in unpredictable conditions, the subjects used combination of movements in the ankle, knee and hip joints: such a strategy has been described in the literature (Nashner 1977; Horak and Nashner 1986). Furthermore, to restore balance, the subjects in the present study utilized considerable knee flexion rather than hip and ankle movements (confirmed by the magnitudes of pc loadings in TABLE II and Figure 8). Similar knee flexions associated with forward displacement of the body, induced by a movement of the force platform on which the subjects were positioned have been described previously (Hughes et al. 1995). A possibility of utilization of such a “knee” or “suspensory strategy” has been mentioned in the literature (Nashner 1977). Thus, there is a likelihood of a general rule by the CNS to use knee flexion while counteracting unpredictable perturbations induced in the sagittal plane.

It is important to note that the expectation of the forthcoming perturbation could potentially change the behavior with the focus, for example, to increase the stiffness of the joints by co-activation of certain postural muscles. However, it was not the case in our study since the exact timing of the unpredictable pendulum impact was not known to the subject and as such no anticipatory postural adjustments were generated.

The specific patterns of muscle activation seen in the current study resulted in the COM and COP differences observed between conditions with predictable and unpredictable perturbations. Significant reduction of the compensatory (peak) COM and COP displacements were seen in conditions when the subjects knew the timing of the forthcoming perturbation, which is when APAs were available. This finding provides additional evidence in support of the importance of the anticipatory postural adjustments in the activity of the trunk and leg muscles in the overall control of vertical posture. Interestingly, even though the peak displacements of the COM and COP (PCOMy, PCOMz, and PCOP) between predictable and unpredictable conditions were considerably different, the times at which they reached their peaks of displacement (TCOMy, TCOMz, and TCOP) after the perturbations were consistently similar between the conditions (Figure 12). It is important to point out that no specific instructions were given to the participants with respect to maintaining balance while performing the experimental tasks. Also, it is interesting to note that the COP was the first to move and reached its peak earlier than COMy in the predictable condition; on the other hand, in experiments with unpredictable conditions the

COP displacement began after the COMy, however, it still reached its peak before COMy. It maybe suggested that instead of controlling only the magnitude of the COP and COM peak displacements the CNS tightly controls the timing of the peak displacement to achieve the functional goal of maintaining balance. As such, during the unpredictable perturbations, the COP moves from its onset to the peak in a very short time as compared to the predictable conditions. On the other hand, when the perturbation could be predicted, more time is available for the COP to reach its peak (refer Figure 9). It is quite possible that the CNS estimates the "ideal" amount of time needed for the COP to respond to a perturbation and reach its peak. This could be achieved by using factors such as a life-long experience, environmental context, information obtained during practice trials, or a combination of these factors. This idea is supported by the outcome of the studies that showed that in experiments involving unpredictable perturbations, in contrast to predictable perturbations, there was a low correlation between magnitude of perturbation and intensity of responses in terms of COM displacement (Rietdyk et al. 1999), EMG activity and ankle torques (Horak et al. 1989a). In others words, the CNS is set to give the initial response and correct it during the course of perturbations, which in the present study corresponded to the CPA1 and CPA2 phases, respectively.

2.4.4 **Interplay between Center of Pressure and Center of Mass**

It has been shown experimentally that unexpected multidirectional surface tilts (Hughey and Fung 2005) or surface translations (Henry et al. 2001; Horak et al. 2005) are associated with the COM shift in the direction of the perturbations. This COM shift is then followed by the COP shift in order to catch up with the COM and recover body equilibrium. Indeed, in the current study the COM displacement during unpredictable perturbations was in the posterior direction (which coincides with the direction of the perturbation) and was followed by the COP displacement in the same direction. Corresponding results were observed in experiments involving standing individuals exposed to unexpected lateral perturbations induced at the shoulder level (Rietdyk et al. 1999). Therefore, one can conclude that any type of unpredictable perturbation (e.g. that induced by a moving surface or pushing at the shoulder level) generates a COM displacement (which coincides with the direction of the perturbation), which is followed by the displacement of the COP in the same direction.

Quite the opposite, during predictable perturbations, the COP was the first to shift, followed by COM movements. Similar order of COP and COM displacement was previously observed in the studies utilizing voluntary leg lifts (Hughey and Fung 2005), rising on tiptoe (Ito et al. 2004), or whole body reaching movements (Stapley et al. 1999). In addition, it looks like the initial displacement of the COP in the posterior direction in the present study created the momentum that resulted in forward (COMy) and downward (COMz) COM displacements (Figure 9). Comparable interplay between the COP and COM displacements was observed in experiments using whole-body reaching task (Crenna et al. 1987; Stapley et al. 1998; Stapley et al. 1999). For example, it was reported that while performing a whole body reaching task in the sagittal plane, the anticipatory backward COP displacement created a negative COM momentum allowing all body segments to move in forward direction: this was confirmed by changes in the ground reaction forces in relation to the position of COM (Stapley et al. 1999). The existence of such a relationship between COP and COM displacements during the APA phase (observed in the present study and described in the literature) suggests that, in the case of predictable perturbations, the CNS utilizes anticipatory activation of muscles to better arrange the body segments; this provides some mechanical advantage while controlling posture. Another possible explanation to the existence of such a relationship could be related to the utilization of adjustment in body balance sway as coined by Cordo and Nashner (Cordo and Nashner 1982). Indeed, small joint movements and COM-COP displacements observed prior to the pendulum impact support the suggestion that the CNS could utilize such balance sway adjustments. Both strategies allow better body stability to counteract the external perturbation and as a consequence, result in smaller EMG activity and substantially smaller displacements of COMy, COMz and COP observed within the CPA time windows (Figure 9). In turn, smaller peaks of COM and COP displacements (PCOMy, PCOMz and PCOP) can be observed after the perturbations (Figure 11).

2.5 **Conclusion**

The outcome of this study highlights the importance of a relationship between APAs and CPAs in control of posture, and points out the effectiveness of optimally utilizing APAs in postural control. While examining the patterns of muscle activation between the anticipatory and compensatory periods of postural control, differences were found in the magnitude and sequence of muscle activation dependent on an availability of APAs. Unpredictable perturbations, that were not associated with any anticipatory activity, induced large compensatory muscle activity, large compensatory changes in the angular positions of the ankle, knee, and hip joints, and larger displacements of the COM followed by displacements of the COP. In contrast, APAs seen in conditions with predictable perturbations (as the EMG activity in the leg and trunk muscles) initiated COP displacements, resulting in better arrangement of the body position prior to the impact; this led to smaller compensatory COP-COM excursions and smaller displacements in the lower extremities joint angles after the impact.

The outcome of this study provides additional knowledge about how body balance is controlled in presence or in absence of information about the forthcoming perturbation. Since a significant number of individuals with neurological disorders and the elderly have difficulties in maintaining their balance, rehabilitation approaches focused on better use of anticipatory postural adjustment might benefit such individuals.

CHAPTER III

ANTICIPATORY CONTROL OF POSTURE IN OLDER ADULTS

3.1 **Background**

3.1.1 **Balance Control in the Elderly**

Performance of successful movements requires efficient control of posture and balance. The relationship between posture, balance and intentional movements is particularly important in the elderly population where a generalized decrease in balance control is accompanied by an increased frequency of movement related falls (Rogers et al. 1992). The ability to maintain balance is also fundamental to the performance of all activities of daily living (ADL) and in essence it shadows human mobility. This relationship between balance control and independent mobility on the whole is vital in the older adults where poor postural control is associated with significant mobility losses (Frank and Patla 2003), physical inactivity and an increase in the fear of falling (Skelton and Beyer 2003). Both, impaired mobility and physical inactivity, are predictors of subsequent dependence, depressive symptoms, institutionalization, and death in men and women aged 65 and older (Guralnik et al. 1995; Hirvensalo et al. 2000; Lampinen and Heikkinen 2003). Mobility-impaired and physically inactive people are at a greater risk of death (2 to 3 times) and dependence (odds ratio being 2.92 to 5.21) than those with intact mobility (Hirvensalo et al. 2000). The scientific knowledge underlying balance rehabilitation in the elderly can be improved through a better understanding of the mechanisms of postural control. A large percentage of individuals requiring balance rehabilitation are treated with conventional rehabilitation strategies, which do not address anticipatory postural control strategies that the CNS uses to preserve body balance. This is partly due to the lack of understanding of such feed-forward mechanisms of postural control.

Age-related changes in systems that contribute to postural control are reflected in the ability to maintain or re-establish balance in the standing position. For instance, older adults show increased spontaneous sway while standing, especially when two or more sensory inputs are eliminated or distorted. Following unexpected perturbations, there is a delay in the onset latencies of postural muscles and more time is needed to stabilize the center of pressure (COP) position. In contrast to young individuals, the elderly tend to use more of a hip strategy and show patterns of increased co-activation of agonist-antagonist muscles. Older adults tend to have difficulties in sensing the onset of perturbations as well (an increase in the threshold of perturbation recognition) and therefore, a limited response capacity (Woollacott and Shumway-Cook 1990). Balancing reactions such as rapid stepping or reaching movements that are critical for preventing falls are also impaired in healthy older adults (Maki and McIlroy 2006).

3.1.2 Anticipatory Postural Adjustments in the Elderly

As is with reactive responses, anticipatory postural adjustments also get modified with increasing age.

A. Onset of Anticipatory Muscle Activity

It was demonstrated that APA activity associated with self generated body perturbations is significantly delayed in the healthy elderly, with postural muscles being recruited closer to the activation of prime mover muscles (Man'kovskii NB 1980; Inglin and Woollacott 1988; Rogers et al. 1992) or after prime mover activation (Woollacott and Manchester 1993). A parallel worsening of the quality of performance of the motor task was also observed with an increase in the frequency of loss of balance (Man'kovskii NB 1980). In addition, under particular movement conditions, tibialis anterior muscle was found to have significant delay in APA onset in the elderly; whereas the onset latency for gastrocnemius muscle did not significantly differ between the younger and older groups (Inglin and Woollacott 1988). These findings were found to be similar to the aging effects noticed for postural responses to external perturbations, suggesting the similarity of organization of postural adjustments to both focal movements and external perturbations.

B. ***Muscle Activation Patterns***

The classic distal to proximal muscle activation pattern was found to be disrupted in the elderly. A study on push and pull arm movements reported that contrary to the classical activation pattern seen in young subjects, older subjects exhibited patterns where either the distal and proximal muscles were activated on opposite body aspects (for push movements), or patterns where only distal muscles were activated (for pull movements) (Inglin and Woollacott 1988). A newer study involving the arm raising paradigm under different conditions has shown that in the self-paced condition, elderly subjects use a hip strategy as compared to the young who use an ankle strategy. In addition, with the triggered condition, the strategy involves an increased activation of certain thigh muscles, rather than a sequence modification. The authors concluded that lack of stability induced by delayed postural preparation in the elderly is compensated for by different muscle strategies (Bleuse et al. 2006).

C. ***Recruitment of Postural Muscles***

Aging, however, does not seem to affect anticipatory recruitment of postural muscles (Rogers et al. 1992; Garland et al. 1997; Bleuse et al. 2006). Elderly subjects have been found to recruit their lower limb and trunk muscles prior to a focal movement as frequently as (96-100% of trials) the young subjects (Rogers et al. 1992). Thus, it seems that deficits in postural control with aging do not appear to be due to an absence of APAs, which have otherwise been found to be sometimes absent in neurological conditions of the aged such as Parkinson's disease.

D. ***<u>Changes in Biomechanical Parameters</u>***

Investigation of APAs in elderly, focusing on center of pressure (COP) excursion speed, found no statistical difference between the elderly and young groups (Garland et al. 1997). Although, the elderly subjects showed two subgroups of arm accelerations; one similar to the younger subjects (higher accelerations) and the other overlapping with the individuals with hemiplegia (low accelerations); they showed no differences in their COP excursion speeds for the two arm accelerations. A recent study involving the arm raising paradigm under different conditions found, that voluntary movements were associated with an early COP backward shift and an anticipatory vertical torque (T_z) in the young subjects (Bleuse et al. 2006). However, in the elderly, at maximal velocity, T_z was delayed in all conditions (self-paced with and without load and externally triggered), whereas COP latency was reduced only in the self-paced condition without load. At low velocity, however, elderly subjects did not show any impairment in stability.

E. ***<u>Voluntary Movement Performance</u>***

Performance of rapid push and pull reaction time arm movements resulted in the elderly subjects showing large significant increases in the onset latencies of the voluntary (prime mover) muscles in comparison to young adults (Inglin and Woollacott 1988). Experiments using the rapid arm raising paradigm, demonstrated prolonged movement times and reduced peak arm accelerations in the elderly as compared to the younger group for both, self-paced (Rogers et al. 1992; Garland et al. 1997) and reaction time movements (Rogers et al.

1992). However, contrasting findings have been reported by some other researchers. When asked to perform arm raising movements at different velocities, results showed that there were no statistical differences between the elderly and the younger groups. That is, for a given velocity both the groups showed similar movement performance.

3.1.3 **Aging Mechanisms**

The possible mechanisms through which aging may affect anticipatory control of posture have also been looked at. In a study involving rapid arm raising task under self-paced and reaction time conditions, the elderly did not show any particular trend of APAs occurring earlier for self-paced movements as compared to reaction time movements, which is generally seen in younger subjects. It was suggested that the older adults may be unable to reorganize their responses so as to presumably take advantage of the greater temporal certainty of task initiation of self-paced versus reaction time movements. Alternatively, it was also suggested that the elderly may have selected to maintain a less variable response strategy than that for younger subjects (Rogers et al. 1992). Another group of researchers found that for rapid pull arm movements, the difference between the younger and older groups in muscle onset latencies was greater for complex reaction time arm movements than for simple (Inglin and Woollacott 1988).

Analysis of neurological impairments in the older subjects demonstrated a strong correlation between those adults showing sub-clinical neural deficits and those with abnormal muscle response characteristics (Woollacott and Manchester 1993). Findings of a recent study on APAs related to predictive perturbations and concurrent cognitive task, suggested that postural control seems to be less automated in the elderly and becomes insufficient during very challenging perturbations (Laessoe and Voigt 2007). Age related morphological and biochemical changes are known to occur in the neural structures implicated in preparatory postural adjustments (Massion 1992). Therefore, the above mentioned deviations in the postural muscle responses in the elderly could be considered as a reflection of age related modifications in the central nervous system structures controlling posture.

3.1.4 **Are Modifications Due to Aging?**

Early results on APAs in elderly gave rise to two main different findings. Delay only in postural muscle response onsets led to a shortening of the time interval between postural muscle and prime mover recruitment (Man;kovskii NB 1980; Rogers et al. 1992). On the other hand, some researchers found delays in both postural and prime mover muscle response onset latencies, but with larger delays in the prime mover response latency, leading to a lengthening of the time interval (Inglin and Woollacott 1988).

This discrepancy in results led investigators to question, whether the changes in APAs seen in the elderly are due to the direct effect of aging or does the aging process slow down voluntary movements, which in turn affect APAs. Investigations involving the arm raising paradigm performed under different velocities have shown that older adults maintain arm velocities comparable to young adults (Woollacott and Manchester 1993; Bleuse et al. 2006). The authors thus concluded that any alterations in APAs could be attributed to the direct effects of aging and velocity is not a mediating variable between age and lack of postural preparation (Woollacott and Manchester 1993). In addition, these researchers found delay only in the onset of postural muscle response and not the focal muscle. Their results are thus similar to previous findings by other researchers (Man;kovskii NB 1980; Rogers et al. 1992) which show a shortening of the postural-voluntary onset difference.

Differences in the postural support conditions and mechanical disturbances to balance, due to variations in the task used, have been considered to be responsible for the conflicting results (shortening versus lengthening of time interval) (Rogers et al. 1992; Woollacott and Manchester 1993). In the push-pull paradigm some postural support may have occurred through the use of a noncompliant handle resulting in inadequate body perturbation and simplification of muscle responses. Whereas, the arm raising paradigm does not allow subjects to use any external support and may therefore be more destabilizing to the body, thereby eliciting differences in muscle onset latencies between the elderly and young individuals.

Although some researchers have shown that performance of voluntary movement is not affected in the elderly as compared to young individuals, others have found that elderly subjects perform focal movements with prolonged time. This inconsistency could be attributed to different testing paradigms (push and pull, arm rising under self-paced or reaction time conditions) and measurement variables (onset latencies, movement times, arm velocity or acceleration).

Some authors have found that, when older individuals were asked to perform focal movements at a comfortable slow speed, a strong correlation between postural activity and local movement existed and they performed the motor task confidently (Man;kovskii NB 1980). However, such correlation decreased when movements were required to be performed rapidly, leading to deterioration of performance of the motor task. It was speculated that given these findings, older individuals may perform motor tasks advantageously slowly so as to achieve optimal postural preparation. Also, studies demonstrating similar movement performance between the elderly and younger groups found that despite this result, differences existed across muscle and velocity conditions between the two groups (Woollacott and Manchester 1993). This indicates that some effect of voluntary performance due to aging may still exist.

The understanding of APAs in the elderly is therefore obscured by two main contrasting issues: whether lack of adequate postural activity affects movement performance or whether impaired anticipatory activity in the elderly are dependent on the movement quality? This contradiction could be attributed to the fact that almost all of the previous investigations involved self generated body perturbations (such as push and pull, arm raising under self-paced or reaction time conditions, etc), where velocity of the voluntary movement may have acted as a mediating variable between aging and postural preparation. In order to have a clear understanding of how aging affects the organization of APAs, it is essential to distinguish the influence of voluntary movement performance and postural preparation.

3.1.5 **Effect of Ageing on the Interaction between Anticipatory and Compensatory Mechanisms of Balance Control**

In view of the fact, that one of the functional goals of both APAs and CPAs is to minimize the body's COM displacement, comprehending the effect of aging on the interplay between these two mechanisms of control is vital. Recently, we studied APA utilization in subsequent control of posture using an experimental paradigm (pendulum impact paradigm) that allowed triggering predictable and unpredictable external perturbations of the same magnitude while the level of generation of the anticipatory postural adjustments was manipulated (section 2.2.2. Experimental Set-up and Procedure, Chapter II). It was found that an unavailability of APAs resulted in huge compensatory muscle activation and greater COM-COP displacements whereas utilization of robust APAs was associated with significantly smaller compensatory muscle activation and COM-COP displacements. As such, these findings highlight the importance of APAs in control of posture, and point out the existence of a relationship between anticipatory and compensatory components of postural control.

While such an association is established in the healthy young adults, little is known about how aging affects the interaction between these two mechanisms of postural control. Therefore, age-related implications on the relationship between APAs and CPAs in balance control need to be examined. While an impairment of anticipatory postural control in the older adults (delayed/reduced APAs) has been demonstrated, it is not specifically known how these changes influence the functional interaction of APAs and CPAs in controlling the body's COM displacement. Inability of the older adults to optimally generate postural adjustments prior to an upcoming balance threat as well as possible impairment of the interaction between the two mechanisms of postural control in the elderly (the CNS of an elderly individual may have difficulties in assessing the effect of involvement of the APAs in control of posture) may put additional demands on their postural control system, thereby, placing them at a greater risk for losing balance.

Thus, the first aim (Experiment 2) of this study was focused on investigating the differences in anticipatory postural adjustments between young and older adults and its effect on subsequent control of posture. We hypothesized that APAs in older adults will be delayed and reduced in magnitude and will be associated with the presence of large CPAs. As a result, peak COP and COM displacements will be larger in older than young adults.

A second aim (Experiment 3) of this study focused on examining the interaction between anticipatory and compensatory mechanisms of balance control in healthy older adults. We hypothesized that (similar to young adults): 1) during an unpredictable perturbation (no vision condition), APAs will be absent; only large CPAs will be observed. As a result, large peak COP and COM displacements will occur and 2) during a predictable perturbation (full vision condition), APAs will be present. As a result, smaller CPAs and smaller peak COP and COM displacements will be seen.

3.2 **Methods**

3.2.1 **Subjects**

Thirteen healthy young adults (7 males and 6 females) and ten healthy older adults (6 males and 4 females) without any neurological or musculoskeletal disorders participated in the study. The mean age of the young adults group was 26.69 ± 3.72 years; mean body mass 68.10 ± 13.61 kg, and mean height 1.74 ± 0.09 m. The mean age of the older adults group was 69.9 ± 4.04 years; mean body mass 76.42 ± 17.39 kg, and mean height 1.70 ± 0.13 m. They all signed a written informed consent approved by the Institutional Review Board of the University of Illinois at Chicago.

3.2.2 **Experimental Set-up and Procedure**

The subjects were instructed to maintain upright stance while standing barefoot on the force platform with their feet shoulder width apart. The pendulum impact paradigm was used to perturb the subjects (for paradigm details refer to section 2.2.2 Experimental Set-up and Procedure, Chapter II). A load (mass, m = 3% of the subjects' body weight) was attached to the pendulum next to its distal end. The subjects were required to receive each pendulum impact with their hands, while their arms, wrists, and fingers were extended at the shoulder level (Figure 1), and to maintain their balance after the perturbation. Two experiments were conducted to test the two hypotheses. For experiment 2 (differences in APAs between young and older adults), both the groups received a series of perturbations while their eyes were open; the perturbations were thus predictable and hence elicited both, APAs and CPAs. For experiment 3 (APA-CPA interaction in older adults), only the older adults group was tested. There were two experimental conditions: 1) a series of perturbations were applied with eyes open and as such were predictable in their timing; "predictable perturbations" and 2) another series of perturbations were applied with eyes closed; "unpredictable perturbations". Two to three practice trials were given prior to each experimental condition. No advance warning of the impending perturbation was provided; instead, both the groups wore wireless headphones and listened to music in all the experimental conditions, to prevent them from obtaining auditory information about the moment of the pendulum release. For safety purposes in all the experiments, the subjects wore a harness (NeuroCom, USA) with two straps attached to the ceiling. Ten trials were performed in each experimental condition and the order of experimental conditions (predictable and unpredictable) was randomized for the second experiment. All participants were allowed to have rest periods as needed.

3.2.3 **Instrumentation**

The details of the instrumentation used for the experiments conducted in this chapter are same as in the section 2.2.3 Instrumentation, described in Chapter II. Kinematic data were collected at 100 Hz, while forces, moments of force, EMG, and accelerometer signals were acquired at 1000 Hz by means of the VICON 612 data station (Oxford Metrics) that controlled data collection of all signals. The only difference is in the number of muscles that were recorded. EMG activity of muscles was recorded from the thirteen right lower limb and trunk muscles: soleus (SOL), lateral gastrocnemius (GASL), medial gastrocnemius (GASM), tibialis anterior (TA), rectus femoris (RF), vastus medialis (VM), vastus lateralis (VL), biceps femoris (BF), semitendinosis (ST), gluteus medius (GMED), external oblique (EO), rectus abdominis (RA), and erector spinae longus (ESL).

