Role of altered vision and proprioception in control of posture

BY

SAMBIT MOHAPATRA
B.Sc (Honors) Physical Therapy, University of Delhi, 2007
M.S Kinesiology, University of Illinois at Chicago, 2009

DISSERTATION

Submitted as partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Kinesiology, Nutrition & Rehabilitation Sciences
(Rehabilitation Sciences) in the Graduate College of the
University of Illinois at Chicago, 2012

Chicago, Illinois

Defense Committee:

Alexander Aruin, Chair and Advisor
Charles Walter
Mark Latash, Pennsylvania State University
Shane Phillips, Physical Therapy
Ziaul Hasan

This thesis is dedicated to my grandfather (Late Dhanurdhar Mohapatra), parents (Mr. Rabinarayan Swain and Mrs. Minati Mohapatra), sister (Manisha Priyadarshini) without whom it would never have been accomplished.

ACKNOWLEDGMENTS

I would like to acknowledge those who have helped me bring my thesis in present shape, as words might be feeble to pen down my sense of gratitude for them. There are many people to whom I owe a debt of thanks for their support.

Institutionally, first and foremost, I wish to especially thank my research guide, **Dr. Alexander S. Aruin**, for his continuous enthusiasm, words of encouragement and conscientious efforts to help me successfully complete my thesis. I would also like to thank other members of my thesis committee (Dr Charles Walter, Dr Mark Latash, Dr Shane Phillips and Dr Ziaul Hasan) for their unwavering support and assistance. They provided guidance in all areas that helped me accomplish my research goals and enjoy myself in the process. I will like to convey my special gratitude to Dr Mary Lou Bareither for her continuous mentorship and guidance.

I would also like to acknowledge lab members for their help during the course of work. In particular I would like to thank Dr Vennila Krishnan, who helped me conduct the initial experiments and write programs for data analysis. I would specially like to thank my colleague Neeta Kanekar for her overwhelming support during my years in the lab. I am also grateful to Dr Hiro Ida with his help in the Virtual Reality project. Also, I would like to thank Nilovana, Bradley, Bing, Anja, Maria, Ketaki and Joe for their help in running pilot experiments. I gratefully thank all my colleagues for all their support and critical appraisal, which made me, learn many things both personally and professionally.

Furthermore, my parents and grandparents deserve special mention for their inseparable support and prayers. My grandfather, in the first place is the person who inculcated discipline and order in me ever since I was a child. My Mother is the one who sincerely raised me with her compassionate love and supported me in whatever I wanted to do in spite of all odds, which she had to face. A deep hearted thank to my father for providing me all the facilities and making me learn taking decisions

ACKNOWLEDGMENTS (continued)

independently. My sister has a great role in what I am today and I want to thank her for being a part of my life. I also extend my thanks to all other family members for making me learn from my mistakes. Above all I express my reverence for the ALMIGHTY who gave me this opportunity.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

A/P	Antero-Posterior
ANOVA	ANalysis Of Variance
APA	Anticipatory Postural Adjustments
BF	Biceps Femoris
CNS	Central Nervous System
COM	Center of Mass
COP	Center of Pressure
CPA	Compensatory Postural Adjustments
EC	Eyes Closed
EMG	ElectroMyoGraphy
EO	Eyes Open
EOb	External Oblique
EOD	Eyes Open in Dark
ES	Erector Spinae
FEC	Foam Eyes Closed
FEO	Foam Eyes Open
FV	Full Vision
GL	Gastronemius Lateralis
GM	Gastronemius Medialis
GMed	Gluteus Medius
HFS	High Frequency Strobe

LIST OF ABBREVIATIONS (continued)

$IEMG_{NORM}$	Normalized Integrated EMG
LFS	Low Frequency Strobe
M/L	Medio-Lateral
MG	Medial Gastronemius
PCA	Principal Component Analysis
RA	Rectus Abdominis
REC	Regular Eyes Closed
REO	Regular Eyes Open
RF	Rectus Femoris
SD	Standard Deviation
Sol	Soleus
ST	SemiTendionsus
TA	Tibialis Anterior
VEC	Vibration Eyes Closed
VEO	Vibration Eyes Open
VL	Vastus Lateralis
VM	Vastus Medialis
WEC	Wobble Eyes Closed
WEO	Wobble Eyes Open

SUMMARY

The main purpose of this thesis is to explore how vision and proprioception play a role in control of vertical posture. First chapter (Chapter One) introduces the thesis by first describing the functioning of various systems such as sensory and musculoskeletal systems and how they interact to control posture. Later on, the role of feedforward (APAs) and feedback (CPAs) in the control of posture are introduced. Finally, the main research questions are posed which investigate how alterations of visual and proprioceptive stimuli affect the control of posture.