3.2.4 **Data Processing**

The data were analyzed off-line using MATLAB (MathWorks, Natick, MA) programs. Five to seven trials per condition were used for further analysis. EMG signals were rectified and filtered with a 100 Hz low-pass, 2nd order, zero-lag Butterworth filter, while the ground reaction forces, moments, COM and joint angles were filtered with a 40 Hz low-pass, 2nd order, zero-lag Butterworth filter. The 'time-zero' (T_0=0, moment of pendulum impact) was calculated from the accelerometer signal as a point in time at which the signal exceeded 5% of the maximum acceleration. This value was confirmed by visual inspection by an experienced researcher. Data in the range from -600 ms (before T_0) to +1000 ms (after T_0) were selected for further analysis. Individual trials were aligned according to T_0 and this was used as a common reference point for all the signals.

The muscle onset or muscle latency (beginning of activation/inhibition) for each trial was detected in a time window from -250 ms to +250 ms in relation to T_0 by a combination of computer algorithm and visual inspection of the trials. The latency for a specific muscle was defined as the instant lasting for at least 50 ms when its EMG amplitude was greater (activation) or smaller (inhibition) than the mean ± 2 SD of its baseline value, measured from -500 to -400 ms. The onset latencies for each muscle were then averaged across the trials within each condition for each subject.

Integrals of anticipatory and compensatory EMG activity were derived using average trials for each subject. Integrals of the EMG activities (Int_{EMG_i}) were calculated for 4 different epochs, each of 150 ms duration in relation to T_0. The time windows for the 4 epochs were: 1) from -250 ms to -100 ms (anticipatory reactions, APA1); 2) -100 ms to +50 ms (anticipatory reactions, APA2); 3) +50 ms to 200 ms (compensatory reactions, CPA1); and 4) + 200 ms to 350 ms (late compensatory reactions, CPA2), (for more details refer to section 2.2.4 Data Processing, described in chapter II). The $Int_{EMG\,i}$ for each of the 4 epochs was further corrected by the EMG integral of the baseline activity from -600 ms to -450 ms in relation to T0 as described below:

$$Int_{EMG\,i} = \int_{tw_i} EMG - \int_{-600}^{-450} EMG \qquad (1)$$

where Int_{EMGi} is the integral of EMG activity of muscles inside each 150 ms epoch tw_i, $i=1, .., 4$, and $\int_{-600}^{-450} EMG$ is the 150 ms background muscle activity defined as the integral of EMG signal from -600 ms to -450 ms with respect to T_0. Then integrals of EMG activity were normalized by the peak muscle activity across all conditions within an experiment.

$$IEMG_{NORM} = \frac{Int_{EMG_i}}{IEMG_{\max}} \qquad (2)$$

This was done for each muscle for each subject. Due to the normalization, all the integral values ($IEMG_{NORM}$) were within the range from +1 to -1. Positive values indicate an activation of the muscle, while negative values indicate a decrease in the background activity (inhibition).

Analysis of kinematic and kinetic data is the same as detailed in the section 2.2.4 Data Processing, described in Chapter II. Additional calculations are described below. The average COP, COM, and angular displacements for each of the four epochs were not calculated for the experiments in this and the next two chapters. Instead, the displacement and velocity of COP, COM, and joint angles at T_0 which is anticipatory in nature and the peak displacement (maximum displacement after T_0) that is compensatory in nature was calculated. Please note that the greater is the value of peak displacement during the compensatory postural control, the larger is the postural instability. The time at which the peak displacement occurred were also calculated for each of the variables. These measures indicated the individuals' balance control ability after the perturbations.

3.2.5 **Statistical Analysis**

Statistical analysis was performed in SPSS 17 for Windows XP (SPSS Inc., Chicago, USA). Means with standard errors are reported. For experiment 2, for $IEMG_{NORM}$, separate 2 x 4 split-plot ANOVAs were performed for each muscle. Group (2 levels: young and older adults) was a between subject factor and epoch (4 levels: APA1, APA2, CPA1, and CPA2) was a within-subject factor. When group x epoch interactions were significant, one-way ANOVA with Tukey's Honestly Significant Difference (HSD) test was used for post hoc comparisons. To compare the latencies of individual muscles between the two groups, an independent t-test was used. Independent t-tests were also performed for comparing displacements and velocities of COP, COM at T_0 and at peak, and time of peak displacements between the two groups.

For experiment 3 for $IEMG_{NORM}$, separate 2 x 4 repeated measures ANOVAs were performed for each muscle. There were two within-subject factors: condition (2 levels: predictable and unpredictable) and epoch (4 levels: APA1, APA2, CPA1, and CPA2). When condition x epoch interactions was significant, paired t-tests with Bonferroni's correction were used for post hoc comparisons. A paired t-test was used for comparison of latencies of individual muscles between the two experimental conditions (predictable and unpredictable). Paired t-tests were also used for comparing displacements and velocities of COP, COM at T_0 and at peak, and time of peak displacements between the two experimental conditions (predictable and unpredictable). Statistical significance was set at $p < 0.05$ for all tests except for the post-hoc comparisons performed for $IEMG_{NORM}$. When post-hoc comparisons were performed for investigating the differences in $IEMG_{NORM}$ between the two conditions across each epoch, Bonferroni's correction was applied such that $p < 0.012$ was considered statistically significant. When post-hoc comparisons were performed for investigating the differences in $IEMG_{NORM}$ between the four epochs within a given condition, Bonferroni's correction was applied such that $p < 0.008$ was considered statistically significant.

3.3 **Results**

A. **Experiment 2 (Differences in Anticipatory Postural Adjustments between Young and Older Adults)**

3.3.1 **Onset of Muscle Activity (Muscle Latency)**

Overall, for all the thirteen muscles recorded, onset of anticipatory postural activity in older adults was delayed as compared to young adults. Thus, APA activity in older adults occurred close to the moment of perturbation and the difference between the two groups was statistically significant for seven muscles, namely: SOL, GASM, BF, ST, GMED, RA, and ESL (Figure 13).

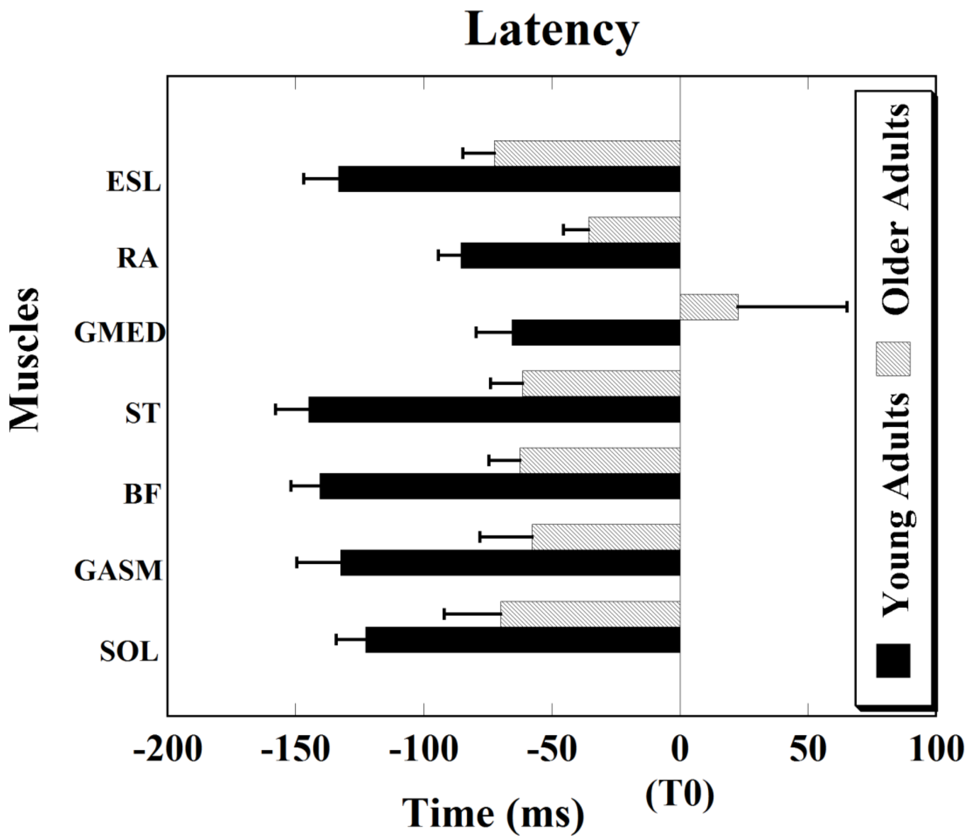

Figure 13. Muscle activity onsets. Note that for older adults the onset of muscle activity was delayed (close to the moment of perturbation (T_0)) as compared to the young adults. Muscles abbreviations: SOL-soleus, GASM-medial gastrocnemius, BF- biceps femoris, ST-semitendinosis, GMED- gluteus medius, RA- rectus abdominis, and ESL- erector spine longus. Differences in latencies are significant for all muscles shown, $p < 0.05$.

The onset of APA activity for the two groups was as follows: SOL (young adults: -122.65 ± 11.43 ms, older adults: -69.96 ± 22.02 ms, $p = 0.03$); GASM (young adults: -132.33 ± 17.12 ms, older adults: -57.61 ± 20.48 ms, p = 0.01); BF (young adults: -140.48 ± 11.35 ms, older adults: -62.45 ± 12.02 ms, p < 0.001); ST (young adults: -144.91 ± 12.80 ms, older adults: -61.45 ± 12.38 ms, p < 0.001); GMED (young adults: -65.55 ± 13.90 ms, older adults: 22.66 ± 42.60 ms, p = 0.03); RA (young adults: -85.40 ± 8.81 ms, older adults: -35.69 ± 9.64 ms, p < 0.01);

ESL (young adults: -133.31 ± 13.37 ms, older adults: - 72.36 ± 12.36 ms, $p < 0.01$). The overall order of activation of muscles for both the groups was from distal to proximal.

3.3.2 **Integrated Electromyographic Activity**

A significant main effect of group was seen for normalized integrals of EMG activity ($IEMG_{NORM}$) in four muscles, namely: RF ($p = 0.01$), VM ($p < 0.01$), VL ($p < 0.05$), and ESL ($p < 0.01$). The main effect was such that anticipatory muscle activity was smaller and compensatory muscle activity was larger in older adults as compared to young adults. Young adults, on the other hand, had larger APAs and smaller CPAs. Specifically, the group x epoch interaction was significant for GASM ($p = 0.02$), ST ($p = 0.04$), and was close to significance for ESL ($p = 0.05$) muscles (Figure 14).

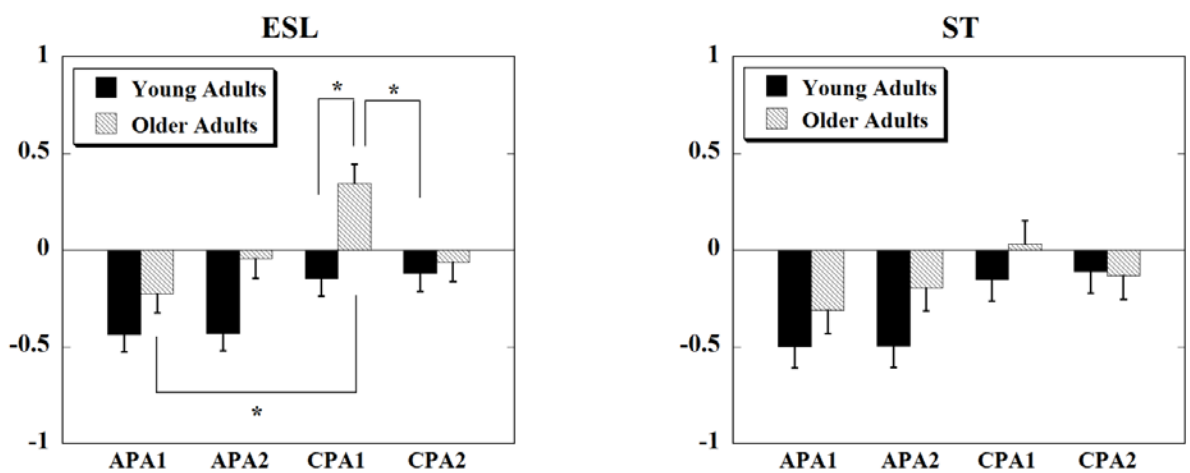

Figure 14. Normalized integrated EMG activities during the four epochs (APA1, APA2, CPA1, and CPA2) are shown for the ESL (erector spinae longus) and ST (semitendinosis) muscles for young and older adults. Positive values indicate an activation of the muscle, while negative values indicate a muscle inhibition. * denotes $p < 0.05$.

Post-hoc analysis demonstrated that in older adults, for ESL muscle, the inhibitory activity during APA1 epoch was significantly smaller than the burst of muscle activity during the CPA1 epoch ($p < 0.01$). Also, the APA1 and APA2 epochs were smaller in older adults than in young adults; however, the effects were not significant. Moreover, older adults had larger compensatory muscle activation during the CPA1 epoch than the inhibitory activity seen in young adults during the same epoch ($p = 0.01$). The CPA1 epoch in older adults was also significantly larger in magnitude than the CPA2 epoch in young adults ($p = 0.02$).

3.3.3 **Displacements and Velocities of Center of Pressure and Center of Mass**

Figures 15 and 16 depict the displacements of COP and COM respectively, at T_0 and the peak displacements after T_0 for the two groups. It can be seen that the anticipatory COP displacement (at T_0) in older adults (17.62 ± 2.21 mm) was smaller than that in young adults (20.99 ± 1.25 mm). At the same time, the peak displacement was larger in older adults (39.12 ± 3.22 mm) than young adults (33.51 ± 2.45 mm). The COP moved in the posterior direction (i.e. in the direction of perturbation) prior to the perturbation and continued moving in the same direction after the perturbation for both, young and older adults.

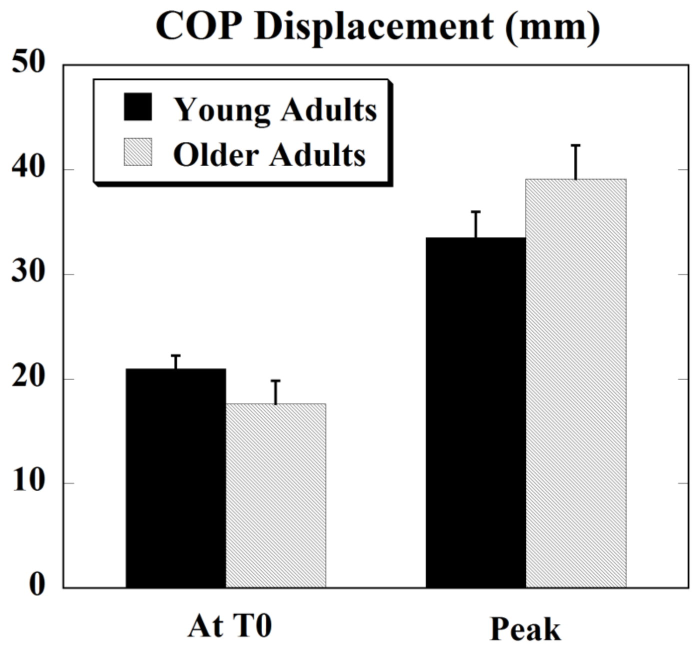

Figure 15. Displacement of COP at T_0 (anticipatory) and peak displacement (after T_0, compensatory) for young and older adults. Positive values indicate displacement in the posterior/backward direction.

The anticipatory COM displacement was of similar magnitude between the two groups. However, while the COM moved forwards (i.e. opposite to the direction of perturbation) in preparation for the impact in young adults (similar to the findings in Chapter II), it moved backwards (i.e. in the direction of perturbation) in older adults. The peak COM displacement was larger for the older adults (25.13 ± 2.36 mm) than the young adults (20.04 ± 1.79 mm) and the COM moved backwards (i.e. in the direction of perturbation) after the impact in both the groups. The differences in COP and COM displacements were, however, not significant between the two groups.

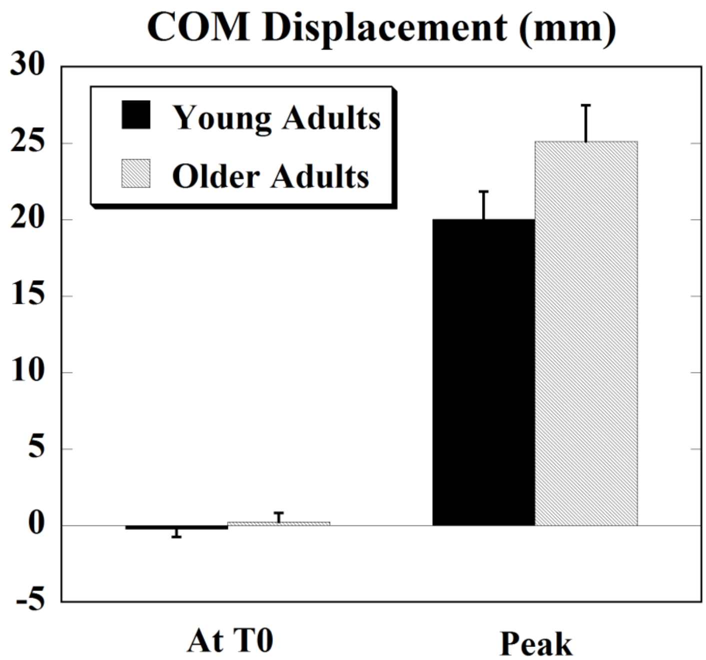

Figure 16. Displacement of COM at T_0 (anticipatory) and peak displacement (after T_0, compensatory) for young and older adults. Positive values indicate displacement in the posterior/backward direction and negative values indicate displacement in the anterior/forward direction.

The COP was the first to reach its peak after the perturbation for both the groups. The time of the peak COP displacement for young adults was 227.11 ± 26.28 ms and for older adults it was 313.14 ± 48.54 ms after T_0. The COM reached its peak after the COP; its times were 511.6 ± 2.46 ms for young adults and 564.2 ± 3.30 ms after T_0 for older adults (Figure 17). The time when the COP and COM variables reached their peaks was not significantly different between the young and older adults.

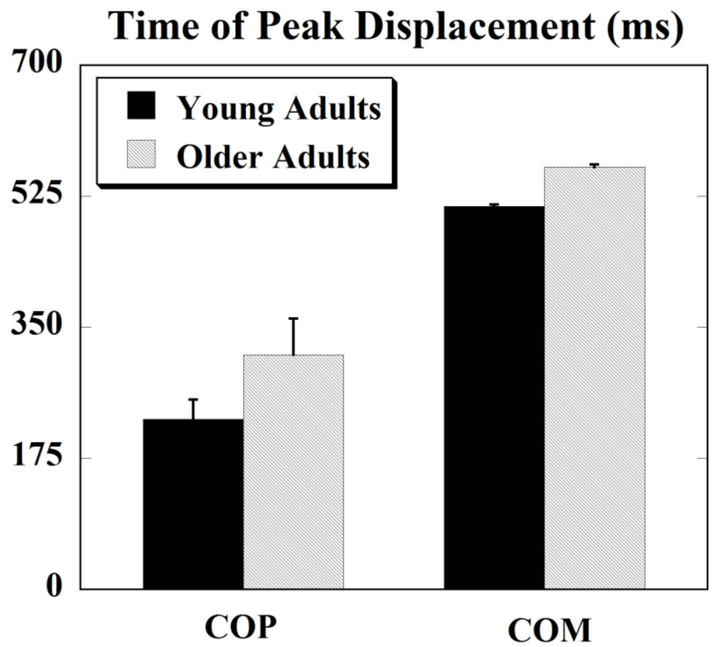

Figure 17. Times at which COP and COM reached their peak displacements after the perturbation for young and older adults.

Figures 18 and 19 depict the velocities of COP and COM respectively, at T_0 and the peak velocities after T_0 for the two groups. It can be seen that the anticipatory COP velocity (at T_0) in older adults (0.132 ± 0.024 mm/ms) was higher than that in young adults (0.091 ± 0.015 mm/ms). At the same time, the peak velocity was also larger in older adults (0.009 ± 0.005 mm/ms) than young adults (0.0004 ± 0.001 mm).

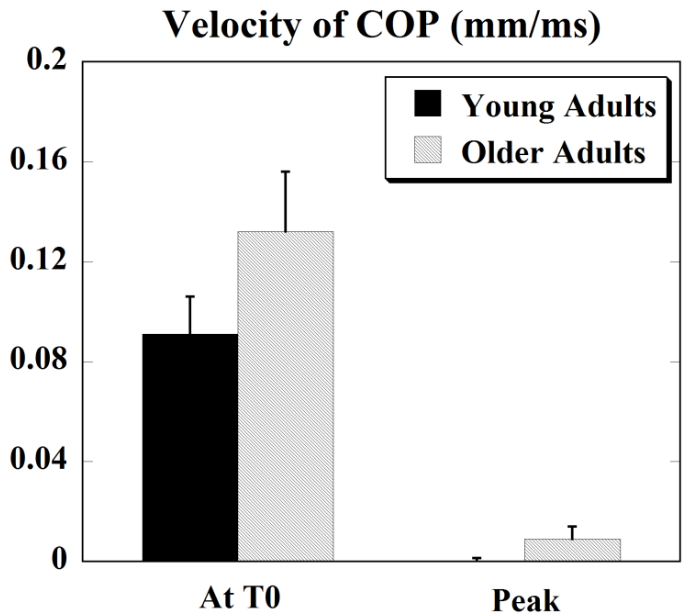

Figure 18. Velocity of COP at T_0 (anticipatory) and peak velocity (after T_0, compensatory) for young and older adults. Positive values indicate movement in the posterior/backward direction.

The anticipatory COM velocity was slower in older adults (0.392 ± 0.052 mm/ms) as compared to the young adults (0.417 ± 0.033 mm/ms). However, the peak COM velocity was higher in older adults (0.014 ± 0.005 mm/ms) than young adults (0.0003 ± 0.004 mm/ms). The differences in COP and COM velocities were, however, not significant between the two groups.

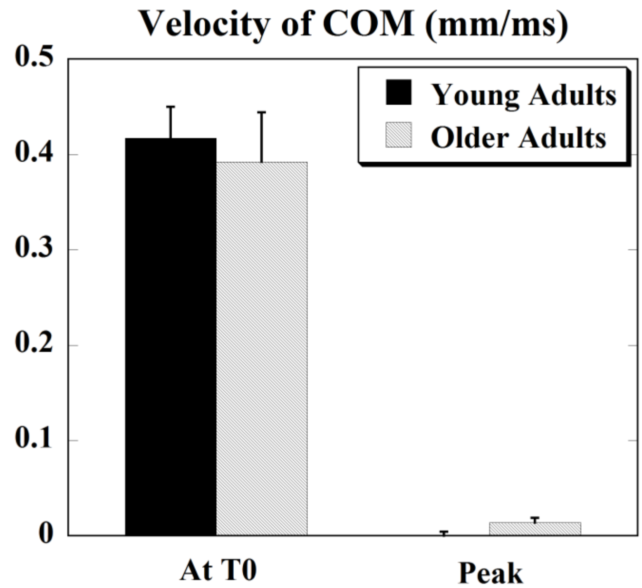

Figure 19. Velocity of COM at T_0 (anticipatory) and peak velocity (after T_0, compensatory) for young and older adults. Positive values indicate movement in the posterior/backward direction.

B. **Experiment 3 (Interaction between Anticipatory and Compensatory Postural Adjustments in Older Adults)**

3.3.4 **Onset of Muscle Activity (Muscle Latency)**

In conditions with the predictable perturbations, onset of EMG activity was seen before the pendulum impact in all the studied muscles, except for GMED (Figures 20 and 21). The APA activity in GMED muscle (22.66 ± 42.60 ms) occurred after the perturbation in older adults, although the condition was predictable. The sequence of muscle activation in the predictable conditions was from distal to proximal for the dorsal muscles; however a clear pattern was not seen for the ventral muscles where the knee extensors were activated before the distal and proximal muscles. In the dorsal muscles, GASL and SOL were the first muscles to be inhibited with latencies at -76.5 ± 16.14 ms and -69.95 ± 22.02 ms before the perturbation, respectively. This was followed by inhibition in the BF (-62.45 ± 12.02 ms) and ST (-61.45 ± 12.38 ms) muscles. The activity in the GASM and ESL muscles did not follow the sequence of activation; their inhibition occurred at -44.12 ± 17.80 ms and at -72.36 ± 12.36 ms, respectively. In the ventral muscles, RF, VM, and VL were the first muscles to be activated with latencies at -86.98 ± 12.50 ms, -86.33 ± 28.73 ms, and -84.16 ± 28.22 ms before the perturbation, respectively. This was followed by anticipatory activation in the EO (-73.33 ± 11.67 ms), TA (-57.58 ± 16.53 ms), and RA (-35.69 ± 9.64 ms) muscles.

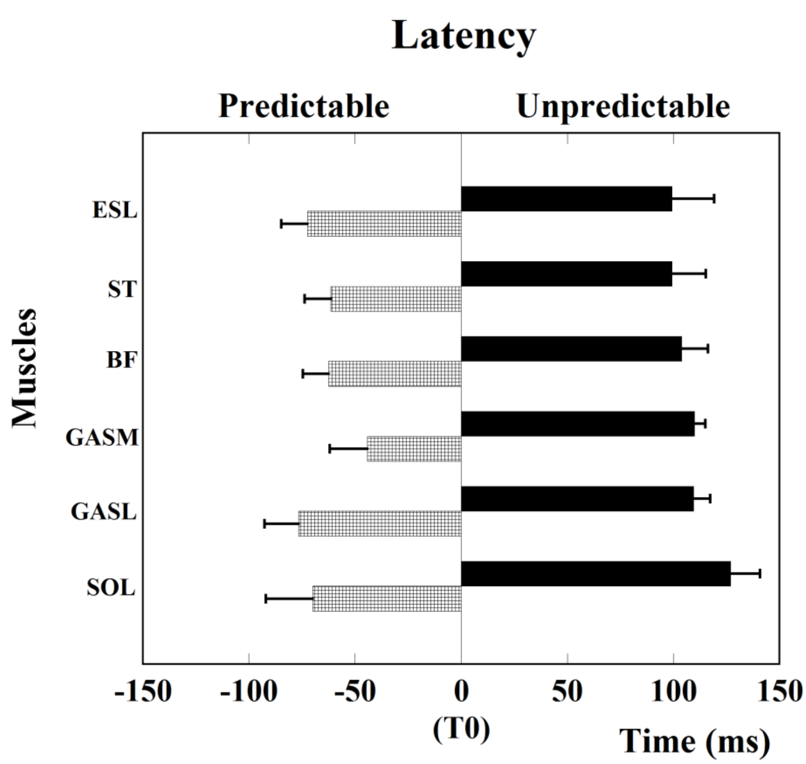

Figure 20. Muscle activity onsets for dorsal muscles. Note that for predictable perturbations the onset of muscle activity occurred prior to the perturbation (T_0). In case of unpredictable perturbations, the muscle onsets occurred after the perturbation. Muscles abbreviations: SOL- soleus, GASL-lateral gastrocnemius, GASM-medial gastrocnemius, BF- biceps femoris, ST- semitendinosis, and ESL- erector spinae longus. Differences in latencies are significant for all muscles shown, $p < 0.01$.

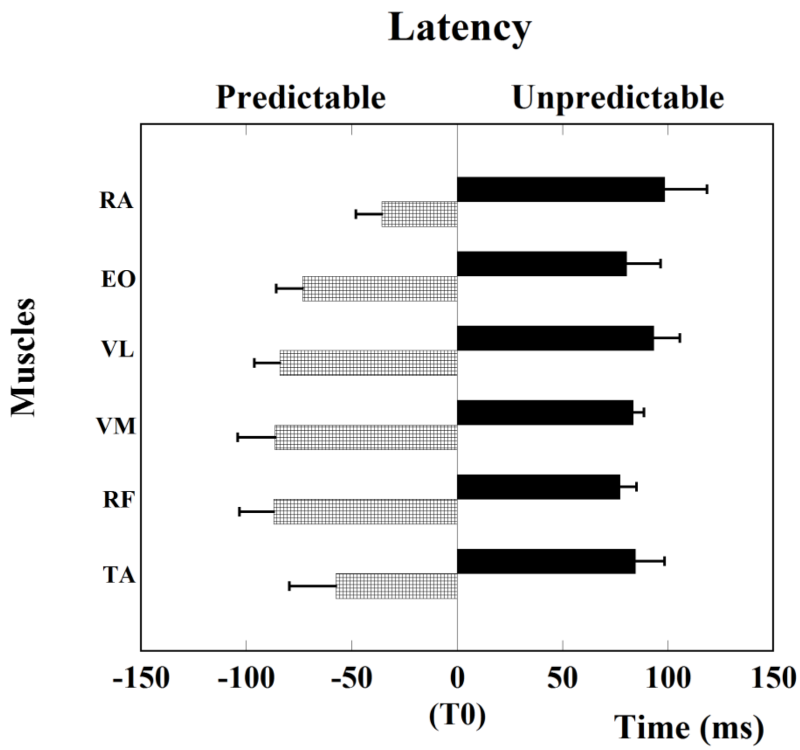

Figure 21. Muscle activity onsets for ventral muscles. Note that for predictable perturbations the onset of muscle activity occurred prior to the perturbation (T_0). In case of unpredictable perturbations, the muscle onsets occurred after the perturbation. Muscles abbreviations: TA-tibilais anterior, RF-rectus femoris, VM-vastus medialis, VL-vastus lateralis, EO-external oblique, and RA-rectus abdominis. Differences in latencies are significant for all muscles shown, $p < 0.01$.

None of the thirteen studied muscles showed changes in their background activity before the pendulum impact during the series with the unpredictable perturbations; instead, all the muscles became active after the perturbation impact. The sequence of activation of muscles was from proximal to distal in the dorsal muscles; however a distinct pattern was not seen in the ventral muscles. In the dorsal muscles, ESL and ST were the first muscles to show compensatory activity with onsets at 99.33 ± 20.01 ms and 99.29 ± 16.05 ms after the perturbation, respectively. This was followed by onsets in BF (103.97 ± 12.35 ms), GASL (109.61 ± 7.88 ms), GASM (109.84 ± 5.22 ms), and SOL (126.98 ± 13.93 ms) muscles. In the ventral muscles, RF was the first to get activated at 77.37 ± 3.34 ms, followed by EO at 80.88 ± 2.75 ms, VM at 83.63 ± .31 ms, TA at 84.51 ± 5.05 ms, VL at 93.37 ± 6.31 ms, RA at 98.60 ± 9.88 ms, and GMED at 112.38 ± 9.44 ms after the perturbation. The differences in the latencies of muscles between predictable and unpredictable conditions were statistically significant for all muscles, except GMED ($p < 0.01$).

3.3.5 **Integrated Electromyographic Activity**

Figures 22 and 23 show integrals of EMG activity ($IEMG_{NORM}$) during predictable and unpredictable perturbations. A significant main effect for condition x epoch interaction was seen for the $IEMG_{NORM}$ in seven muscles, namely: TA ($p < 0.001$), RF ($p < 0.001$), VM ($p < 0.001$), VL ($p < 0.001$), RA ($p < 0.01$), EO ($p < 0.001$), and GMED ($p < 0.001$). In the series with unpredictable perturbations, $IEMG_{NORM}$ observed prior to the perturbation onset during both the APA1 and APA2 epochs were negligible for all the muscles. Instead, large $IEMG_{NORM}$ could be seen after the pendulum impact. On the other hand, in series with predictable perturbations, larger $IEMG_{NORM}$ were observed prior to the perturbation onset during both the APA1 and APA2 epochs in most of the muscles. At the same time, smaller $IEMG_{NORM}$ were seen after the pendulum impact. Similar patterns of muscle activity were seen for the GASM, BF, and ST muscles, however, the differences between conditions were not significant.

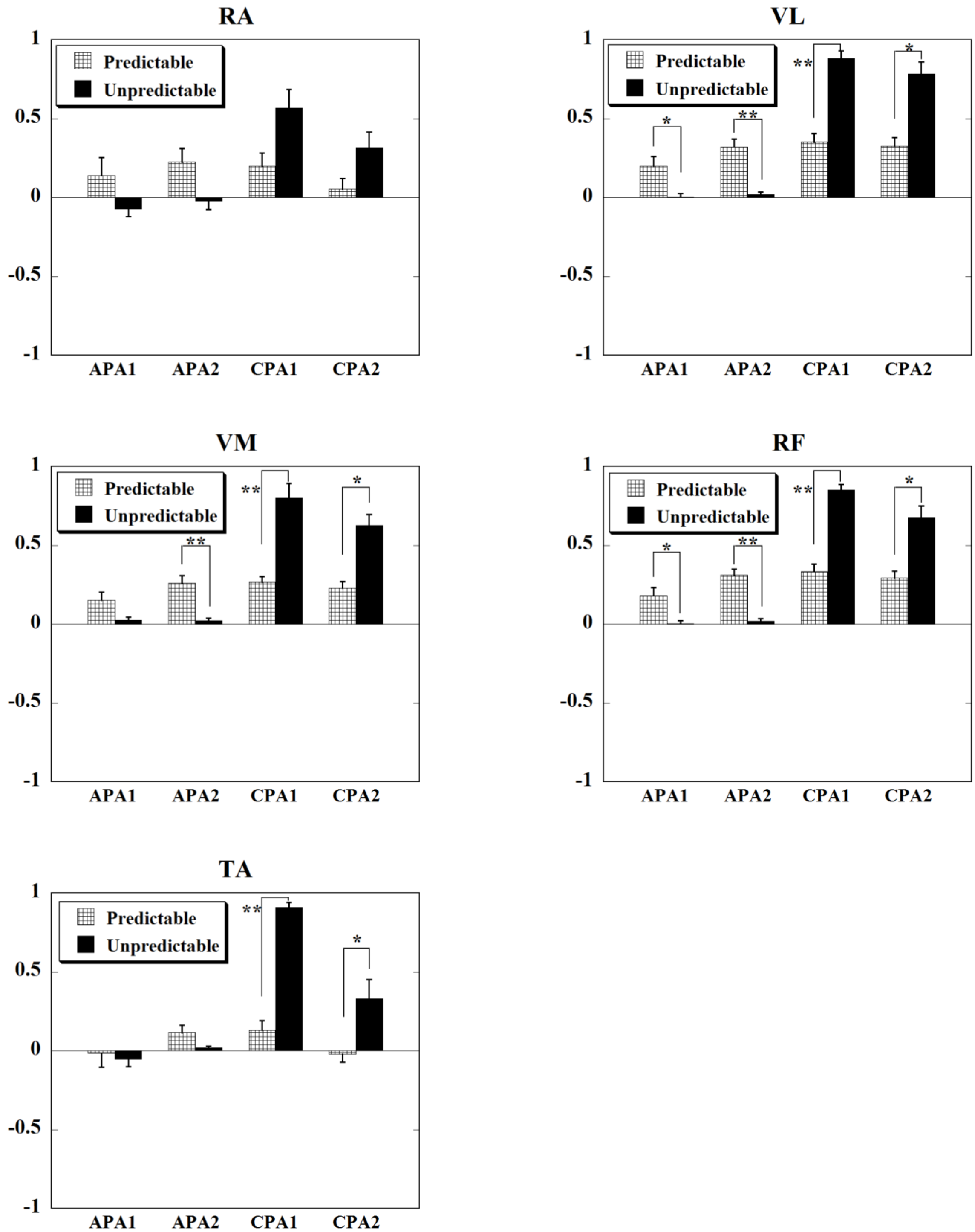

Figure 22. Normalized integrated EMG activities in older adults during the four epochs (APA1, APA2, CPA1, and CPA2) are shown for the ventral muscles: TA (tibialis anterior), RF (rectus femoris), VM (vastus medialis), VL (vastus lateralis), and RA (rectus abdominis). Positive values indicate an activation of the muscle, while negative values indicate a muscle inhibition. * denotes $p < 0.01$ and ** denotes $p < 0.001$.

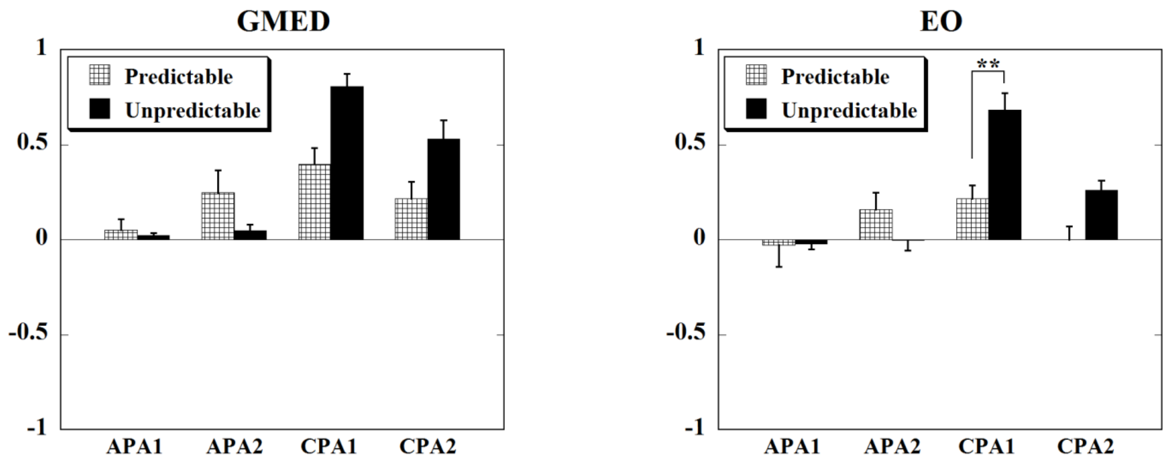

Figure 23. Normalized integrated EMG activities in older adults during the four epochs (APA1, APA2, CPA1, and CPA2) are shown for the lateral muscles: GMED (gluteus medius) and EO (external oblique). Positive values indicate an activation of the muscle, while negative values indicate a muscle inhibition. ** denotes $p < 0.001$.

Post-hoc analysis revealed significant differences for five muscles. The $IEMG_{NORM}$ during the APA1 epoch for the unpredictable condition was significantly smaller than the predictable condition for RF ($p < 0.01$) and VL ($p = 0.01$) muscles, whereas during the APA2 epoch, the same pattern was significant in RF ($p < 0.001$), VM ($p < 0.001$), and VL ($p < 0.001$) muscles. For the RA muscle, the difference in the anticipatory muscle activity between the two conditions was close to significance for the APA2 epoch ($p = 0.015$). Consequently, the $IEMG_{NORM}$ during the CPA1 epoch for the unpredictable condition was significantly larger than for the predictable condition for TA ($p < 0.001$), RF ($p < 0.001$), VM ($p < 0.001$), VL ($p < 0.001$), and EO ($p < 0.001$) muscles, whereas during the CPA2 epoch, the same pattern was significant in TA ($p < 0.01$), RF ($p < 0.01$), VM ($p < 0.01$), and VL ($p < 0.01$) muscles. For the RA and GMED muscles, the difference in the compensatory muscle activity between the two conditions was close to significance for the CPA1 epoch ($p = 0.017$ for both the muscles).

Post-hoc analysis comparing the four epochs within the unpredictable condition showed that, the $IEMG_{NORM}$ during both, the APA1 and APA2 epochs, was significantly smaller (negligible) than that during both, the CPA1 and CPA2 epochs, for RF, VM, VL,RA, EO, and GMED muscles ($p < 0.001$ for all comparisons) and significantly smaller than only the CPA1 epoch for TA muscle ($p < 0.001$). Also for the unpredictable condition, the $IEMG_{NORM}$ during the CPA1 epoch was significantly larger than that during the CPA2 epoch for TA ($p < 0.001$) and EO ($p = 0.001$) muscles.

Post-hoc analysis comparing the four epochs within the predictable condition showed that, the $IEMG_{NORM}$ during the APA2 epoch was significantly larger than that during the CPA2 epoch for the EO muscle ($p = 0.005$) and the muscle activity for GMED during the APA1 epoch was smaller than the CPA1 epoch ($p = 0.009$, close to significance). Also for the predictable condition, the $IEMG_{NORM}$ during the CPA1 epoch was significantly larger than that during the CPA2 epoch for TA and RA muscles ($p = 0.001$ for both the muscles).

3.3.6 **<u>Displacements and Velocities of Center of Pressure and Center of Mass</u>**

Figures 24 and 25 depict the displacements of COP and COM respectively, at T_0 and the peak displacements after T_0 for the predictable and unpredictable conditions. It can be seen that there was minimal anticipatory COP displacement (at T_0) during unpredictable condition (-1.62 ± .00 mm) as compared to the predictable condition (17.62 ± 2.21 mm); the difference was statistically significant ($p < 0.001$). At the same time, the peak displacement was larger (almost 1.5 times greater) for the unpredictable perturbation (64.36 ± 5.97 mm) than for the predictable perturbation (39.12 ± 3.22 mm); the difference was also statistically significant ($p = 0.019$).

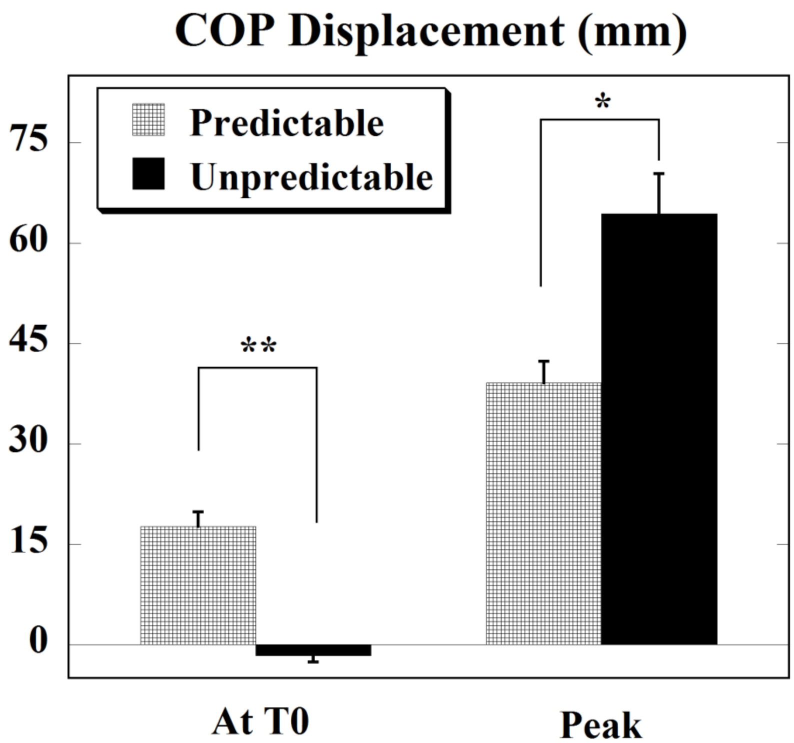

Figure 24. Displacement of COP at T_0 (anticipatory) and peak displacement (after T_0, compensatory) for predictable and unpredictable conditions in older adults. Positive values indicate displacement in the posterior/backward direction and negative values indicate displacement in the anterior/forward direction. ** denotes $p < 0.001$ and * denotes $p < 0.05$.

The anticipatory COM displacement for unpredictable condition (2.82 ± 0.65 mm) was higher than that for predictable condition (0.23 ± 0.60 mm); the difference was close to significance ($p = 0.05$). The peak COM displacement was significantly larger for the unpredictable condition (35.41 ± 2.61 mm) as compared to the predictable condition (25.13 ± 2.36 mm); the difference was statistically significant ($p < 0.001$). During the predictable condition, the COP moved in the posterior direction (i.e. in the direction of perturbation) prior to the perturbation and continued moving in the same direction after the perturbation (similar to the young adults in Chapter II). However, the COM moved backwards (i.e. in the direction of perturbation) prior to the perturbation (as opposed to movement in the forward direction, in preparation for the impact in young adults) and continued moving in the same direction after the impact (similar to the young adults in Chapter II). During the unpredictable condition, the COP moved slightly forwards (i.e. opposite to the direction of perturbation) prior to the impact and then moved backwards (i.e. in the direction of perturbation) after the impact, whereas the COM moved backwards prior to the impact (similar to young adults in Chapter II) and continued moving in the same direction after the impact.

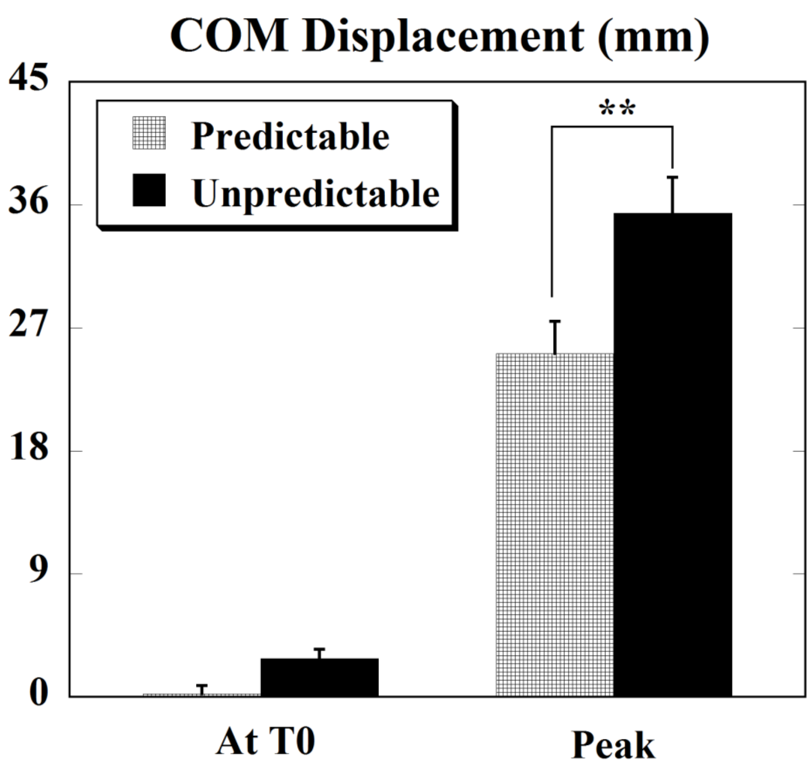

Figure 25. Displacement of COM at T_0 (anticipatory) and peak displacement (after T_0, compensatory) for predictable and unpredictable conditions in older adults. Positive values indicate displacement in the posterior/backward direction. ** denotes $p < 0.001$.