Chapter Two describes the common methods used in all the experiments conducted. The methods section first describes the common experimental set-up (the pendulum) and then the instrumentation and how the data were processed in the experiments.

Chapter Three describes the first experiment with the primary goal of investigating the effect of visual acuity on the anticipatory (APAs) and compensatory (CPAs) components of postural control. Ten individuals participated in the experiments involving perturbations induced by the pendulum while their visual acuity was altered. The different visual acuity conditions were no glasses, blurred vision induced by wearing glasses with positive or negative lenses, and no vision. EMG activity of trunk and leg muscles and ground reaction forces were recorded during the typical anticipatory and compensatory periods. We found that in the no vision condition the subjects did not generate APAs, which resulted in the largest displacements of the center of pressure (COP) after the perturbation ($p<0.01$). In all other visual conditions APAs were present showing a distal to proximal order of muscle activation. The subjects wearing positive glasses showed earlier and larger anticipatory EMGs than subjects wearing negative glasses or no glasses at all.

Chapter Four further evaluates the visual system in terms of visual cues. The main purpose of this study was to investigate the role of different visual cues on APAs as little is known about how variation in the available visual information affects generation of APAs. Ten healthy young subjects were exposed to external perturbations induced at the shoulder level in standing while the level of visual information about the forthcoming perturbation was varied. The visual conditions were 1) dynamic cues (full vision and high frequency strobe light), 2) static cues (low frequency strobe light), and 3) no cues (eyes open in dark room). Electrical activity of the trunk and leg muscles and center of pressure (CoP) displacements were recorded and quantified within the time intervals typical for APAs. The results showed that significantly larger APAs were generated in conditions with dynamic visual cues as compared to the conditions with static cues ($p<0.05$). Finally, no APAs were observed in the condition where there was complete absence of any visual cues. Principal Component Analysis (PCA) further revealed different muscle coupling patterns in the full vision and high frequency strobe light conditions.

The next chapter (Chapter Five) explored the role of proprioception in control of vertical posture. Thus, the objective of this study was to investigate the role of altered proprioception on anticipatory (APAs) and compensatory (CPAs) postural adjustments and their interaction. Nine healthy adults were exposed to external perturbations induced at the shoulder level while standing with intact or altered proprioception induced by bilateral Achilles tendon vibration. Visual information was altered (eyes open or closed) in both the conditions. Electrical activity of the eight trunk and leg muscles and center of pressure (COP) displacements were recorded and quantified within the time intervals typical for APAs and CPAs. The results showed that when proprioceptive information was altered in eyes open conditions, anticipatory muscle activity was delayed. Moreover, altered proprioceptive information resulted in smaller magnitudes of compensatory muscle activity as well as smaller COP displacements after the perturbation in both eyes open and eyes closed conditions.

SUMMARY (continued)

The final study (Chapter Six) explores the role of both somatosensory as well as proprioceptive information in the control of vertical posture by investigating the effect of different support surfaces on feed forward and feedback components of postural control. Nine healthy subjects were positioned on a rigid platform, foam, and wobble board with their eyes open or closed and were exposed to external perturbations applied to their shoulders. Electrical activity of ten trunk and leg muscles and displacements of the CoP were recorded and analyzed during the time frames typical of feedforward and feedback postural adjustments. Earliest muscle activity was noted for the most unstable condition (FOAM) followed by most stable condition (FIRM) and was most delayed for the single axis unstable condition (WOBBLE). Moreover, FOAM showed the least APAs for distal muscles; WOBBLE for the intermediate and FIRM condition showed a mix of proximal and distal muscles. When eyes were closed (EC), all the anterior muscles were the first to show activity after perturbation followed by the posterior muscles irrespective of the nature of surface. Maximum CoP displacement in EC condition occurred when subjects were stable (FIRM) followed by relatively unstable condition (WOBBLE) and least displacement was recorded for the most unstable condition (FOAM). Thus, the character of the support surface affects both feed forward and feedback components of postural control.

The final chapter (Chapter Seven) concludes the thesis and also describes some of the future directions which can be taken into consideration from the knowledge gained by this thesis as a whole.

CHAPTER I

INTRODUCTION

Human posture is controlled by the integration of information from the vestibular, proprioceptive, and visual systems. Numerous studies have demonstrated the importance of individual sensory systems in maintenance of balance. They have confirmed that stimulation of visual (Bronstein 1986; Dijkstra et al. 1994), vestibular (Nashner and Wolfson 1974; Hlavacka and Njiokiktjien 1985; Pavlik et al. 1999), and proprioceptive (Allum 1983; Kavounoudias et al. 1999) systems evoke body sway.

Each sensory system detects an error indicating deviation of body orientation from a certain reference position, individual error signals are summed and an appropriate corrective torque is generated as a function of this summed signal (Peterka 2002).

Each of the sensory system provides substantial information (about itself and the environment) that is transferred from the sensory receptors to the CNS via afferent pathways. Sensory receptors convert energy of various forms, such as light, pressure, temperature, and sound to electrical energy to be transmitted by various neurons (Enoka 2008).

1.1 Sensory systems and their role in control of posture

1.1.1 Role of Vision

Retina receives the visual information from where they are directed to at least two different locations in the brain. These pathways of information have been assumed to be specialized for different purposes; the focal system for object identification and the ambient system for movement control (Trevarthen 1968). The later has also been shown to affect strongly both stability and balance (Lee and Aronson 1974). A crucial role for controlling posture is carried out by vision, but it can be compensated for by other information sources. Vision seems to influence balance by reacting to motion as a relative image shift on the retina (Brandt et al. 1986). Visual acuity (Paulus et al. 1984), visual contrast (Leibowitz et al. 1979), object distances (Brandt et al. 1986) and room illumination determine the efficiency of vision in control of posture.

Sensory systems
1. Vestibular system: Inner ear (semicircular canals, otholiths, maculaes) 2. Vision (retina) 3. Proprioceptive system (muscle spindle-type I and II, Golgi tendon organ, joint receptors) 4. Cutaneous receptors (Soles of feet)

1.1.2 Role of proprioception and exteroception

Muscles, tendons and joints have the proprioceptive receptors (Enbom 1990), and give information about the position of the limbs and the body and the distension of the respective muscles. Proprioceptors include muscle spindles (type Ia and II), Golgi tendon organs (Ib) and joint receptors (McComas 1996).

Different types of pressoreceptors from the sole of the foot deliver the exteroceptive information. Exteroceptive receptors are located in the cutaneous and subcutaneous tissue (Johansson and Vallbo 1980). The major types of cutaneous receptors are Meissner corpuscles and Merkel disks, located closest to the skin surface, and Ruffini ending and Pacinian corpuscles, which are located deeper (Latash 1998).

Although the receptors located in the joint capsules provide information about the movements and positions of the body parts relative to each other, their role in postural control has not been fully understood. The crucial role of the muscle spindles is to detect the changes in muscle length and tension (dynamic stretch), and they can also be activated by passively stretching the entire muscle. In addition to an afferent system, the intrafusal fibers in the muscle spindles also receive an efferent input via γ -motoneuron (Enoka 2008). Moreover, the pressoreceptors detect the body sway, whereas the mechanoreceptors can determine both the site and velocity of an indentation of the skin, as well as acceleration and pressure changes (Johansson and Vallbo 1980; Magnusson et al. 1990).

Some essential inputs for postural control during stance are produced by proprioception. The information from ankle joints could be affected by the movement of the centre of gravity, resulting in torque around the ankle joint. Another source which also provides inputs is the neck muscles which give important references concerning head movement in relation to the trunk.