The COP was the first to reach its peak after the impact for both, unpredictable and predictable perturbations. The time of the peak COP displacement for unpredictable perturbation was 345.14 ± 36.85 ms and for predictable perturbation it was 313.14 ± 48.54 ms after T_0. The COM reached its peak after the COP; its times were 510 ± 4.26 ms for unpredictable perturbation and 564.3 ± 3.30 ms after T_0 for predictable perturbation. The time when the COP and COM variables reached their peaks was not significantly different between the two conditions (similar to young adults in Chapter II).

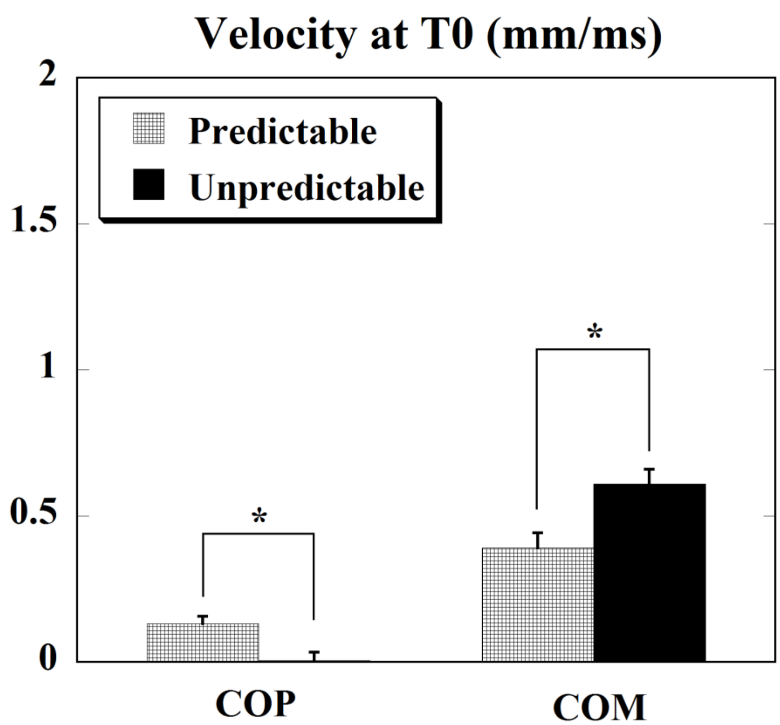

Figure 26. Anticipatory velocity (at T_0) of COP and COM for predictable and unpredictable conditions in older adults. Positive values indicate movement in the posterior/backward direction. * denotes $p < 0.05$.

Figure 26 depicts the anticipatory (at T_0) COP and COM velocity for the predictable and unpredictable conditions. It can be seen that the anticipatory COP velocity (at T_0) was significantly lower for the unpredictable perturbation (0.006 ± 0.027 mm/ms) than the predictable perturbation (0.132 ± 0.024 mm/ms) (p = 0.023). At the same time, the anticipatory COM velocity was significantly higher for the unpredictable perturbation (0.61 ± 0.05 mm/ms) as compared to the predictable perturbation (0.39 ± 0.05 mm/ms) (p = 0.022).

3.4 **Discussion**

This study was focused on investigating the differences in anticipatory postural adjustments between young and older adults and its effect on subsequent control of posture. An additional aim was to examine the interaction between anticipatory and compensatory mechanisms of balance control in healthy older adults. Overall, the study hypotheses were supported such that as compared to young adults, APAs in older adults were delayed and reduced in magnitude, resulting in larger peak COP and COM displacements after the perturbation. However, while, APAs were not optimally generated in older adults, their ability to utilize anticipatory postural adjustments in compensatory control of posture was retained.

3.4.1 **Differences in Anticipatory Postural Adjustments between Young and Older Adults**

Previous studies have used self-generated perturbations to study anticipatory postural activity in older adults. Overall, a delay in anticipatory postural activity was seen in older adults prior to the movement onset; however, several studies also found a delay in the onset of movement as well smaller peak accelerations of the movement (Man'kovskii NB 1980; Inglin and Woollacott 1988; Rogers et al. 1992; Woollacott and Manchester 1993; Garland et al. 1997).

The understanding of APAs in the elderly has therefore been obscured by two main contrasting issues: whether lack of adequate postural activity affects movement performance or whether impaired anticipatory activity in the elderly is dependent on the movement quality? This contradiction could be attributed to the fact that almost all of the previous investigations involved self generated body perturbations (such as push and pull, arm raising under self-paced or reaction time conditions, etc), where velocity of the voluntary movement may have acted as a mediating variable between aging and postural preparation. In order to have a clear understanding of how aging affects the organization of APAs, it is essential to distinguish the influence of voluntary movement performance from postural preparation. To this end, the pendulum-impact paradigm which generates external predictable perturbations used in this study, allowed investigating the direct effect of ageing on anticipatory postural activity without the influence of age-related changes in voluntary movement performance.

In the present study, anticipatory muscle activity was significantly delayed in older adults as compared to young adults, such that the muscles were either activated or inhibited very close to the moment of perturbation. In fact, the GMED muscle was activated only after the impact, although the perturbation was predictable. Similarly, previous studies have demonstrated that APA activity associated with self generated body perturbations is significantly delayed in the healthy elderly, with postural muscles being recruited closer to the activation of prime mover muscles (Man'kovskii NB 1980; Inglin and Woollacott 1988; Rogers et al. 1992) or after prime mover activation (Woollacott and Manchester 1993). Apart from the muscles onsets, the magnitude of muscle activity during the two APA epochs was also smaller in older adults. This was associated with large magnitudes of compensatory muscle activity (during CPA1 epoch) in older than young adults.

Delayed and reduced anticipatory muscle activity in older adults was also associated with smaller anticipatory COP displacements, while the anticipatory COM displacement was of similar magnitude between the two groups in this study. This resulted in larger peak displacements of both, the COP and COM, in older adults after the perturbation, indicating greater instability. A study involving the arm raising paradigm under different conditions found, that voluntary movements were associated with an early COP backward shift and an anticipatory vertical torque (T_z) in the young subjects (Bleuse et al. 2006). However, in the elderly, at maximal velocity, T_z was delayed in all conditions (self-paced with and without load and externally triggered), whereas COP latency was reduced only in the self-paced condition without load.

Moreover, in the present study, while the COM moved forwards (i.e. opposite to the direction of perturbation) in preparation for the impact in young adults (similar to the findings in Chapter II), it moved backwards (i.e. in the direction of perturbation) in older adults. Such impaired directional control in older adults, wherein the anticipatory movement of the COM was in the direction of the eventual perturbation, may have in fact contributed to the larger displacement after the disturbance. Thus, while the older adults had similar magnitude of anticipatory COM movement, it was not directionally specific, thereby augmenting the instability.

Thus, the findings of this study have demonstrated that ageing does directly affect the organization of anticipatory postural control in humans. Additionally, inadequate postural preparation in the elderly is associated with a need for larger compensatory muscle activity which may not be sufficient to overcome the impact of large perturbations. Thus, impaired postural preparation comes with a potential for loss of balance in older adults.

3.4.2 <u>**Interaction between Anticipatory and Compensatory Postural Adjustments in Older Adults**</u>

In the present study, although APA activity was delayed in older adults, all muscles except GMED showed at least some anticipatory muscle activity. Aging, thus, does not seem to affect anticipatory recruitment of postural muscles as has been demonstrated in previous studies (Rogers et al. 1992; Garland et al. 1997; Bleuse et al. 2006). Elderly subjects have been found to recruit their lower limb and trunk muscles prior to a focal movement as frequently as (96-100% of trials) the young subjects (Rogers et al. 1992). Thus, it seems that deficits in postural control with aging do not appear to be due to an absence of APAs, which have otherwise been found to be sometimes absent in neurological conditions of the aged such as Parkinson's disease. Moreover, the present study also illustrated the ability of older adults in utilizing APAs for postural control, when available. Thus when the perturbation was predictable, muscles were recruited prior to the perturbation, as opposed to being activated after the impact when the perturbation was unpredictable. Also, a distal to proximal sequence of anticipatory recruitment was maintained for the dorsal muscles in the older adults during the predictable perturbation (similar to findings in young adults described in Chapter II). The ventral muscles, however, depicted a different strategy wherein the knee extensor muscles were activated prior to the hip and leg muscles. Such, differences in anticipatory strategies have also been reported in the literature on self-generated perturbations (Inglin and Woollacott 1988). The authors concluded that lack of stability induced by delayed postural preparation in the elderly is compensated for by different muscle strategies. On the other hand, when the perturbation was unpredictable, the dorsal muscles in the older adults were recruited after the impact in a proximal to distal sequence (similar to findings in young adults described in Chapter II). However, the ventral muscles did not show a clear sequence of activation in older adults as opposed to the same proximal to distal sequence seen in young adults (Chapter II).

The interplay between the anticipatory and compensatory postural control mechanisms (in terms of magnitude of muscle activity) was also maintained in older adults and the relationship was similar to that observed in young adults (Chapter II). Thus for older adults, in the series with unpredictable perturbations, $IEMG_{NORM}$ observed prior to the perturbation onset during both the APA1 and APA2 epochs were negligible for all the muscles. Instead, large $IEMG_{NORM}$ could be seen after the pendulum impact, especially during the first compensatory phase (CPA1 epoch) when compared with the second compensatory phase (CPA2 epoch). On the other hand, in series with predictable perturbations, larger $IEMG_{NORM}$ were observed prior to the perturbation onset during both the APA1 and APA2 epochs (greater for APA2 epoch) in most of the muscles. At the same time, smaller $IEMG_{NORM}$ were seen after the pendulum impact.

Furthermore, during predictable perturbations a reciprocal pattern of activation was seen both, before and after T_0; dorsal muscles were generally inhibited whereas ventral and lateral muscles were activated. On the other hand, during unpredictable perturbations a co-activation pattern was seen during the CPA1 epoch between the thigh and the trunk muscle pairs, whereas during the CPA2 epoch a reciprocal pattern was seen (dorsal muscles inhibited and ventral and lateral muscles remained activated). The distal leg muscle pair showed more of a reciprocal strategy during the CPA1 and CPA2 epochs (SOL, GASM were inhibited and GASL and TA were activated). Increasing joint stiffness with co-activation of trunk and thigh muscles in response to a perturbation has been previously reported (Allum et al. 1989; Berger et al. 1992; Dimitrova et al. 2004). Thus, when the perturbations were unpredictable, the older adults chose to increase the stiffness of the upper body while a reciprocal strategy was used to control the ankle joint during the first compensatory phase. Thereafter, during the second compensatory phase, a reciprocal pattern was used across all the joints. Thus, it seems that in order to maintain the vertical head-trunk orientation during the unpredictable perturbation, older adults initially employed a more conservative strategy of increasing the trunk stiffness.

Larger compensatory reactions were seen during the unpredictable perturbations because these conditions were not associated with any anticipatory activity. However, when the perturbations were predictable, so that the subjects knew the timing of the perturbation, they generated strong APAs: this resulted in significantly smaller compensatory reactions. Changes in EMG activity were also associated with differences in COP and COM displacements between the two conditions. Thus, when anticipatory EMG activity was present (predictable perturbation), larger COP displacements were seen in preparation to the perturbation, whereas, COM movement was minimal. This was associated with significantly smaller peak COP and COM displacements after the perturbation. Thus, the observed changes in the electrical activity of muscles, COP, and COM displacements suggest that in spite of aging, the CNS of the older adults is capable of assessing the effect of involvement of the APAs and generates or scales down CPAs accordingly.

3.5 **Conclusion**

The process of aging affects an individual's ability to control posture putting him/her at an increased risk of suffering falls. Particularly anticipatory postural control which helps deal with body perturbations in a feedforward manner has been found to be affected in the elderly. This study demonstrated the direct effects of aging on anticipatory postural control in humans. Anticipatory postural adustments are delayed and reduced in magnitude in older adults as compared to young adults. Impaired generation of APAs is associated with larger compensatory muscle responses in older adults. However, in spite of such larger reactive responses, older adults are more unstable than young adults when exposed to similar perturbations. Nonetheless, while APAs are impaired in older adults, the ability to recruit muscles anticipatorily is largely preserved. In fact, the CNS of older adults is able to assess the presence of APAs and is capable of utilizing APAs (when available) to improve body stability. Thus, the age-related decline in control of posture is not due to an inability to utilize anticipatory postural adjustments, per se. Anticipatory postural adjustments are largely preserved in older adults, however, due to their smaller magnitudes and delayed onsets, it is likely that their effectiveness in reducing the magnitude of CPAs is smaller. As such, there is potential that training-related improvements in APAs of older adults may result in smaller magnitudes of compensatory muscle responses. The outcome of this study, therefore, lends support towards investigating the role of training in improving anticipatory postural control in people with balance impairments due to ageing or neurological disorders.

CHAPTER IV

IMMEDIATE EFFECTS OF TRAINING ON ANTICIPATORY POSTURAL ADJUSTMENTS IN BALANCE CONTROL OF HEALTHY YOUNG ADULTS

4.1 Background

Anticipatory postural control strategies are mostly acquired through learning and based on previous experience of the postural disturbance. A general process implies transformation of feedback postural correction in feed-forward control – an adaptive network builds up an internal image of the disturbance to be minimized or control needed to cancel it (Massion 1992). Anticipatory activity is seen as early as 4-6 months in children during reaching and sitting (van der Fits et al. 1999). By 13.5 months infants reach out for support in anticipation of a presumed perturbation during early walking whereas APAs in standing infants develop between 10-17 months and scaling occurs by 15 months. 4-6 yr olds demonstrate increased variability in APAs than 7-14 year olds who demonstrate more adult-like APAs (for details on development of APAs in children, see (Girolami et al. 2010).

For the longest period, it was considered that APAs are acquired only in preparation of a self-generated perturbation (commonly due to a voluntary movement). Anticipatory postural adjustments were considered to differ from CPAs because their organization was thought to be based on experience in performing intentional actions (Massion 1992). This has long been shown to be only partially correct. While APAs are certainly generated prior to an intentional motor action, they are also produced in preparation of an external predictable perturbation. Several studies including bimanual loading and unloading tasks, where the subject or an experimenter triggered the release of the load (or lifting of the load) onto the subject's hand/s have demonstrated the presence of anticipatory adjustments in the postural forearm and the trunk and leg muscles, even in the absence of an explicit voluntary movement (Massion 1992; Aruin et al. 2001; Shiratori and Latash 2001). It was concluded that, perturbations where the kinetic energy of the impact can be estimated through visual or proprioceptive cues will elicit the anticipatory adjustments. Likewise, perturbations that disturb the whole body (experiments with pendulum-impact paradigm) have also shown that APAs are generated in trunk and leg muscles based on an accurate prediction of the timing of perturbation through visual inputs (Santos and Aruin 2008b; Santos and Aruin 2009). Thus, APAs are generated prior to a perturbation that is “predictable”, irrespective of its internal or external origin.

While APAs are acquired based on previous experiences and learning, they are also capable of short-term adaptation in response to or to account for immediate environmental changes. Thus, APAs are scaled according to the actual or perceived level of body stability. For example, in experiments where a standard action initiated a standard perturbation, APAs were lowered in conditions of low initial stability (such as standing on a narrow beam or see-saw) and the magnitude of APAs was scaled according to the magnitude of postural instability. In some muscles the onset of activation was also delayed as the instability levels increased. Also, the effect of instability was stronger when the direction of perturbation coincided with the direction of instability (Gantchev and Dimitrova 1996; Aruin et al. 1998). In other experiments, where leg flexions were performed from initial bipedal and unipedal stance conditions, APAs were reduced when the initial conditions were unstable (unipedal stance) (Nouillot et al. 1992). This suppression of APAs was thought to be protective in nature, since APAs by definition are based on an approximation of the perturbation and they may act as a source of instability if inappropriately executed. Besides the presence of instability, it has been found that the nature of the instability is also important to the generation of APAs. If the instability is due to reduced base of support, APAs are reduced, however if the instability is due to reduced friction between the feet or shoes and the surface (such as standing on roller skates) or due to other causes that are not mechanical in nature (such as under conditions of muscle vibration that induce postural illusion), APAs are found to be increased in magnitude (Shiratori and Latash 2000; Slijper and Latash 2004). At the other extreme are the very high stable conditions, wherein APAs are found to be reduced as well, for example in sitting condition (Aruin and Shiratori 2003), or with an additional finger touch support during arm flexion in standing (Slijper and Latash 2000) or hand support during rocking on heels movement (Noe et al. 2003). In highly stable conditions, APAs would not be required to maintain equilibrium and they are therefore scaled down. These changes in APAs that occur immediately following modifications in the environmental factors are considered to be short-term adaptations based on sensory cues about the new environmental conditions (Massion 1992).

On the other hand, changes in feedforward postural strategies that are observed after several trials or after several days of exposure to new environmental conditions signify short-term learning related changes. For example, in experiments involving patients with low back pain, isolated voluntary contraction of the transverses abdominis muscle was found to cause early APA onset in this muscle during arm flexion movements immediately after a single training session (Tsao and Hodges 2007). With four weeks of such training early onsets were seen along with consistent activation of this muscle during walking as opposed to phasic activity prior to training. These effects were retained at six month follow up. Thus these studies show that motor adaptive changes in feed forward postural adjustments or APAs are possible with training (Tsao and Hodges 2008). While changes in APAs have been seen with training, it is not known how training-related modifications in anticipatory postural activity can affect the functional role of APAs, mainly control of equilibrium. Particularly, previous studies on training based changes in APAs have focused on the role of APAs with respect to perturbations that were self-initiated, either directly or indirectly (Massion et al. 1999; Tsao and Hodges 2007). It is not known how a short training session that involves a functional activity such as catching a ball may affect the generation of APAs prior to a predictable external perturbation and the effect of these enhanced APAs on subsequent balance control. Thus, the objective of this study was to investigate the immediate effects of a single training session in enhancing the utilization of anticipatory postural adjustments in balance control of healthy young adults. For experiment 4 conducted in this study, we hypothesized that early onset of anticipatory muscle activity will be observed with training. This will result in reduced COM and COP peak displacements following a predictable external perturbation.

4.2 **Methods**

4.2.1 **Subjects**

Thirteen healthy young adults (7 males and 6 females) without any neurological or musculoskeletal disorders participated in the study. The mean age of the group was 26.69 ± 3.72 years; mean body mass 68.10 ± 13.61 kg, and mean height 1.74 ± 0.09 m. They all signed a written informed consent approved by the Institutional Review Board of the University of Illinois at Chicago.

4.2.2 **Experimental Set-up and Procedure**

The subjects were instructed to maintain upright stance while standing barefoot on the force platform with their feet shoulder width apart. The pendulum impact paradigm was used to perturb the subjects (for paradigm details refer to section 2.2.2 Experimental Set-up and Procedure, Chapter II). A load (mass, *m* = 3% of the subjects' body weight) was attached to the pendulum next to its distal end. The subjects were required to receive each pendulum impact with their hands, while their arms, wrists, and fingers were extended at the shoulder level (Figure 1), and to maintain their balance after the perturbation. No advance warning of the impending perturbation was provided; instead, the subjects wore wireless headphones and listened to music in all the experimental conditions, to prevent them from obtaining auditory information about the moment of the pendulum release. Two to three practice trials were given prior to initial testing. The subjects received a series of predictable perturbations (eyes open) before (pre-training) and immediately after (post-training) a short training session. The training session consisted of 130 catches of a medicine ball thrown at the shoulder level from a distance of 3 m and lasted for about 20-25 minutes. The catches included the ball being thrown either directly towards the subjects' body midline or a little away from the midline on the right or the left side. The subjects' caught the ball while standing with feet shoulder width apart. Thus, the training session involved perturbations that were predictable (would generate both, APAs and CPAs) and similar to the testing paradigm (specificity of testing and training). A 2 or 4 lb medicine ball was used for subjects weighing below or above 120 lb, respectively. The weight of the ball and the number of catches was decided based on pilot experiments. For safety purposes in all the experiments, the subjects wore a harness (NeuroCom, USA) with two straps attached to the ceiling. Ten trials were performed in each experimental condition. All participants were allowed to have rest periods as needed.

4.2.3 Instrumentation

The details of the instrumentation used for the experiment conducted in this chapter are same as in the section 3.2.3 Instrumentation, described in Chapter III. Kinematic data were collected at 100 Hz, while forces, moments of force, EMG, and accelerometer signals were acquired at 1000 Hz by means of the VICON 612 data station (Oxford Metrics) that controlled data collection of all signals.

4.2.4 Data Processing

The details of the data processing used for the experiment conducted in this chapter are same as in the section 3.2.4 Data Processing, described in Chapter III. Muscle latency, normalized EMG integrals for four epochs, displacement and velocity of COP and COM at $T_{0,}$ peak displacement, and time of peak displacement were calculated.

4.2.5 Statistical Analysis

Statistical analysis was performed in SPSS 17 for Windows XP (SPSS Inc., Chicago, USA). Means with standard errors are reported. For $IEMG_{NORM}$, separate 2 x 4 repeated measures ANOVAs were performed for each muscle. There were two within-subject factors: experimental condition (2 levels: pre-training and post-training) and epoch (4 levels: APA1, APA2, CPA1, and CPA2). When condition x epoch interactions was significant, paired t-tests with Bonferroni's correction were used for post hoc comparisons. A paired t-test was used for comparison of latencies of individual muscles between the two experimental conditions (pre-training and post-training). Paired t-tests were also used for comparing displacements and velocities of COP, COM at T_0 and at peak, and time of peak displacements between the two experimental conditions (pre-training and post-training). Statistical significance was set at $p <$ 0.05 for all tests except for the post-hoc comparisons performed for $IEMG_{NORM}$. When post-hoc comparisons were performed for investigating the differences in $IEMG_{NORM}$ between the two conditions across each epoch, Bonferroni's correction was applied such that $p < 0.012$ was considered statistically significant. When post-hoc comparisons were performed for investigating the differences in $IEMG_{NORM}$ between the four epochs within a given condition, Bonferroni's correction was applied such that $p < 0.008$ was considered statistically significant.

4.3 **Results**

4.3.1 **Onset of Muscle Activity (Muscle Latency)**

Overall, after a single training session, postural activity in anticipation of the perturbation occurred earlier as compared to the pre-training condition in the young adults. The difference between the two conditions was statistically significant for six out of thirteen muscles, namely: SOL, RF, VM, VL, BF, and ST (Figure 27).