1.1.3 Role of the controller: Central Nervous System

Control of posture is a function of both the parts of the central nervous system (CNS), which is the brain and spinal cord. The thalamic nuclei, which transmit information from the spinal cord, basal ganglia and cerebellum and from the parietal and frontal areas of the cortex, provide the major input signals to the cortical neurons. The first and fastest response to a change in stance is triggered by spinal reflexes (Allum and Keshner 1986). The synapses consisting of afferent fibers, mediate the excitation of the CNS whereas the inhibitory synapses use special mediators which are the interneurons. For example, reciprocal Ia inhibition is evoked by the low-threshold afferents in antagonist muscles, and recurrent inhibition of motoneurons is meditated by interneurons called Renshaw cells (Pierrot-Deseilligny et al. 1983).

The CNS controls posture by the output commands which are sent to the muscles via the pyramidal and extra-pyramidal systems. The pyramidal cells, with their connections to the pre-motor and parietal cortex, transmit information to the spinal motor neurons and interneurons, which control voluntary movements and the segmental reflexes needed for balancing posture (Pyykko et al. 1990). The output of the cortical motor areas also includes projections to the basal ganglia, cerebellum and red nucleus. The basal ganglia and the nuclear groups facilitate and plan both voluntary and reflex movement during postural control. The cerebellum and its connections maintain co-ordination and smoothing of the reflex movements and the regulation of voluntary movement.

CNS
1. Stretch reflex 2. Long-loop reflexes 3. Preprogrammed reactions (Learned skills) 4. Synergistic action

1.2 Musculoskeletal system and its role in control of posture

Muscles of upper and lower extremities, trunk and neck especially play an important role in control of posture. Interestingly enough, although the calf musculature is activated first to provide postural control during body movements (Nashner 1983), the co-activation of certain "prime postural muscles", such as the muscles of neck, the hamstrings, the soleus and supraspinalis muscles, is also necessary (Nashner 1983; Johansson and Magnusson 1991). In addition to the above, several muscles also participate in producing both reflective movements with different latency times (Nashner 1983) and voluntary movements to balance the body position. Moreover, when these muscles are stretched, the proprioceptive receptors within the muscle and tendon, signal the change in muscle length to the central mechanism of the postural control system (Prochazka and Wand 1980; Spirduso et al. 2005).

Skeletal muscle system
1. Muscles of the upper and lower extremities 2. Trunk muscles 3. Neck muscles

Control of posture requires coordinated muscle action (Johansson and Magnusson 1991), for example, to produce adequate muscular contractions (Era et al. 1996). Such muscles and their actions around the ankle, knee and hip joints are essential in balancing the body. According to the passive stiffness control model, ankle stiffness, as a result of the CNS being limited to the selection of appropriate muscle tonus, stabilizes the unstable mechanical system in quiet stance (Winter et al. 1998). However, other researchers have pointed out mechanisms such as principle of reciprocal innervations in which stretch reflex responses of the muscles acting antagonistically about a joint are oppositely directed; with the agonists being activated by the stimulus and antagonists being relaxed (Lacquaniti and Maioli 1987) have been suggested. In addition to the above mechanisms, active mechanisms of postural stabilization in balanced stance (Morasso and Schieppati 1999), where the muscle and foot skin receptors play an essential role (Morasso and Schieppati 1999) have been studied as well.

1.3 Interplay between sensory systems and musculoskeletal system: concept of Anticipatory and Compensatory Postural Adjustments

The CNS with various inputs to and outputs from the sensory and the musculoskeletal system controls the body posture. This is achieved by generating certain postural adjustments which either precede (feedforward or APAs) or occur after a desired movement (feedback or CPAs).

1.3.1 Anticipatory Postural Adjustments

This is the first type of correction that occurs prior to a forthcoming perturbation, is based on predictions of the effect of the perturbation, and is called anticipatory postural adjustments (APAs) or feedforward postural control (Massion 1992). Multiple studies documented that the APAs are dependent on many factors including, but not limited to, direction (Aruin and Latash 1995; Santos and Aruin 2008) and magnitude of a perturbation (Aruin and Latash 1996; Nouillot et al. 2000) , body stability (Nouillot et al. 1992; Aruin et al. 1998; Nouillot et al. 2000), characteristics of motor action used to induce a perturbation (Aruin and Latash 1995; Aruin 2003), body configuration (van der Fits et al. 1998; Aruin 2003) and fear of falling (Adkin et al. 2002).