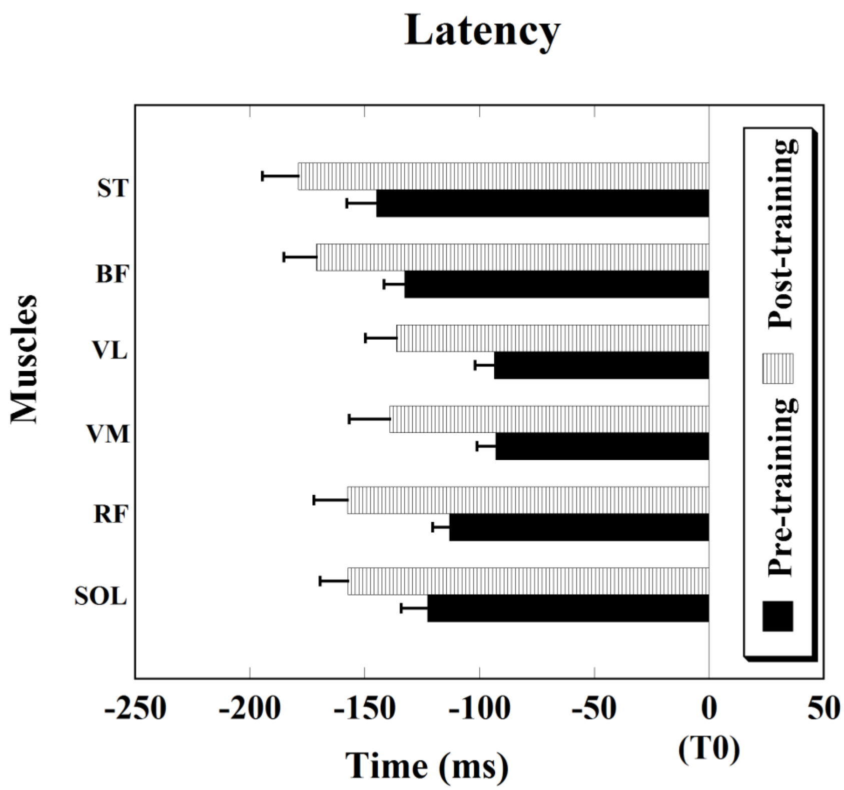

Figure 27. Muscle activity onsets. Note the early onsets of anticipatory postural activity (prior to the moment of perturbation (T_0)) after a single training session in young adults. Muscles abbreviations: SOL-soleus, RF – rectus femoris, VM – vastus medialis, VL – vastus lateralis, BF- biceps femoris, and ST-semitendinosis. Differences in latencies are significant for all muscles shown, $p < 0.05$.

The onset of APA activity before and after training was as follows: SOL (pre-training: -122.65 ± 11.43 ms, post-training: -157.26 ± 12.01 ms, $p = 0.02$); RF (pre-training: -113.04 ± 7.22 ms, post-training: -157.40 ± 14.68 ms, p = 0.03); VM (pre-training: -92.91 ± 7.98 ms, post-training: -138.95 ± 17.72 ms, p = 0.025); VL (pre-training: -93.42 ± 8.35 ms, post-training: -136.17 ± 13.56 ms, p = 0.047); BF (pre-training: -132.60 ± 8.89 ms, post-training: -171.02 ± 14.18 ms, p = 0.004); ST (pre-training: -144.91 ± 12.80 ms, post-training: -178.95 ± 15.58 ms, p = 0.016). Early APA onsets after training were also seen in GASM (pre-training: -144.17 ± 18.58

ms, post-training: -199.68 ± 19.88 ms, p = 0.071) and TA (pre-training: -86.69 ± 14.72 ms, post-training: -118.65 ± 19.83 ms, p = 0.076) muscles, and the differences were close to significance.

4.3.2 **Integrated Electromyographic Activity**

A significant condition x epoch interaction effect was seen for the TA muscle (p = 0.021). The interaction effect was close to significance for the VL muscle (p = 0.055). Post-hoc analysis demonstrated larger EMG activity during APA1 and APA2 epochs following training as compared to pre-training condition in the TA and VL muscles. In the VL muscle, higher APA activity was associated with lower compensatory activity during the CPA1 and CPA2 epochs following training. The post-hoc effects were, however, not statistically significant.

4.3.3 **Displacements of Center of Pressure and Center of Mass**

Figures 28 and 29 depict the displacements of COP and COM respectively, at T_0 and the peak displacements after T_0 for the two conditions. It can be seen that the anticipatory COP displacement (at T_0) following training (24.53 ± 1.57 mm) was significantly larger than before training (20.99 ± 1.25 mm) (p = 0.02). At the same time, the peak displacements were similar between the two conditions (before and after the training).

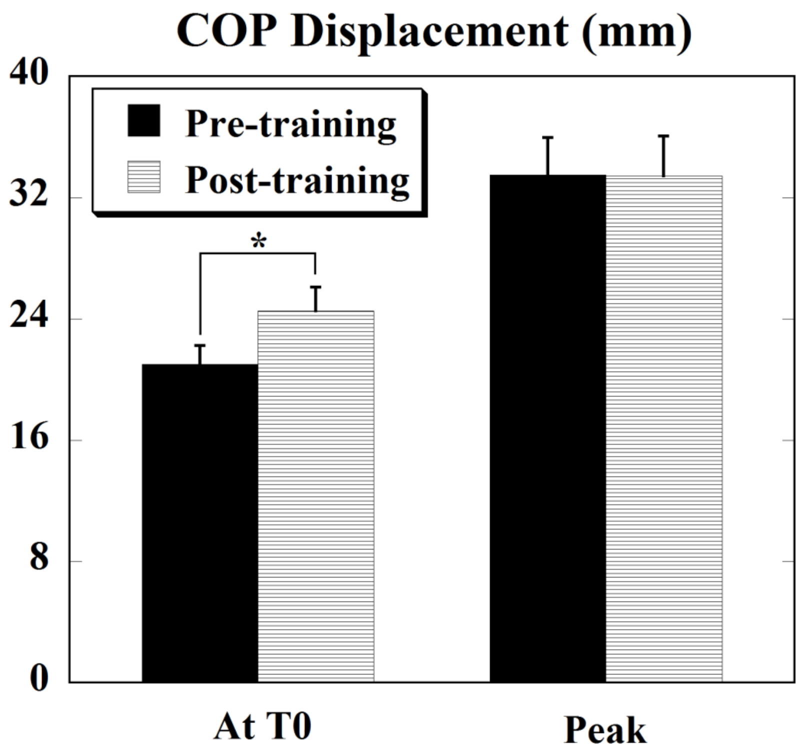

Figure 28. Displacement of COP at T_0 (anticipatory) and peak displacement (after T_0, compensatory) before (pre-training) and after (post-training) training. Positive values indicate displacement in the posterior/backward direction. * denotes $p < 0.05$.

The anticipatory COM displacement in the forward direction (i.e. opposite to the direction of perturbation) was greater following training (-1.04 ± 0.48 mm) as compared to the pre-training (-0.22 ± 0.52 mm) condition, the difference was, however, not statistically significant. This resulted in significantly smaller peak COM displacement following training (16.18 ± 2.30 mm) as compared to the peak displacement before training (20.04 ± 1.79 mm) ($p = 0.003$).

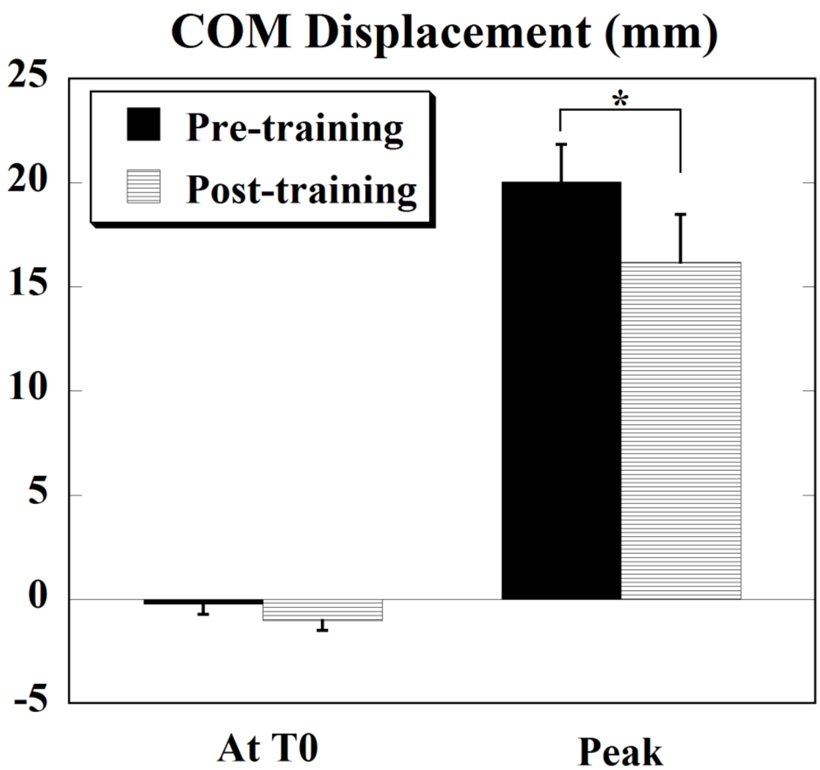

Figure 29. Displacement of COM at T_0 (anticipatory) and peak displacement (after T_0, compensatory) before (pre-training) and after (post-training) training. Positive values indicate displacement in the posterior/backward direction and negative values indicate displacement in the anterior/forward direction. * denotes $p < 0.01$.

4.4 **Discussion**

The present study was focused on examining the immediate effects of training on the utilization of anticipatory postural adjustments in balance control of healthy young adults. The findings of the study demonstrated the effectiveness of a single training session in enhancing anticipatory postural activity that results in greater postural stability following a perturbation.

After the training session, the anticipatory activity in young adults was earlier in the leg and thigh muscles; however, no changes were seen in the trunk muscles. Also, the magnitude of activity prior to the moment of perturbation was larger in two muscles (TA and VL). Such early onsets and greater magnitude indicate greater postural preparation in anticipation of the expected disturbance. As a result of larger preparation, smaller compensatory activity was required to deal with the destabilizing effects of the perturbation. Changes in EMG activity were also associated with changes in COP and COM displacements. Thus, following training larger displacements of the COP in the posterior direction and the COM in the anterior direction were observed in preparation of the forthcoming perturbation. As a result of this enhanced preparation, the eventual peak displacement of the body's COM after the impact was significantly smaller indicating improved postural stability.

In the past some studies have shown training related improvements in anticipatory postural activity in healthy individuals or in people with low back pain. One of the early studies by Pauligan and his group showed that healthy individuals could acquire APAs in their postural forearm during a load lifting task initiated by the opposite hand without a direct movement of the triggering hand after about 40 to 60 repetitions (Paulignan et al. 1989). However when the arms were switched, the acquisition was not transferred to the new postural forearm (Massion et al. 1999). In experiments involving patients with low back pain, isolated voluntary contraction of the transverses abdominis muscle was found to cause early APA onset in this muscle during arm flexion movements immediately after a single training session (Tsao and Hodges 2007) as opposed to training that involved sit-ups where all abdominal muscles were exercised as a group. Thus, these studies show that motor adaptive changes in feed forward postural adjustments or APAs are possible with training and changes in APAs depend on the type of motor training (Tsao and Hodges 2008). However, the previous studies conducted have shown improvements in APAs with respect to their role in stabilization of a postural segment or with respect to movement performance. Since APAs are known to play a significant role in whole body balance control and are also known to be impaired with aging (Inglin and Woollacott 1988; Rogers et al. 1992; Woollacott and Manchester 1993) and with neurological disorders such as stroke (Garland et al. 1997), Parkinson's disease (Latash et al. 1995), and multiple sclerosis (Krishnan et al. 2012; Krishnan et al. 2012); it is important to understand how training-related modifications in anticipatory postural activity can affect the functional role of APAs, mainly control of equilibrium following a perturbation. This study for the first time demonstrates that training involving a functional activity such as catching a ball that causes whole body predictable perturbation is capable of enhancing anticipatory postural activity in several trunk and leg muscles. Moreover, when exposed to a predictable but external perturbation, the improved anticipatory postural control is used more efficiently such that the compensatory postural responses are scaled down and greater postural stability is achieved.

4.5 **Conclusion**

This study has demonstrated that anticipatory postural activity prior to a predictable external perturbation can be augmented in healthy young adults. Training-related changes are reflected as early onsets and larger magnitude of APA activity as well as larger anticipatory COP displacements. Increased postural preparation is also accompanied by reduced magnitude of compensatory postural responses. The ability to utilize increased anticipatory activity is enhanced following training and is reflected in smaller displacements of COM after the perturbation, indicating greater postural stability. The outcome of the study suggests that training could be used in enhancement of APAs in individuals in need and as such provides a background for examining the role of training in enhancement of APAs in the elderly.

CHAPTER V

TRAINING-RELATED ENHANCEMENT OF ANTICIPATORY POSTURAL CONTROL IN OLDER ADULTS

5.1 Background

Bipedal stance in humans has stringent stability demands and is usually associated with maintenance of vertical orientation. The ability to maintain the body's center of mass (COM) over the base of support during quiet stance, movement, and in response to balance threats is one of the main goals of postural control (Hess et al. 2005). The integrity and efficiency of the postural control system eventually determines the ability to perform independent and safe movements. However, with increasing age this ability to maintain balance deteriorates. Sensory and motor resources required for postural stability and orientation decline with ageing. Proprioceptive and vestibular losses are associated with increased reliance on visual inputs, which itself is affected by the process of ageing. Reduction in muscle strength and power along with reduced joint mobility are some of the problems faced by the motor system. On top of this, there is poor integration of the sensory and motor systems at the higher levels. These changes affect the ability to resolve sensory conflicts and generate appropriate muscle responses in order to maintain or restore balance. Additionally, older adults are less active and this can lead to a detuning of the balance control system. It is likely that a lack of constant challenge along with systemic changes contribute to the deterioration of balance and mobility in older adults

(Frank and Patla 2003).

Age-related changes in systems that contribute to postural control are reflected in the ability to maintain or re-establish balance in the standing position. For instance, postural sway is larger in older adults, especially when two or more sensory inputs are conflicting. Following unexpected perturbations, there is a delay in the onset latencies of postural muscles and more time is needed to stabilize the COP movement. In contrast to young individuals, the elderly tend to use more of a hip strategy and show patterns of increased co-activation of agonist-antagonist muscles. Older adults tend to have difficulties in sensing the onset of perturbations as well (an increase in the threshold of perturbation recognition) and therefore, a limited response capacity (Woollacott and Shumway-Cook 1990). Balancing reactions such as rapid stepping or reaching movements that are critical for preventing falls are also impaired in healthy older adults (Maki and McIlroy 2006). As is with reactive responses, anticipatory postural adjustments (APAs) also get modified with increasing age. Postural muscle APA activity associated with self generated and external body perturbations is significantly delayed in the healthy elderly. The classic distal to proximal muscle activation pattern is disrupted, with a shift from an ankle to a hip strategy. However, the ability to recruit postural muscles anticipatorily (Man;kovskii NB 1980; Inglin and Woollacott 1988; Rogers et al. 1992; Woollacott and Manchester 1993) as well as utilization of APAs in subsequent control of posture is retained (as shown in Chapter III) in spite of other ageing effects . These impairments of balance control in the elderly are associated with higher falling rates and related injuries which lead to significant morbidity or death (Kannus et al. 1999). Loss of functional independence and reduced quality of life in the elderly, eventually amount to huge healthcare costs.

Several intervention programs have attempted to improve balance control in the healthy elderly. Since postural control is an emergent property, treatment paradigms have either targeted single or multiple sub-systems. Some training methods involve exercises that target different sub-systems of postural control. For example, a 12-month exercise program attempted to improve dynamic postural stability in older women (Lord et al. 1996). The training protocol included aerobic, balance, coordination, strengthening and stretching exercises performed twice weekly for four 10- to 12- week sessions. Post-intervention the exercise group showed significant improvements in maximum balance range and coordinated stability tests as compared to no changes in the control group. Improvements in coordinated stability were associated with corresponding improvements in strength of ankle dorsiflexors, hip flexors and extensors indicating some possible mechanisms of such changes.

Effects of another popular form of training, Tai Chi were compared with a low- intensity and low-impact exercise program consisting of simple stretching and breathing exercises, after a 6-month intervention period (Li et al. 2004). Tai Chi participants demonstrated significant improvements in measures of functional balance (Bergs Balance Score, Dynamic Gait Index and Functional Reach tests), with slower deterioration of improvements at 6 months follow-up. Also, during the 6-month post-intervention period there was a significant reduction in rate of falls for the Tai Chi group. Thus, improved functional balance gained through Tai Chi training was found to be associated with subsequent reductions in fall frequency in older individuals.

The ability of the central nervous system (CNS) to select pertinent sensory information and generate appropriate muscle responses, in other words sensorimotor integration, is affected by the process of ageing. Virtual reality (VR) is considered as a valuable therapeutic tool which provides an ideal environment very similar to the real world to understand the balance strategies employed by the CNS (Virk and McConville 2006). One such investigation attempted to study the effects of VR on balance control in the healthy elderly. Ageing was found to affect the interaction of somatosensory and visual systems on equilibrium control during standing and the ability of the CNS to resolve sensory conflicts. However, even with 1-hour immersion in virtual environment, the CNS was able to recalibrate and adapt to the changes, while improving balance control in older adults (Bugnariu and Fung 2007).

A 10-week study compared the effects of VR and biofeedback training on balance control in healthy elderly (Bisson et al. 2007). Significant improvements on the Community Balance and Mobility Scale were seen in both groups; which were retained at 4 weeks as well. Both training groups also had significant reductions in reaction time (during a dual task paradigm) but no changes in quiet stance postural sway, indicating that the task of postural control had become more automatic with training. This training effect was retained at the 4-week follow-up.

Most of the studies on balance rehabilitation in the elderly have demonstrated improvements in balance performance of the elderly as assessed by clinical measures of balance such as Berg Balance Scale, Dynamic Gait Index, and Activities-Specific Balance Confidence scale. While these measures provide useful information on the effectiveness of different interventions, they do not elaborate on the postural control mechanisms through which training-related improvements occur. A few studies have investigated the underlying changes in postural control strategies in older adults following different training approaches.

Muscular strength is known to decline with age and drops by up to 50% by age 70 years; this is associated with a decline in both the number and size of muscle fibers (Frank and Patla 2003). A number of interventions have tried to look at the effects of a muscle strengthening program on postural control. For example, following high intensity knee and ankle strength training, significant increases in ankle moments and ankle rate of torque production in response to unexpected platform perturbations have been observed (Hess et al. 2005).

The ability to quickly reweigh and select reliable sensory information when faced with conflicting sensory conditions is affected to a large extent in older adults. A training program designed to improve multisensory processing ability in the elderly, was found to have significant improvements in postural stability, when somatosensory inputs were changed or when two or more sensory systems were simultaneously manipulated (Hu and Woollacott 1994a). At 4 weeks follow-up, there was a decrease in the frequency of falls when ankle inputs were minimized and an increase in single-leg stance time. Moreover, after training in response to support surface translations, the onset latency of the neck flexor muscle was found to be significantly shortened (Hu and Woollacott 1994b). The authors suggested that this finding indicates that with training the interaction between the vestibular and the somatosensory systems in the elderly is more efficient. The results also support improvements in sensorimotor integration and the ability of elderly to reweigh and select reliable sensory inputs more efficiently following a period of training.

While, a few studies have investigated the mechanisms through which balance can be improved in the elderly, there are no studies investigating the effect of training on improvement of anticipatory postural control in the elderly. Moreover, no studies have been conducted on older adults that demonstrate training related improvements in APAs during standing balance control. It is known that APAs in older adults are delayed and reduced in preparation of a forthcoming perturbation (self-generated or external). Also, the findings of the previous chapter (Chapter III) have shown that as a result of impaired postural preparation, older adults have larger displacements of COP and COM following a perturbation. This indicates that they are more unstable even when the perturbations are predictable. Since APAs and anticipatory displacements of the COP are known to be delayed and reduced in the older adults, they would be forced to rely on corrective adjustments which by themselves are known to be delayed and reduced with aging (Horak et al. 1989b; Horak 2006). As a result older adults may be at a greater risk of losing balance due to inadequate use of anticipatory strategies. At the same time, our previous study also showed that the ability of older adults to utilize APAs in subsequent control of posture is maintained (Chapter III). In addition, the outcome of the study involving training of young adults (Chapter IV) suggests that utilization of APAs for postural control can be enhanced. Thus, it would be relevant to study the effect of training on the utilization of anticipatory postural adjustments in the elderly and whether training related improvements in APAs result in reduced COP and COM displacements following body perturbation. It is likely, that if APAs can be enhanced in older adults through training, it would lead to greater postural stability.

This study was thus aimed at investigating the immediate effects of a single training session in enhancing anticipatory postural control in healthy older adults. For experiment 5 conducted in this study, we hypothesized that with training, early onset and larger magnitude of anticipatory muscle activity will be observed prior to a perturbation. This will result in reduced COP and COM peak displacements following the perturbation.

5.2 Methods

5.2.1 Subjects

Ten healthy older adults (6 males and 4 females) without any neurological or musculoskeletal disorders participated in the study. The mean age of the group was 69.9 ± 4.04 years; mean body mass 76.42 ± 17.39 kg, and mean height 1.70 ± 0.13 m. They all signed a written informed consent approved by the Institutional Review Board of the University of Illinois at Chicago.

5.2.2 Experimental Set-up and Procedure

The subjects were instructed to maintain upright stance while standing barefoot on the force platform with their feet shoulder width apart. The pendulum impact paradigm was used to perturb the subjects (for paradigm details refer to section 2.2.2 Experimental Set-up and Procedure, Chapter II). A load (mass, m = 3% of the subjects' body weight) was attached to the pendulum next to its distal end. The subjects were required to receive each pendulum impact with their hands, while their arms, wrists, and fingers were extended at the shoulder level (Figure 1), and to maintain their balance after the perturbation. No advance warning of the impending perturbation was provided; instead, the subjects wore wireless headphones and listened to music in all the experimental conditions, to prevent them from obtaining auditory information about the moment of the pendulum release. Two to three practice trials were given prior to initial testing. The subjects received a series of predictable perturbations (eyes open) before (pre-training) and immediately after (post-training) a short training session. The training session consisted of 130 catches of a medicine ball thrown at the shoulder level from a distance of 3 m and lasted for about 20-25 minutes. The catches included the ball being thrown either directly towards the subjects' body midline or a little away from the midline on the right or the left side. The subjects' caught the ball while standing with feet shoulder width apart. Thus, the training session involved perturbations that were predictable (would generate both, APAs and CPAs) and similar to the testing paradigm (specificity of testing and training). A 2 or 4 lb medicine ball was used for subjects weighing below or above 120 lb, respectively. The weight of the ball and the number of catches was decided based on pilot experiments. For safety purposes in all the experiments, the subjects wore a harness (NeuroCom, USA) with two straps attached to the ceiling. Ten trials were performed in each experimental condition. All participants were allowed to have rest periods as needed.

5.2.3 **Instrumentation**

The details of the instrumentation used for the experiment conducted in this chapter are same as in the section 3.2.3 Instrumentation, described in Chapter III. Kinematic data were collected at 100 Hz, while forces, moments of force, EMG, and accelerometer signals were acquired at 1000 Hz by means of the VICON 612 data station (Oxford Metrics) that controlled data collection of all signals.

5.2.4 **Data processing**

The details of the data processing used for the experiment conducted in this chapter are same as in the section 3.2.4 Data Processing, described in Chapter III. Muscle latency, normalized EMG integrals for four epochs, displacement and velocity of COP and COM at $T_{0,}$ peak displacement, and time of peak displacement were calculated.

5.2.5 **Statistical Analysis**

Statistical analysis was performed in SPSS 17 for Windows XP (SPSS Inc., Chicago, USA). Means with standard errors are reported. For $IEMG_{NORM}$, separate 2 x 4 repeated measures ANOVAs were performed for each muscle. There were two within-subject factors:

experimental condition (2 levels: pre-training and post-training) and epoch (4 levels: APA1, APA2, CPA1, and CPA2). When condition x epoch interactions was significant, paired t-tests with Bonferroni's correction were used for post hoc comparisons. A paired t-test was used for comparison of latencies of individual muscles between the two experimental conditions (pre-training and post-training). Paired t-tests were also used for comparing displacements and velocities of COP, COM at T_0 and at peak, and time of peak displacements between the two experimental conditions (pre-training and post-training). Statistical significance was set at $p < 0.05$ for all tests except for the post-hoc comparisons performed for $IEMG_{NORM}$. When post-hoc comparisons were performed for investigating the differences in $IEMG_{NORM}$ between the two conditions across each epoch, Bonferroni's correction was applied such that $p < 0.012$ was considered statistically significant. When post-hoc comparisons were performed for investigating the differences in $IEMG_{NORM}$ between the four epochs within a given condition, Bonferroni's correction was applied such that $p < 0.008$ was considered statistically significant.

5.3 **Results**

5.3.1 **Onset of Muscle Activity (Muscle Latency)**

Overall, after a single training session, postural activity in anticipation of the perturbation occurred earlier as compared to the pre-training condition in the older adults. The difference between the two conditions was statistically significant for six out of thirteen muscles, namely: SOL, GASM, TA, BF, ST, and RA (Figure 30).

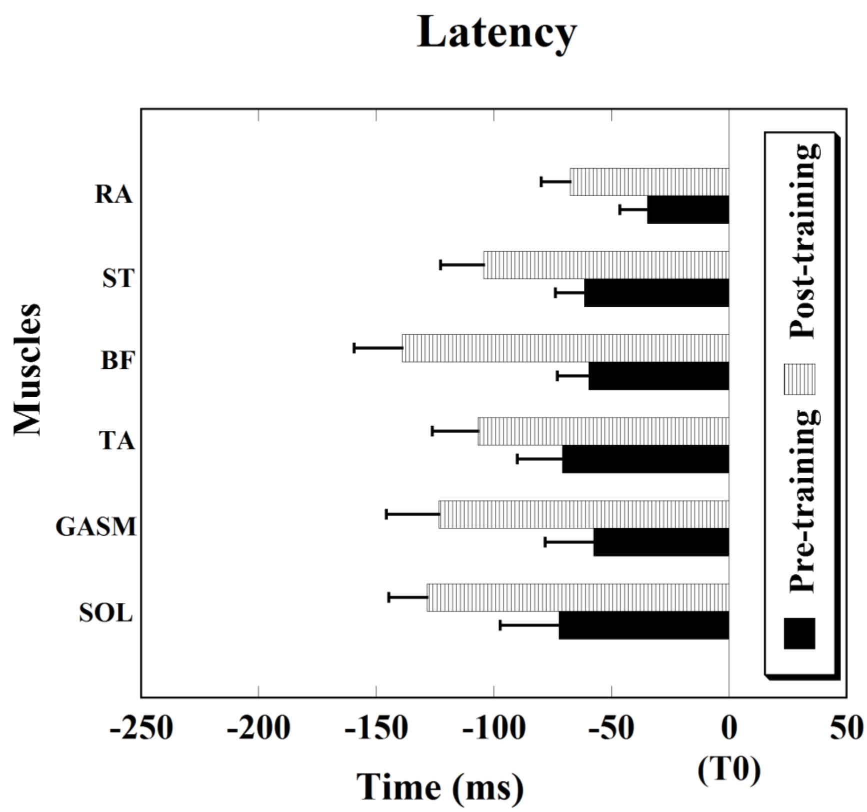

Figure 30. Muscle activity onsets. Note the early onsets of anticipatory postural activity (prior to the moment of perturbation (T_0)) after a single training session in older adults. Muscles abbreviations: SOL-soleus, GASM – medial gastrocnemius, TA – tibialis anterior, BF- biceps femoris, ST-semitendinosis, and RA – rectus abdominis. Differences in latencies are significant for all muscles shown, $p < 0.05$.

The onset of APA activity before and after training was as follows: SOL (pre-training: -72.39 ± 24.82 ms, post-training: -128.36 ± 16.30 ms, *p* = 0.041); GASM (pre-training: -57.61 ± 20.48 ms, post-training: -123.38 ± 22.27 ms, p = 0.034); BF (pre-training: -59.63 ±1 3.25 ms, post-training: -139.05 ± 20.40 ms, p = 0.015); ST (pre-training: -61.45 ± 12.38 ms, post-training: -104.34 ± 18.36 ms, p = 0.046); RA (pre-training: -34.62 ± 11.74 ms, post-training: -67.56 ± 12.26 ms, p = 0.015). Early APA onset after training was also seen in RF muscle (pre-training: -85.48 ± 15.79 ms, post-training: -122.84 ± 16.19 ms) and the difference was close to significance (p = 0.061). Similar patterns of early anticipatory activity with training were seen in GASL, VM, VL, and ESL muscles.

5.3.2 **Integrated Electromyographic Activity**

A significant condition x epoch interaction effect was seen for the TA ($p < 0.001$), RF ($p = 0.042$), and GMED ($p = 0.045$) muscles. The interaction effect was close to significance for the VM muscle ($p = 0.07$). Post-hoc analysis demonstrated larger EMG activity during the APA1 epoch following training as compared to pre-training condition in the RF and GMED muscles (Figure 31). Post-hoc effects were, however, not statistically significant. Additionally, lower compensatory activity was observed during the CPA1 and CPA2 epochs in the TA, RF, VM, VL, ST, GMED, and RA muscles following training as compared to the pre-training condition. The differences for the CPA1 and CPA2 epochs were not statistically significant for any of the muscles.

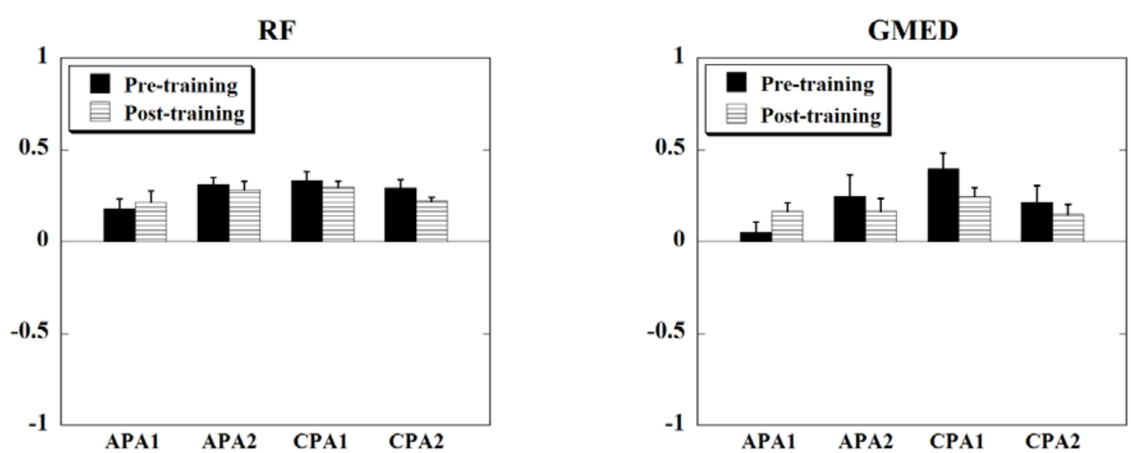

Figure 31. Normalized integrated EMG activities during the four epochs (APA1, APA2, CPA1, and CPA2) are shown for the RF (rectus femoris) and GMED (gluteus medius) muscles before (pre-training) and after (post-training) training for older adults. Positive values indicate an activation of the muscle, while negative values indicate a muscle inhibition.

5.3.3 <u>Displacements of Center of Pressure and Center of Mass</u>

Figures 32 and 33 depict the displacements of COP and COM respectively, at T_0 and the peak displacements after T_0 for the two conditions. It can be seen that the anticipatory COP displacement (at T_0) following training (18.85 ± 2.56 mm) was a little higher than the displacement before training (17.62 ± 2.21 mm); the difference was not statistically significant. At the same time with training, the peak displacement after the perturbation (35.38 ± 3.32 mm) was smaller than the pre-training condition (39.12 ± 3.22 mm); the difference was not significant ($p = 0.08$). Additionally, the peak velocity of the COP was also significantly smaller after training (0.0005 ± 0.003 mm/ms) as compared to the pre-training condition (0.009 ± 0.005 mm/ms) ($p = 0.006$).

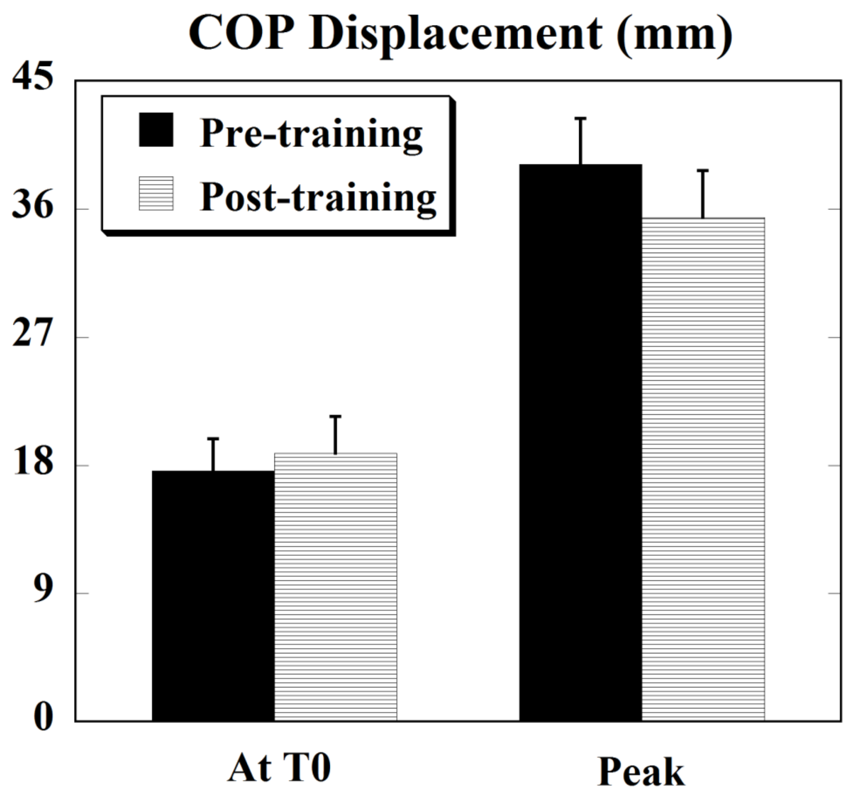

Figure 32. Displacement of COP at T_0 (anticipatory) and peak displacement (after T_0, compensatory) before (pre-training) and after (post-training) training. Positive values indicate displacement in the posterior/backward direction.

The anticipatory COM displacement was of similar magnitude before (0.12 ± 0.66 mm) and after (-0.15 ± 0.98 mm) training and the difference was not statistically significant. However, following training the anticipatory COM displacement was in the forward direction (i.e. opposite to the direction of perturbation). This resulted in smaller peak COM displacement following training (20.83 ± 3.86 mm) as compared to the peak displacement before training (25.13 ± 2.36 mm); the difference was, however, not statistically significant.

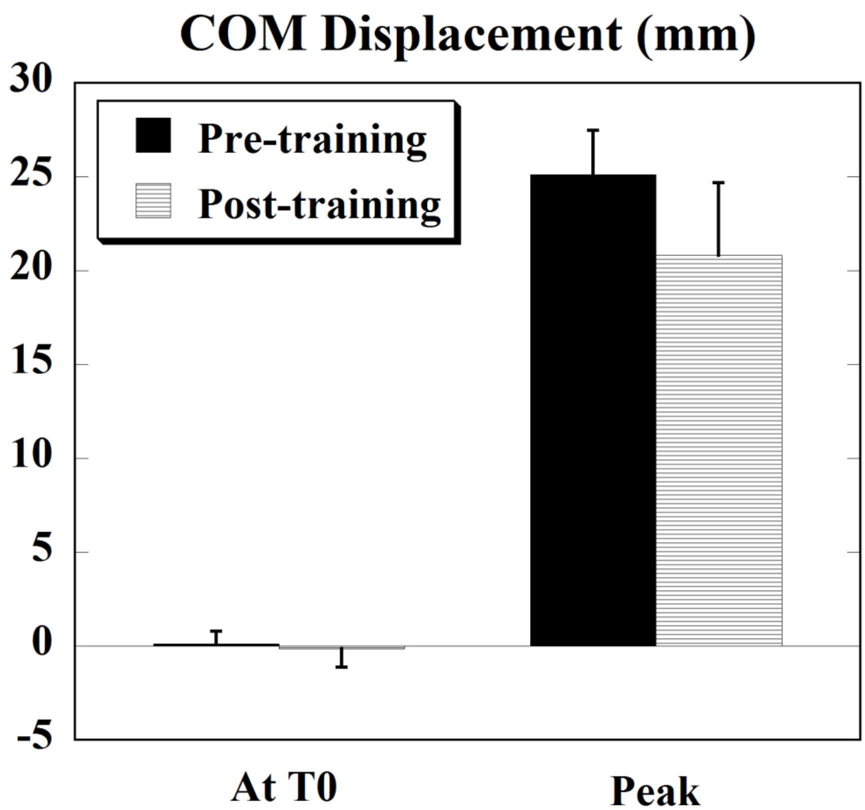

Figure 33. Displacement of COM at T_0 (anticipatory) and peak displacement (after T_0, compensatory) before (pre-training) and after (post-training) training. Positive values indicate displacement in the posterior/backward direction and negative values indicate displacement in the anterior/forward direction.

5.4 **Discussion**

This study was focused on examining the effect of short-term training in enhancing anticipatory postural control in the elderly. Overall, training improved postural preparation, thereby, resulting in greater postural stability in response to a perturbation.

5.4.1 **Changes in Motor Control of Balance Following Training in Older Adults**

Impairments of postural control with advancing age are associated with a high incidence of falls and fall related injuries in the older adults. Poor balance control in the older adults is also associated with decreased levels of physical activity, increased dependence and a significantly low quality of life. Several intervention programs and studies have been employed towards balance rehabilitation in older adults (Sturnieks et al. 2008). While most of the evidence on training related improvements in the elderly is related to changes in performance on clinical measures of balance (such as the Berg's Balance test, Timed Up and Go test, Forward Reach test), very few studies relate this improvement to the actual changes occurring at the neuromuscular level. That is to ask, what component of postural control has been improved with training and how does that relate to improved performance? Have sensory or motor strategies or sensorimotor integration improved? It is important to know the control mechanisms that may be pliable to change with balance training. Such knowledge can help build the foundation for designing new methods of balance rehabilitation in the elderly.

In the past, few studies have reported changes in motor control associated with balance maintenance and restoration following training. Thus following multisensory training in older adults, it was seen that with an increase in sensory interactions, the ability of the older adults to resolve sensory conflicts, and reweigh and select a reliable sensory input was improved. As a consequence, they were able to stand for longer time in one leg stance conditions and these effects were retained at four weeks follow up. At the same time, when exposed to unexpected platform translations following training, early onset of neck flexors was seen in response to a perturbation and a decreased response frequency of the antagonists. Neck flexor early onsets indicated integration of vestibular and proprioceptive inputs and improved sensorimotor integration with multisensory training (Hu and Woollacott 1994b; Hu and Woollacott 1994a). In another study, the ability of proprioceptive reintegration and ankle velocity discrimination sense were found to be improved with sensory training (Westlake and Culham 2007; Westlake et al.

2007). Similarly improvements in sensory reweighing strategies have been found to occur even with 1 hour immersion in a virtual environment that causes sensory conflict (Bugnariu and Fung 2007). Improvements in central processing time have also been observed with virtual reality and biofeedback training, as evidenced by a decrease in reaction time on dual task condition, indicating increased automation of postural control (Bisson et al. 2007). Training paradigms such as Tai Chi have shown improvements in sensory integration such as increase in vestibular ratio on a sensory organization test and improved directional control in limits of stability test at four weeks of training which was found to be comparable to that of experienced practioners (Tsang and Hui-Chan 2004). The effect of training is also seen in improvements in the compensatory postural adjustments. Following high intensity ankle and knee strength training, older adults showed higher ankle moments and faster rate of torque production, suggesting quicker and effective responses and a shift towards an ankle strategy from a hip strategy common with aging (Hess et al. 2005). Recently it was demonstrated that following practice with unexpected continuous variable amplitude platform oscillations, elderly showed improvements in temporal control of COM and increased trunk stability which was retained the next day (Van Ooteghem et al. 2009). However, older adults adopted a more rigid platform based strategy whereas younger adults adopted a multi-segment, gravity based strategy of control. Thus from the above studies, it can said that training-related improvements in older adults are reflected in changes in sensory organization, sensorimotor integration, and compensatory postural adjustments.

5.4.2 Training Related Improvements in Anticipatory Postural Control of Older Adults

Anticipatory postural adjustments prior to a forthcoming internal or external perturbation are found to be delayed with ageing. Initially, this delay in muscle activation was thought to be due to inadequate magnitude of voluntary movement and also a delay in the execution of voluntary movement. However, findings from our previous study (described in Chapter III) have shown that when the influence of voluntary movement is eliminated, such that the perturbation is still predictable but externally produced, APAs are present in older adults. However, such APAs are still delayed (close to the moment of perturbation) and reduced in magnitude. This impairment of anticipatory postural preparation is also seen in the biomechanical measures, wherein the anticipatory COP and COM displacements are reduced in older adults and they are not directionally specific. As a result of this reduced and directionally impaired postural preparation, older adults are more unstable following the perturbation and require larger corrective muscle activation in order to restore and maintain balance. Nonetheless, the CNS of older adults is still able to assess the involvement of APAs (even though they are reduced) and is capable of scaling down the compensatory adjustments in conditions when the perturbations are predictable.

In this study, we found that following training, the postural muscles of older adults were either activated or inhibited about 30-80 ms earlier than the pre-training condition. Along with early onsets, the anticipatory postural activity also showed a pattern of increased magnitude, especially during the APA1 epoch. Likewise, larger anticipatory COP displacement in the backward direction was also observed after training. On the other hand, the magnitude of anticipatory COM displacement did not change with training, however a change in directional specificity was observed. Prior to training, even though the perturbation was predictable, the COM moved in the direction of the perturbation (backwards) in contrast to moving opposite to the perturbation direction (forwards). As a result, the COM was already displaced in a direction that would further increase its displacement due to the actual perturbation. Following training, the improvements seen in anticipatory muscle activity were also reflected in its effect on subsequent postural control. The CNS of older adults was able to take advantage of the enhanced postural preparation such that it scaled down the magnitude of compensatory muscle activity as compared to the pre-training condition. Also, the simultaneous larger anticipatory COP displacement resulted in a reduction in the peak displacement of the COP after the perturbation. In addition, the directional specificity of the COM movement in preparation of the perturbation was improved with training, although the magnitude of movement remained unchanged. The COM now moved opposite to the direction of perturbation (forwards) prior to the impact. This directional shift of the body away from the perturbation could be due to better estimation of the upcoming disturbance by the older adults following training. Such directionally specific movement of the COM in anticipation of the impact resulted in smaller peak displacement of the COM after the impact as compared to the peak displacement seen in the pre-training condition.

A few other studies have shown improvements in anticipatory postural control with training, either in healthy individuals or in people with low back pain. One of the early studies by Pauligan et al showed that healthy individuals could acquire APAs in their postural forearm during a load lifting task initiated by the opposite hand without a direct movement of the triggering hand after about 40 to 60 repetitions (Paulignan et al. 1989). However when the arms were switched, the acquisition was not transferred to the new postural forearm (Massion et al. 1999). In other experiments involving patients with low back pain, isolated voluntary contraction of the transverses abdominis muscle was found to cause early APA onset in this muscle during arm flexion movements immediately after a single training session (Tsao and Hodges 2007). With four weeks of such training early onsets were seen along with consistent activation of this muscle during walking as opposed to phasic activity prior to training. These effects were retained at six month follow up. Thus these studies show that motor adaptive changes in feed forward postural adjustments or APAs are possible with training (Tsao and Hodges 2008). Indeed, our findings also lend support in this direction. Older adults are a greater risk of losing balance due to inadequate use of anticipatory strategies. A single training session used in this study demonstrated that improvements in postural control of older adults could be explained by enhanced postural preparation.

5.5 **Conclusion**

This study demonstrated that impairments of anticipatory postural control due to ageing can be reduced with training that involves whole body postural perturbations such as catching a ball. Improvements in APAs in older adults are characterized by early onset of anticipatory postural activity and directionally specific movement of the COM in preparation of a forthcoming perturbation. Improved postural preparation in older adults results in greater postural stability. Thus, changes in APAs are a possible mechanism through which balance control can be enhanced in people with advancing age. However, studies involving long-term training are needed to evaluate the maintenance and utilization of anticipatory postural strategies in balance control of older adults.

CHAPTER VI

CONCLUSIONS AND FUTURE DIRECTIONS

6.1 **Conclusions**

The broad purpose of this thesis was to advance the understanding of the role played by anticipatory postural adjustments in control of human balance. The interaction between anticipatory and compensatory postural adjustments was investigated; particularly how the availability of anticipatory postural adjustments influences compensatory postural reactions and postural stability was studied. In addition the thesis was focused on understanding the effect of aging on the organization of APAs in maintaining postural stability. Finally, the immediate effect of training in improving the utilization of APAs in subsequent control of posture in the healthy young and older individuals was investigated.

The first chapter presented a framework of how posture and movement are two integral components of a motor act and the crucial interaction between the two. The chapter then elaborated the mechanisms and significance of postural control. Particularly anticipatory/feedforward and compensatory/feedback postural strategies were discussed.

The research findings were presented in chapters two, three, four, and five.

Chapter two discussed the individual role of APAs and CPAs in balance control and thereafter focused on investigating the effect of APAs in subsequent control of posture (CPAs) in healthy young adults. A pendulum-impact paradigm was used to apply external predictable and unpredictable perturbations that were of identical magnitude, thereby, allowing a comparison of APAs and CPAs. The outcome of this study highlighted the importance of a relationship between APAs and CPAs in control of posture, and demonstrated the effectiveness of optimal utilization of APAs in postural control.

Chapter three discussed the changes in anticipatory postural control of self-generated perturbation in older adults. It also highlighted the importance of investigating the direct effect of aging on APAs without the intermediate effect of ageing on voluntary movement performance. The study while investigating the differences in APAs between young and older adults also examined the interaction between APAs and CPAs in balance control of healthy older adults. This study demonstrated the direct effects of aging on anticipatory postural control in humans. Anticipatory postural adjustments were delayed and reduced in magnitude in older adults as compared to young adults in preparation of a predictable external perturbation. Impaired generation of APAs was associated with larger compensatory muscle responses in older adults. However, in spite of larger reactive responses, older adults were more unstable than young adults when exposed to similar perturbations. The study also showed that in spite of age-related impairments of APAs, the older adults were able to assess the presence of APAs and utilized APAs (when available) to improve body stability. The outcome of this study laid a foundation for investigating the role of training in improving anticipatory postural control in older adults.

Chapter four provided a background of how APAs are acquired and adapted to environmental demands. It also discussed the role of training in acquisition and improvement of anticipatory postural activity. The study examined the effect of training in enhancing the generation of anticipatory postural adjustments and their utilization in subsequent balance control in healthy young adults. A single training session that involved catching a ball activity was used. It was found that anticipatory postural activity prior to a predictable external perturbation can be augmented in healthy young adults. Also, the ability to utilize increased anticipatory activity is enhanced following training and is reflected in smaller displacements of COM after the perturbation, indicating greater postural stability.

Chapter five discussed the different balance training methods in older adults and the studies that have demonstrated changes in compensatory postural strategies, sensorimotor integration and central processing capabilities of older adults. The goal of the study described in that chapter was to determine whether training-related changes in anticipatory postural control could be a possible mechanism of improvement in balance control of older adults. The study demonstrated that impairments of anticipatory postural control due to ageing can be reduced with training that involves whole body postural perturbations such as catching a ball. Improved postural preparation in older adults also resulted in greater postural stability. Thus, changes in APAs are a possible mechanism through which balance control can be enhanced in people with advancing age.

6.2 **Future Directions**

The series of studies conducted in this thesis illustrated the role of APAs in control of balance after a perturbation. At the same time, changes in anticipatory postural control of older adults were investigated. While anticipatory recruitment was preserved in older adults, APAs were delayed and reduced and were found to be a source of instability in older adults. However, when existing, older adults were able to account for the availability of APAs and use them effectively to maintain postural stability in response to a perturbation. The study also showed the immediate effects of training in enhancing the utilization of APAs in balance control of healthy young and older adults.

Building up on the knowledge gained from this thesis, future research can be directed in several areas of postural control. A primary health concern for aging adults is balance deterioration, which severely limits their activities of daily living and community participation. One of the next steps would be to look at the effects of long-term training on anticipatory postural control in older adults. Also, it is important to understand, how the effect of training translates into functional performance of daily activities. The research on anticipatory postural control in older individuals bears the impression that increasing age is a primary driving factor behind these changes. Despite the fact that the process of postural control changes with aging, it is important to note that older adults are not a homogeneous population. Differences in balance capacities, may contribute to the generation and utilization of APAs in older adults. Consequently, differentiating the effects of aging *per se* from impairment of functional capacity is essential in understanding how the elderly individuals organize anticipatory postural strategies. As compared to stable older adults, the functionally unstable older adults may demonstrate larger delays in APA onsets or even reduced anticipatory recruitment of muscles (which is largely preserved in healthy older adults). Such impairments of APAs may predispose them to a greater risk of losing balance. Targeting such individuals who are at a higher risk of experiencing balance losses with appropriate rehabilitation strategies is therefore vital. Likewise, APAs are known to be affected in people with neurological disorders such as stroke, Parkinson's disease, and multiple sclerosis amongst others. It would be interesting to study how anticipatory postural control can be improved in people with balance impairments due to neurological lesions.

Another direction of future research would be to understand the neural mechanisms that underlie age and disease-related changes in feedforward postural strategies. Research from a neurophysiological approach would throw light on the neural basis of motor control related to balance. Understanding the cortical and corticospinal mechanisms of APA impairment would help design training approaches that are focused on improving these impaired mechanisms or approaches that elicit alternative mechanisms of control.

Thus, it is important to investigate the mechanisms of balance control following brain lesions as well as to understand the pathways through which motor recovery and motor learning occurs. Such an approach would help design future balance rehabilitation strategies.

CITED LITERATURE

Adkin AL, Frank JS, Carpenter MG, Peysar GW (2002) Fear of falling modifies anticipatory postural control. Exp Brain Res 143: 160-170

Alexandrov AV, Frolov AA, Horak FB, Carlson-Kuhta P, Park S (2005) Feedback equilibrium control during human standing. Biol Cybern 93: 309-322

Allison GT, Henry SM (2002) The influence of fatigue on trunk muscle responses to sudden arm movements, a pilot study. Clin Biomech (Bristol, Avon) 17: 414-417

Allum JH, Honegger F, Pfaltz CR (1989) The role of stretch and vestibulo-spinal reflexes in the generation of human equilibrating reactions. Prog Brain Res 80: 399-409; discussion 395-397

Aruin A, Almeida G (1997) A coactivation strategy in anticipatory postural adjustment in persons with Down syndrome. Motor Control 2: 178-197

Aruin A, Mayka M, Shiratori T (2003) Could a motor action that has no direct relation to expected perturbation be associated with anticipatory postural adjustments in humans? Neurosci Lett 341: 21-24

Aruin A, Shiratori T (2003) Anticipatory postural adjustments while sitting: the effects of different leg supports. Exp Brain Res 151: 46-53

Aruin AS (2003) The effect of changes in the body configuration on anticipatory postural adjustments. Motor Control 7: 264-277

Aruin AS, Forrest WR, Latash ML (1998) Anticipatory postural adjustments in conditions of postural instability. Electroencephalogr Clin Neurophysiol 109: 350-359

Aruin AS, Latash ML (1995a) Directional specificity of postural muscles in feed-forward postural reactions during fast voluntary arm movements. Exp Brain Res 103: 323-332

Aruin AS, Latash ML (1995b) The role of motor action in anticipatory postural adjustments studied with self-induced and externally triggered perturbations. Exp Brain Res 106: 291-300

Aruin AS, Latash ML (1996) Anticipatory postural adjustments during self-initiated perturbations of different magnitude triggered by a standard motor action. Electroencephalogr Clin Neurophysiol 101: 497-503

Aruin AS, Shiratori T, Latash ML (2001) The role of action in postural preparation for loading and unloading in standing subjects. Exp Brain Res 138: 458-466

Barnett A, Smith B, Lord SR, Williams M, Baumand A (2003) Community-based group exercise improves balance and reduces falls in at-risk older people: a randomised controlled trial. Age Ageing 32: 407-414

Basmajian JV (1980) Electromyography--dynamic gross anatomy: a review. Am J Anat 159: 245-260

Bateni H, Zecevic A, McIlroy WE, Maki BE (2004) Resolving conflicts in task demands during balance recovery: does holding an object inhibit compensatory grasping? Exp Brain Res 157: 49-58

Bazalgette D, Zattara M, Bathien N, Bouisset S, Rondot P (1987) Postural adjustments associated with rapid voluntary arm movements in patients with Parkinson's disease. Adv Neurol 45: 371-374

Belen'kiĭ V, Gurfinkel V, Pal'tsev Y (1967) Elements of control of voluntary movements. Biofizika 10: 135-141

Berger W, Trippel M, Discher M, Dietz V (1992) Influence of subjects' height on the stabilization of posture. Acta Otolaryngol 112: 22-30

Bisson E, Contant B, Sveistrup H, Lajoie Y (2007) Functional balance and dual-task reaction times in older adults are improved by virtual reality and biofeedback training. Cyberpsychol Behav 10: 16-23

Black AA, Wood JM, Lovie-Kitchin JE, Newman BM (2008) Visual impairment and postural sway among older adults with glaucoma. Optom Vis Sci 85: 489-497

Bleuse S, Cassim F, Blatt JL, Labyt E, Derambure P, Guieu JD, Defebvre L (2006) Effect of age on anticipatory postural adjustments in unilateral arm movement. Gait Posture 24: 203-210

Blievernicht J, Don Tinder D, Ellenbecker T (2000) Conditioning Programs for Golf and Tennis. IDEA Resource Series

Bloem BR, Allum JH, Carpenter MG, Verschuuren JJ, Honegger F (2002) Triggering of balance corrections and compensatory strategies in a patient with total leg proprioceptive loss. Exp Brain Res 142: 91-107

Bonnetblanc F, Martin O, Teasdale N (2004) Pointing to a target from an upright standing position: anticipatory postural adjustments are modulated by the size of the target in humans. Neurosci Lett 358: 181-184

Bouisset S, Do MC (2008) Posture, dynamic stability, and voluntary movement. Neurophysiol Clin 38: 345-362

Bouisset S, Richardson J, Zattara M (2000) Are amplitude and duration of anticipatory postural adjustments identically scaled to focal movement parameters in humans? Neurosci Lett 278: 153-156

Bouisset S, Zattara M (1987a) Biomechanical study of the programming of anticipatory postural adjustments associated with voluntary movement. J Biomech 20: 735-742

Bouisset S, Zattara M (1987b) Biomechanical study of the programming of anticipatory postural adjustments associated with voluntary movement. J Biomechanics 20: 735-742

Bugnariu N, Fung J (2007) Aging and selective sensorimotor strategies in the regulation of upright balance. J Neuroeng Rehabil 4: 19

Burleigh A, Horak F (1996) Influence of instruction, prediction, and afferent sensory information on the postural organization of step initiation. J Neurophysiol 75: 1619-1628

Cavanagh PR, Komi PV (1979) Electromechanical delay in human skeletal muscle under concentric and eccentric contractions. Eur J Appl Physiol Occup Physiol 42: 159-163

Cordasco FA, Wolfe IN, Wootten ME, Bigliani LU (1996) An electromyographic analysis of the shoulder during a medicine ball rehabilitation program. Am J Sports Med 24: 386-392

Cordo PJ, Nashner LM (1982) Properties of postural adjustments associated with rapid arm movements. J Neurophysiol 47: 287-302

Crenna P, Frigo C, Massion J, Pedotti A (1987) Forward and backward axial synergies in man. Exp Brain Res 65: 538-548

Danna-Dos-Santos A, Degani AM, Latash ML (2007) Anticipatory control of head posture. Clin Neurophysiol 118: 1802-1814

Dimitrova D, Horak FB, Nutt JG (2004) Postural muscle responses to multidirectional translations in patients with Parkinson's disease. J Neurophysiol 91: 489-501

Duran FS, Lugo L, Ramirez L, Eusse E (2001) Effects of an exercise program on the rehabilitation of patients with spinal cord injury. Arch Phys Med Rehabil 82: 1349-1354

Frank JS, Patla AE (2003) Balance and mobility challenges in older adults: implications for preserving community mobility. Am J Prev Med 25: 157-163

Friedli WG, Hallett M, Simon SR (1984) Postural adjustments associated with rapid voluntary arm movements 1. Electromyographic data. J Neurol Neurosurg Psychiatry 47: 611-622

Gage WH, Zabjek KF, Hill SW, McIlroy WE (2007) Parallels in control of voluntary and perturbation-evoked reach-to-grasp movements: EMG and kinematics. Exp Brain Res 181: 627-637

Gantchev GN, Dimitrova DM (1996) Anticipatory postural adjustments associated with arm movements during balancing on unstable support surface. Int J Psychophysiol 22: 117-122

Garland SJ, Stevenson TJ, Ivanova T (1997) Postural responses to unilateral arm perturbation in young, elderly, and hemiplegic subjects. Arch Phys Med Rehabil 78: 1072-1077

Georgoulis AD, Ristanis S, Papadonikolakis A, Tsepis E, Moebius U, Moraiti C, Stergiou N (2005) Electromechanical delay of the knee extensor muscles is not altered after harvesting the patellar tendon as a graft for ACL reconstruction: implications for sports performance. Knee Surg Sports Traumatol Arthrosc 13: 437-443

Girolami GL, Shiratori T, Aruin AS (2010) Anticipatory postural adjustments in children with typical motor development. Exp Brain Res 205: 153-165

Granata KP, Slota GP, Bennett BC (2004) Paraspinal muscle reflex dynamics. J Biomech 37: 241-247

Guralnik JM, Ferrucci L, Simonsick EM, Salive ME, Wallace RB (1995) Lower-extremity function in persons over the age of 70 years as a predictor of subsequent disability. N Engl J Med 332: 556-561

Hadders-Algra M (2005) Development of postural control during the first 18 months of life. Neural Plast 12: 99-108; discussion 263-172

Hafstrom A, Fransson PA, Karlberg M, Ledin T, Magnusson M (2002) Visual influence on postural control, with and without visual motion feedback. Acta Otolaryngol 122: 392-397

Henry SM, Fung J, Horak FB (1998) EMG responses to maintain stance during multidirectional surface translations. J Neurophysiol 80: 1939-1950

Henry SM, Fung J, Horak FB (2001) Effect of stance width on multidirectional postural responses. J Neurophysiol 85: 559-570

Hess JA, Woollacott MH, Shivitz N (2005) Ankle force and rate of force production increase following high intensity strength training in frail older adults. Aging Clinical and Experimental Research 18: 107-115

Hirvensalo M, Rantanen T, Heikkinen E (2000) Mobility difficulties and physical activity as predictors of mortality and loss of independence in the community-living older population. J Am Geriatr Soc 48: 493-498

Hodges PW (2001) Changes in motor planning of feedforward postural responses of the trunk muscles in low back pain. Exp Brain Res 141: 261-266

Horak FB (2006) Postural orientation and equilibrium: what do we need to know about neural control of balance to prevent falls? Age Ageing 35 Suppl 2: ii7-ii11

Horak FB, Diener HC, Nashner LM (1989a) Influence of central set on human postural responses. J Neurophysiol 62: 841-853

Horak FB, Dimitrova D, Nutt JG (2005) Direction-specific postural instability in subjects with Parkinson's disease. Exp Neurol 193: 504-521

Horak FB, Nashner LM (1986) Central programming of postural movements: adaptation to altered support-surface configurations. J Neurophysiol 55: 1369-1381

Horak FB, Shupert CL, Mirka A (1989b) Components of postural dyscontrol in the elderly: a review. Neurobiol Aging 10: 727-738

Hu MH, Woollacott MH (1994a) Multisensory training of standing balance in older adults: I. Postural stability and one-leg stance balance. J Gerontol 49: M52-61

Hu MH, Woollacott MH (1994b) Multisensory training of standing balance in older adults: II. Kinematic and electromyographic postural responses. J Gerontol 49: M62-71

Hughes MA, Schenkman ML, Chandler JM, Studenski SA (1995) Postural responses to platform perturbation: kinematics and electromyography. Clin Biomech (Bristol, Avon) 10: 318-322

Hughey LK, Fung J (2005) Postural responses triggered by multidirectional leg lifts and surface tilts. Exp Brain Res 165: 152-166

Inglin B, Woollacott M (1988) Age-related changes in anticipatory postural adjustments associated with arm movements. J Gerontol 43: M105-113

Ito T, Azuma T, Yamashita N (2004) Anticipatory control related to the upward propulsive force during the rising on tiptoe from an upright standing position. Eur J Appl Physiol 92: 186-195

Jones SL, Henry SM, Raasch CC, Hitt JR, Bunn JY (2008) Responses to multi-directional surface translations involve redistribution of proximal versus distal strategies to maintain upright posture. Exp Brain Res 187: 407-417

Kanekar N, Santos MJ, Aruin AS (2008) Anticipatory postural control following fatigue of postural and focal muscles. Clin Neurophysiol 119(10): 2304-13

Kannus P, Parkkari J, Koskinen S, Niemi S, Palvanen M, Jarvinen M, Vuori I (1999) Fall-induced injuries and deaths among older adults. Jama 281: 1895-1899

Kisner C, Colby LA (2007) Therapeutic exercise : foundations and techniques. F.A. Davis, Philadelphia

Kourtis D, Kwok HF, Roach N, Wing AM, Praamstra P (2008) Maintaining grip: anticipatory and reactive EEG responses to load perturbations. J Neurophysiol 99: 545-553

Krishnan V, Kanekar N, Aruin AS (2012) Anticipatory postural adjustments in individuals with multiple sclerosis. Neurosci Lett 506: 256-260

Krishnan V, Kanekar N, Aruin AS (2012) Feedforward postural control in individuals with multiple sclerosis during load release. Gait Posture 36: 225-230

Laessoe U, Voigt M (2007) Anticipatory postural control strategies related to predictive perturbations. Gait Posture 28: 62-68

Lampinen P, Heikkinen E (2003) Reduced mobility and physical activity as predictors of depressive symptoms among community-dwelling older adults: an eight-year follow-up study. Aging Clin Exp Res 15: 205-211

Latash ML (2008) Neurophysiological basis of movement. Human Kinetics, Champaign, IL

Latash ML, Aruin AS, Neyman I, Nicholas JJ (1995) Anticipatory postural adjustments during self inflicted and predictable perturbations in Parkinson's disease. J Neurol Neurosurg Psychiatry 58: 326-334

Lee WA, Buchanan TS, Rogers MW (1987) Effects of arm acceleration and behavioral conditions on the organization of postural adjustments during arm flexion. Exp Brain Res 66: 257-270

Li F, Harmer P, Fisher KJ, McAuley E (2004) Tai Chi: improving functional balance and predicting subsequent falls in older persons. Med Sci Sports Exerc 36: 2046-2052

Li X, Aruin AS (2007) The effect of short-term changes in the body mass on anticipatory postural adjustments. Exp Brain Res 181: 333-346

Li X, Aruin AS (2008) The effect of short-term changes in body mass distribution on feed-forward postural control. J Electromyogr Kinesiol 19: 931-941

Lord SR, Ward JA, Williams P (1996) Exercise effect on dynamic stability in older women: a randomized controlled trial. Arch Phys Med Rehabil 77: 232-236

Macpherson JM, Horak FB, Dunbar DC, Dow RS (1989) Stance dependence of automatic postural adjustments in humans. Exp Brain Res 78: 557-566

Maki BE, McIlroy WE (1996) Postural control in the older adult. Clin Geriatr Med 12: 635-658

Maki BE, McIlroy WE (2006) Control of rapid limb movements for balance recovery: age-related changes and implications for fall prevention. Age Ageing 35 Suppl 2: ii12-ii18

Man'kovskii NB MA, Lysenyuk VP (1980) Regulation of the preparatory period for complex voluntary movement in old and extreme old age. Hum Physiol (Moscow)

Massion J (1992) Movement, posture and equilibrium: interaction and coordination. Prog Neurobiol 38: 35-56

Massion J, Ioffe M, Schmitz C, Viallet F, Gantcheva R (1999) Acquisition of anticipatory postural adjustments in a bimanual load-lifting task: normal and pathological aspects. Exp Brain Res 128: 229-235

McIlroy WE, Maki BE (1993) Changes in early 'automatic' postural responses associated with the prior-planning and execution of a compensatory step. Brain Res 631: 203-211

Moseley GL, Hodges PW, Gandevia SC (2003) External perturbation of the trunk in standing humans differentially activates components of the medial back muscles. J Physiol 547: 581-587

Nardone A, Schieppati M (1988) Postural adjustments associated with voluntary contraction of leg muscles in standing man. Exp Brain Res 69: 469-480

Nashner LM (1977) Fixed patterns of rapid postural responses among leg muscles during stance. Exp Brain Res 30: 13-24

Nashner LM, Cordo PJ (1981) Relation of automatic postural responses and reaction-time voluntary movements of human leg muscles. Exp Brain Res 43: 395-405

Noe F, Quaine F, Martin L (2003) Mechanical effect of additional supports in a rocking on heels movement. Gait Posture 18: 78-84

Nouillot P, Bouisset S, Do MC (1992) Do fast voluntary movements necessitate anticipatory postural adjustments even if equilibrium is unstable? Neurosci Lett 147: 1-4

Nouillot P, Do MC, Bouisset S (2000) Are there anticipatory segmental adjustments associated with lower limb flexions when balance is poor in humans? Neurosci Lett 279: 77-80

Park S, Horak FB, Kuo AD (2004) Postural feedback responses scale with biomechanical constraints in human standing. Exp Brain Res 154: 417-427

Paulignan Y, Dufosse M, Hugon M, Massion J (1989) Acquisition of co-ordination between posture and movement in a bimanual task. Exp Brain Res 77: 337-348

Preuss R, Fung J (2008) Musculature and biomechanics of the trunk in the maintenance of upright posture. J Electromyogr Kinesiol 18: 815-828

Rietdyk S, Patla AE, Winter DA, Ishac MG, Little CE (1999) NACOB presentation CSB New Investigator Award. Balance recovery from medio-lateral perturbations of the upper body during standing. North American Congress on Biomechanics. J Biomech 32: 1149-1158

Rocchi L, Mancini M, Chiari L, Cappello A (2006) Dependence of anticipatory postural adjustments for step initiation on task movement features: a study based on dynamometric and accelerometric data. Conf Proc IEEE Eng Med Biol Soc 1: 1489-1492

Rogers MW, Kukulka CG, Soderberg GL (1992) Age-related changes in postural responses preceding rapid self-paced and reaction time arm movements. J Gerontol 47: M159-165

Santos MJ, Aruin AS (2008a) Effects of lateral perturbations and changing stance conditions on anticipatory postural adjustment. J Electromyogr Kinesiol

Santos MJ, Aruin AS (2008b) Role of lateral muscles and body orientation in feedforward postural control. Exp Brain Res 184: 547-559

Santos MJ, Aruin AS (2009) Effects of lateral perturbations and changing stance conditions on anticipatory postural adjustment. J Electromyogr Kinesiol 19: 532-541

Santos MJ, Kanekar N, Aruin AS (2010a) The role of anticipatory postural adjustments in compensatory control of posture: 1. Electromyographic analysis. J Electromyogr Kinesiol 20: 388-397

Santos MJ, Kanekar N, Aruin AS (2010b) The role of anticipatory postural adjustments in compensatory control of posture: 2. Biomechanical analysis. J Electromyogr Kinesiol 20: 398-405

Shiratori T, Aruin A (2007) Modulation of anticipatory postural adjustments associated with unloading perturbation: effect of characteristics of a motor action. Exp Brain Res 178: 206-215

Shiratori T, Latash M (2000) The roles of proximal and distal muscles in anticipatory postural adjustments under asymmetrical perturbations and during standing on rollerskates. Clin Neurophysiol 111: 613-623

Shiratori T, Latash ML (2001) Anticipatory postural adjustments during load catching by standing subjects. Clin Neurophysiol 112: 1250-1265

Shumway-Cook A WM (2000) Motor Control: Theory and Practical Applications. Lippincott Williams & Wilkins

Skelton DA, Beyer N (2003) Exercise and injury prevention in older people. Scand J Med Sci Sports 13: 77-85

Slijper H, Latash M (2000) The effects of instability and additional hand support on anticipatory postural adjustments in leg, trunk, and arm muscles during standing. Exp Brain Res 135: 81-93

Slijper H, Latash ML (2004) The effects of muscle vibration on anticipatory postural adjustments. Brain Res 1015: 57-72

Stapley P, Pozzo T, Grishin A (1998) The role of anticipatory postural adjustments during whole body forward reaching movements. Neuroreport 9: 395-401

Stapley PJ, Pozzo T, Cheron G, Grishin A (1999) Does the coordination between posture and movement during human whole-body reaching ensure center of mass stabilization? Exp Brain Res 129: 134-146

Sturnieks DL, St George R, Lord SR (2008) Balance disorders in the elderly. Neurophysiol Clin 38: 467-478

Tsang WW, Hui-Chan CW (2004) Effect of 4- and 8-wk intensive Tai Chi Training on balance control in the elderly. Med Sci Sports Exerc 36: 648-657

Tsao H, Hodges PW (2007) Immediate changes in feedforward postural adjustments following voluntary motor training. Exp Brain Res 181: 537-546

Tsao H, Hodges PW (2008) Persistence of improvements in postural strategies following motor control training in people with recurrent low back pain. J Electromyogr Kinesiol 18: 559-567

van der Fits IB, Klip AW, van Eykern LA, Hadders-Algra M (1998) Postural adjustments accompanying fast pointing movements in standing, sitting and lying adults. Exp Brain Res 120: 202-216

van der Fits IB, Klip AW, van Eykern LA, Hadders-Algra M (1999) Postural adjustments during spontaneous and goal-directed arm movements in the first half year of life. Behav Brain Res 106: 75-90

van der Heide JC, Otten B, van Eykern LA, Hadders-Algra M (2003) Development of postural adjustments during reaching in sitting children. Exp Brain Res 151: 32-45

Van Ooteghem K, Frank JS, Horak FB (2009) Practice-related improvements in posture control differ between young and older adults exposed to continuous, variable amplitude oscillations of the support surface. Exp Brain Res 199: 185-193

Vint PF, McLean SP, Harron GM (2001) Electromechanical delay in isometric actions initiated from nonresting levels. Med Sci Sports Exerc 33: 978-983

Virk S, McConville KM (2006) Virtual reality applications in improving postural control and minimizing falls. Conf Proc IEEE Eng Med Biol Soc 1: 2694-2697

Wang Y, Asaka T, Zatsiorsky VM, Latash ML (2006) Muscle synergies during voluntary body sway: combining across-trials and within-a-trial analyses. Exp Brain Res 174: 679-693

Westlake KP, Culham EG (2007) Sensory-specific balance training in older adults: effect on proprioceptive reintegration and cognitive demands. Phys Ther 87: 1274-1283

Westlake KP, Wu Y, Culham EG (2007) Sensory-specific balance training in older adults: effect on position, movement, and velocity sense at the ankle. Phys Ther 87: 560-568; discussion 569-571

Winter DA, Prince F, Frank JS, Powell C, Zabjek KF (1996) Unified theory regarding A/P and M/L balance in quiet stance. J Neurophysiol 75: 2334-2343

Woollacott MH, Manchester DL (1993) Anticipatory postural adjustments in older adults: are changes in response characteristics due to changes in strategy? J Gerontol 48: M64-70

Woollacott MH, Shumway-Cook A (1990) Changes in posture control across the life span--a systems approach. Phys Ther 70: 799-807

Zattara M, Bouisset S (1988) Posturo-kinetic organisation during the early phase of voluntary upper limb movement. 1. Normal subjects. J Neurol Neurosurg Psychiatry 51: 956-965

APPENDIX

UNIVERSITY OF ILLINOIS
AT CHICAGO

Office for the Protection of Research Subjects (OPRS)
Office of the Vice Chancellor for Research (MC 672)
203 Administrative Office Building
1737 West Polk Street
Chicago, Illinois 60612-7227

Approval Notice

Continuing Review (Response To Modifications)

June 18, 2013

Alexander Aruin, PhD

Physical Therapy

406 HHDS

M/C 898

Chicago, IL 60612

Phone: (312) 355-0904 / Fax: (312) 996-4583

RE: Protocol # 2000-0771

"The Organization of Anticipatory Postural Adjustments"

Dear Dr. Aruin:

Your Continuing Review (Response To Modifications) was reviewed and approved by the Expedited review process on June 14, 2013. You may now continue your research

Please note the following information about your approved research protocol:

Protocol Approval Period: June 14, 2013 - June 14, 2014

Approved Subject Enrollment #: 400 (229 enrolled to date)

Additional Determinations for Research Involving Minors: These determinations have not been made for this study since it has not been approved for enrollment of minors.

Performance Sites: UIC

Sponsor: National Institutes of Health

PAF#: 2010-05244

Grant/Contract No: 1R03HD064838

Grant/Contract Title: The Role of Anticipatory Postural Adjustments In Balance Control of Older Adults

Research Protocol(s):

a) Grant application: The Role of Anticipatory Postural Adjustments in Balance Control of Older Adults, signed March 15, 2010
b) Anticipatory Postural Adjustments; 2000-0771/Version 3 Date: 06/12/13

Recruitment Material(s):

a) Flyer - Healthy Young Individuals, Version 3, Date: 10/08/09
b) Internet Announcement - Healthy Young Individuals, Version 2, Date: 10/08/09
c) Email Notice - Healthy Young Individuals, Version 2, Date: 10/08/09
d) Flyer - ND, Version 2, Date: 10/08/09
e) Internet Announcement - ND, Version 2, Date: 10/08/09
f) Email Notice - ND, Version 2, Date: 10/08/09
g) Flyer - Healthy Elderly Individuals, Version 4, Date: 03/02/11; UIC IRB #2000-0771
h) Internet Announcement - Healthy Elderly Individuals, Version 3, Date: 03/02/11; UIC IRB #2000-0771
i) Email Notice - Healthy Elderly Individuals, Version 3, Date: 03/02/11; UIC IRB #2000-0771
j) Telephone Screening Script - Healthy Volunteers, UIC IRB #2000-0771, Version 4 Date: 04/13/12
k) Telephone Screening Script - ND, UIC IRB #2000-0771, Version 2 Date: 04/13/12

Informed Consent(s):

a) Anticipatory Postural Adjustments 2000-0771/Healthy Volunteers/Version 16 Date:

06/12/2013

b) Anticipatory Postural Adjustments 2000-0771/ND/Version 12 Date: 06/12/2013

HIPAA Authorization(s):

a) UIC: Anticipatory Postural Adjustments 2000-0771-Authorization, Version 3, Date 10/03/06 (Please continue to use the Authorization form, approved and stamped on October 16, 2006.)

Please note the Review History of this submission:

Receipt Date	Submission Type	Review Process	Review Date	Review Action
05/21/2013	Continuing Review	Convened	06/05/2013	Modifications Required
06/10/2013	Response To Modifications	Expedited	06/11/2013	Modifications Required
06/12/2013	Response To Modifications	Expedited	06/14/2013	Approved

Please remember to:

→ Use your **research protocol number** (2000-0771) on any documents or correspondence with the IRB concerning your research protocol.

→ Review and comply with all requirements on the enclosure,

"UIC Investigator Responsibilities, Protection of Human Research Subjects"
(*http://tigger.uic.edu/depts/ovcr/research/protocolreview/irb/policies/0924.pdf*)

Please note that the UIC IRB has the prerogative and authority to ask further questions, seek additional information, require further modifications, or monitor the conduct of your research and the consent process.

Please be aware that if the scope of work in the grant/project changes, the protocol must be amended and approved by the UIC IRB before the initiation of the change.

We wish you the best as you conduct your research. If you have any questions or need further help, please contact OPRS at (312) 996-1711 or me at (312) 413-7323. Please send any correspondence about this protocol to OPRS at 203 AOB, M/C 672.

Sincerely,

Jennifer Joaquin, MPH, CIP

Assistant Director, IRB # 1

Office for the Protection of Research Subjects

Enclosure(s):

1. **Informed Consent Document(s):**
   a) Anticipatory Postural Adjustments 2000-0771/Healthy Volunteers/Version 16 Date: 06/12/2013
   b) Anticipatory Postural Adjustments 2000-0771/ND/Version 12 Date: 06/12/2013
2. **Recruiting Material(s):**
   a) Flyer - Healthy Young Individuals, Version 3, Date: 10/08/09
   b) Internet Announcement - Healthy Young Individuals, Version 2, Date: 10/08/09
   c) Email Notice - Healthy Young Individuals, Version 2, Date: 10/08/09
   d) Flyer - ND, Version 2, Date: 10/08/09
   e) Internet Announcement - ND, Version 2, Date: 10/08/09
   f) Email Notice - ND, Version 2, Date: 10/08/09
   g) Flyer - Healthy Elderly Individuals, Version 4, Date: 03/02/11; UIC IRB #2000-0771
   h) Internet Announcement - Healthy Elderly Individuals, Version 3, Date: 03/02/11; UIC IRB #2000-0771
   i) Email Notice - Healthy Elderly Individuals, Version 3, Date: 03/02/11; UIC IRB #2000-0771
   j) Telephone Screening Script - Healthy Volunteers, UIC IRB #2000-0771, Version 4 Date: 04/13/12
   k) Telephone Screening Script - ND, UIC IRB #2000-0771, Version 2 Date:

04/13/12

cc: Christina Hui-Chan, Physical Therapy, M/C 898
OVCR Administration, M/C 672

VITA

NAME

Neeta Kanekar

EDUCATION

- **Ph.D. Candidate in Kinesiology, Nutrition, and Rehabilitation Sciences**
  Department of Kinesiology and Nutrition, University of Illinois at Chicago (UIC), 2008 – 2013 (expected)

- **M.S. in Physical Therapy**
  Department of Physical Therapy, University of Illinois at Chicago (UIC), 2006 – 2008

- **Bachelor of Physiotherapy (B.P.Th.)**
  Seth G. S. Medical College and King Edward Memorial (K.E.M.) Hospital
  Maharashtra University of Health Sciences (MUHS), India 2000 – 2005

RESEARCH EXPERIENCE AND PROJECTS

- **Pre-doctoral Fellow of the American Heart Association/American Stroke Association**
  Knecht Movement Science Laboratory, Department of Physical Therapy,
  University of Illinois at Chicago (UIC), 2011 – 2013
  Project: Enhancement of postural control (feedforward and feedback components) through Compelled Body Weight Shift paradigm in individuals with stroke-related asymmetries.

- **Graduate Research Assistant**
  Knecht Movement Science Laboratory, Department of Physical Therapy,
  University of Illinois at Chicago (UIC), 2006 – 2011
  Projects: 1) Role of anticipatory postural adjustments in compensatory postural control. 2) Anticipatory postural adjustments in the healthy elderly and the effect of training. 3) Postural control and fatigue in individuals with multiple sclerosis.

- **MS Thesis in Physical Therapy**
  Knecht Movement Science Laboratory, Department of Physical Therapy,
  University of Illinois at Chicago (UIC), 2006 – 2008
  Project: Effect of postural and focal muscle fatigue on anticipatory postural adjustments in healthy young adults.

- **B.P.Th Internship Project**
  Seth G. S. Medical College and King Edward Memorial (K.E.M.) Hospital

Maharashtra University of Health Sciences (MUHS), India, 2004 – 2005
Project: Core stabilization on a static v/s dynamic surface. Awarded the "Best Internship Project".

- **Final Year B.P.Th Project**
  Seth G. S. Medical College and King Edward Memorial (K.E.M.) Hospital
  Maharashtra University of Health Sciences (MUHS), India, 2003 – 2004
  Project: Retrospective Study on the type of adult neurology cases in the Physiotherapy Outpatient department.

TEACHING EXPERIENCE

- **Teaching Assistant**
  Department of Physical Therapy, University of Illinois at Chicago (UIC), 2008 – 2011
  Course: Laboratory Sessions for Biophysics (PT 616), DPT program

- **Teaching Assistant**
  Department of Kinesiology and Nutrition, University of Illinois at Chicago (UIC), 2010 – 2012
  Course: Laboratory Sessions for Instrumentation for Motor Control Research (KN/PT 574), MS and PhD programs

- **Graduate Teaching Assistant**
  Department of Kinesiology and Nutrition, University of Illinois at Chicago (UIC), 2008 - 2009
  Course: Human Physiological Anatomy (KN 251 and 252), Taught human anatomy and physiology labs with cadaver dissection.

- **Graduate Teaching Assistant**
  Department of Biological Sciences, University of Illinois at Chicago (UIC), 2007 – 2007
  Course: Basic Biology (BIOS100), Taught labs on statistics, microscopy techniques, processes of cellular and organismic function, structure and physiology of plants and animals, and animal dissection.

- **Supervision and training of MS students**
  Knecht Movement Science Laboratory, Department of Physical Therapy, University of Illinois at Chicago (UIC), 2008 – 2013

CLINICAL EXPERIENCE

- **Resident Physiotherapist**
  Department of Physiotherapy, Lilavati Hospital and Research Centre, Mumbai, India, 2005 - 2006
  Independent clinical postings in the neurology, orthopedic, surgical and cardiac intensive care units, in-patient, and out-patient clinical settings. Actively participated in and led programs organized for patient health care.

- **Physiotherapy Clinical Intern**
  Seth. G. S. Medical College, King Edward Memorial Hospital, Mumbai, India, 2004 – 2005
  Clinical rotations through orthopedics, neurology, medical and surgical wards, burns unit, plastic surgery unit, obesity clinic, women's health, cerebral palsy clinic.

AWARDS AND HONORS

Research/Clinical

- Love of Learning Award, National Honor Society of Phi Kappa Phi, 2012
  As support for career development. Selected as one of 140 recipients nationwide from over 1,000 applications based on superior academic record and life/career ambitions.

- Graduate Student Council Research Travel Award, UIC, 2012

- Finalist for the Kevin Granata Young Investigator Award, Student Awards Podium Session, GCMAS Annual Conference, 2012
  One of the six finalists selected amongst the top 25% of all abstract and podium presentations.

- Gait and Clinical Movement Analysis Society (GCMAS) Student Travel Award, 2012
  Selected as one of the twelve recipients based on demonstrated potential to advance scientific knowledge, technical capabilities, and/or clinical practice in the field of human movement.

- Force and Motion Foundation Travel Scholarship, 2011
  Awarded to promising graduate students across the nation in fields related to multi-axis force measurement and testing; based on quality, contribution, and innovation of research.

- Student Presenter Award, Graduate College, UIC, 2011

- Graduate Student Council Research Travel Award, UIC, 2011

- American Heart/Stroke Association – Predoctoral Fellowship Award, 2011-2013

- Provost's Award for Graduate Research, UIC, 2011
  Recognizes outstanding researchers among UIC graduate students who will make exceptional contributions to learning and society.

Academic/Scholastic

- Lillian B. Torrance Scholarship Award, College of Applied Health Sciences, UIC, 2012
  Recognizes academic achievements of students in biomedical visualization, occupational therapy, and physical therapy who have expressed an interest in rehabilitative activities or studies.

- Donna K. Roach Award, Department of Physical Therapy, UIC, 2011
  For the professional development of meritorious students in the Department of Physical Therapy.

- Donna K. Roach Award, Department of Physical Therapy, UIC, 2009

- Inducted as a Member to the National Honor Society of Phi Kappa Phi, 2008

- Van Doren Scholarship, College of Applied Health Sciences, UIC, 2007

- Certificates of Merit from MUHS, India for being in the top three positions in the university during all the four years of the B.P.Th program (amongst 450 students), 2001-2004

- Silver Medal from MUHS, India for securing the top position in the university in the first year of B.P.Th, in a class of 450 students, June 2001

PROFESSIONAL MEMBERSHIPS

- Gait and Clinical Movement Analysis Society (GCMAS), 2011 – present

- Society for Neuroscience, 2011 – 2012

- International Society of Motor Control, 2011 – 2012

- National Honor Society of Phi Kappa Phi, 2008 – present

- Life Member of Indian Association of Physiotherapists (IAP), India; recognized by World Confederation of Physical Therapy, 2005 - present

SPECIALIZED COURSES/CONFERENCES

- Gait Course, Vienna, Austria, organized by the European Society of Movement Analysis for Adults and Children, September 2011

- Matlab Fundamentals, MathWorks, May 2011

- Motor Control Summer School-VI, Pennsylvania, USA, organized by the International Society of Motor Control, June 2009.

PUBLICATIONS

Manuscripts Published

- **Kanekar N**, Aruin AS (2013) The role of clinical and instrumented outcome measures in balance control of individuals with multiple sclerosis. Mul Scler Int (Epub ahead of print)

- **Kanekar N**, Lee YJ, Aruin AS (2013) Effect of light finger touch in balance control of individuals with multiple sclerosis. Gait and Posture (Epub ahead of print)

- Krishnan V, **Kanekar N**, Aruin AS (2012) Feedforward postural control in individuals with multiple sclerosis during load release. Gait and Posture 36(2): 225-30

- Krishnan V, **Kanekar N**, Aruin AS (2012) Anticipatory postural adjustments in individuals with multiple sclerosis. Neuroscience Letters 506(2): 256-60

- Santos MJ, **Kanekar N**, Aruin AS (2010) The role of anticipatory postural adjustments in compensatory control of posture: 1. Electromyographic analysis. Journal of Electromyography and Kinesiology 20(3): 388-97

- Santos MJ, **Kanekar N**, Aruin AS (2010) The role of anticipatory postural adjustments in compensatory control of posture: 2. Biomechanical analysis. Journal of Electromyography and Kinesiology 20(3): 398-405.

- **Kanekar N**, Santos MJ, Aruin AS (2008) Anticipatory postural control following fatigue of postural and focal muscles. Clinical Neurophysiology 119(10): 2304-13

Conference Papers and Presentations

- **Kanekar N**, Lee YJ, Aruin AS. The role of light finger touch in enhancing balance control of people with multiple sclerosis. 2nd International Symposium on Gait and Balance in Multiple Sclerosis: Interventions for Gait and Balance in MS, Portland, Oregon, USA, October 2012.

- **Kanekar N**, Krishnan V, Aruin AS. Clinical assessment of balance control in individuals with multiple sclerosis. Annual Conference of the Gait and Clinical Movement Analysis Society (GCMAS), Grand Rapids, Michigan, USA, May 2012.

- Krishnan V, **Kanekar N**, Aruin AS. Anticipatory postural adjustments during standing in individuals with multiple sclerosis. Annual Conference of the Gait and Clinical Movement Analysis Society (GCMAS), Grand Rapids, Michigan, USA, May 2012.

- **Kanekar N**, Krishnan V, Aruin AS. Improvement of anticipatory postural control in older adults following a single training session. Combined Sections Meeting of the American Physical Therapy Association, Chicago, IL, USA, February 2012.

- **Kanekar N**, Krishnan V, Aruin AS. The role of anticipatory postural adjustments in balance control of older adults. Neuroscience 2011, Society for Neuroscience's 41st Annual Meeting, Washington, DC, November 2011.

- **Kanekar N**, Krishnan V, Aruin AS. Enhancement of anticipatory postural control following a single training session. 20th Annual Meeting of European Society for Movement Analysis in Adults and Children (ESMAC), Vienna, Austria, September 2011; Abstract: pg 118.

- **Kanekar N**, Santos MJ, Aruin AS. The relationship between anticipatory and compensatory components of human balance control. Progress in Motor Control VIII, Cincinnati, OH, USA, July 2011.

- **Kanekar N**, Santos MJ, Aruin AS. Balance Control in Humans: interplay between anticipatory and compensatory mechanisms. UIC Student Research Forum, April 2010. Proceedings from UIC Student Research Forum (Abstract), 2010.

- **Kanekar N**, Santos MJ, Aruin A. Effect of muscle fatigue on anticipatory postural control. UIC Student Research Forum, April 2008.
Proceedings from UIC Student Research Forum (Abstract), 2008:35.

INVITED LECTURES/PODIUM PRESENTATIONS

- **Kanekar N.** Invited talk on "Control of posture in health and disease." at University of Pittsburgh, Department of Physical Medicine and Rehabilitation, Systems Neuroscience Institute, Pittsburgh, Pennsylvania, USA, April 2013.

- **Kanekar N.** Invited lecture on "Organization of feedforward postural control in health and disease." at the All India Institute of Physical Medicine and Rehabilitation (AIIPMR), Haji Ali, Mumbai, India, January 2013.

- **Kanekar N.** Invited lecture on "Anticipatory postural adjustments in health and disease." at Lilavati Hospital and Research Center, Department of Physical Therapy, Mumbai, India, January 2013.

- **Kanekar N.** Podium Presentation (Finalist for the Kevin Granata Young Investigator Award, Student Awards Podium Session): "Clinical assessment of balance control in individuals with multiple sclerosis." at the Annual Conference of the Gait and Clinical Movement Analysis Society (GCMAS), Grand Rapids, Michigan, USA, May 2012.

- **Kanekar N.** Invited lecture on "A Look at AHA-Funded Research: Enhancement of postural control in individuals with stroke-related asymmetries." at the American Heart Association Integration Team Meeting, Chicago, Illinois, USA, April 2012.

- **Kanekar N.** Presentation of the AHA funded stroke research project to the Stroke Survivors Empowering Each Other (SSEEO) Board of Directors. SSEEO is the first non-profit patient-supported stroke advocacy group in the nation, Chicago, Illinois, USA, March 2012.

RESEARCH GRANTS/AWARDS

- **Title: Enhancement of postural control in individuals with stroke-related asymmetries**
  Source: Predoctoral Fellowship Award, American Heart Association/American Stroke Association
  PI: Neeta Kanekar PT, MS
  Role: Principal Investigator
  Date: 07/01/2011 – 06/30/2013

- **Title: The role of anticipatory postural adjustments in balance control of older adults**
  Source: R03 (NIH10558095), NIH/NICHD NIH, National Institute of Child Health and Human Development
  PI: Alexander S. Aruin PhD
  Role: Investigator
  Date: 2011-2013

- **Title: Anticipatory postural control in individuals with multiple sclerosis**
  Source: PP1871, National Multiple Sclerosis Society
  PI: Alexander S. Aruin PhD
  Role: Investigator
  Date: 2013-2014

INVENTIONS AND PATENTS

- Aruin AS, **Kanekar N**. Gait performance enhancing innersole and method. Patent pending (2012). The United States Patent and Trademark Office.

PUBLIC RELATIONS

Research cited and/or subject of interview, popular press:

- "Learning how the brain controls balance after stroke." AHS (Applied Health Sciences) Magazine, The Research Issue - Cover Story, UIC. 2011-2012, p.14

- "Examining how brain controls balance after stroke." UIC News. April 4, 2012, p.11 http://www.uic.edu/htbin/cgiwrap/bin/uicnews/articledetail.cgi?id=16250