APAs play a crucial role during conditions where our stability and thus balance is challenged. Postural stability is usually challenged by perturbations. Perturbations can be classified into two different types: internal and external. While reaching for a book or lifting a leg during gait initiation are examples of internal perturbations that we experience daily; standing on a moving bus or being hit by another person while walking in a crowded train station are examples of external perturbations. Thus, APAs serve the

CNS to ensure that human beings maintain their balance while being challenged in various situations.

1.3.2 Compensatory Postural Adjustments

The second type of postural reaction is called Compensatory Postural Adjustments or CPAs. Such CPAs are initiated by sensory feedback signals (Park et al. 2004; Alexandrov et al. 2005), and serve to restore the body's position (Macpherson et al. 1989; Maki and McIlroy 1996; Henry et al. 1998a; Henry et al. 1998b). Past literature suggests that CPAs depend upon many factors including, but not limited to, direction and magnitude of perturbation, dimensions of base of support (Horak and Nashner 1986; Henry et al. 1998a; Dimitrova et al. 2004; Jones et al. 2008), predictability of perturbation characteristics (Burleigh and Horak 1996), instructions given to the subject (McIlroy and Maki 1993), and the implementation of a secondary task (Bateni et al. 2004).

Thus, CPAs are a way in which the CNS devises a strategy to minimize the damage to the system after sustaining a perturbation. This, adjustment ensures the activity of postural muscles occurs after the body perturbation and thus try to maintain equilibrium.

1.4 Alteration of vision and proprioception: How it affects Anticipatory Postural Adjustments and Compensatory Postural Adjustments?

The goal of this thesis is to understand how alteration of vision and proprioception will affect posture by laying the emphasis on the key postural corrections: APAs and CPAs.

A common methods section stated in Chapter Two was used for the four experiments described from Chapter Three to Six.

Chapters Three and Four will help us understand how altering vision will affect control of posture. The first experiment described in this thesis focuses on understanding how conditions of different visual acuity (by differently powered glasses) affect APAs and CPAs (Chapter Three). The second experiment investigates how visual cues (static vs. dynamic) affect generation of APAs in control of posture (Chapter Four).

Chapters Five and Six explore the role of proprioceptive and somatosensory systems in control of vertical posture. The third experiment lays foundation in understanding how disrupted proprioceptive inputs from the ankle joints (by a miniature tendon vibrator) affect control of posture under different visual conditions (Chapter Five). The fourth and the final experiment further explores the role of somatosensory and proprioceptive information while individuals stand on different support surfaces such as foam, rigid surface or a wobbling board (Chapter Six).

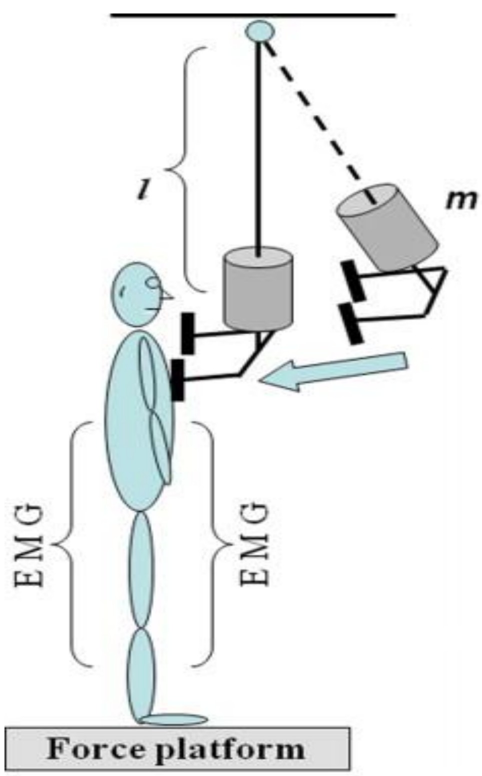
Finally Chapter Seven concludes the thesis and also describes some of the future directions which can be taken into consideration from the knowledge gained by this thesis as a whole.

CHAPTER II

METHODS

This chapter describes the common methods that will be used in all the subsequent experiments presented in this thesis.

2.1 Experimental Set-up



The subjects were instructed to maintain an upright stance with their feet shoulder width apart while standing bare feet on the force platform. They were positioned in front of an aluminum pendulum attached to the ceiling (Fig 1). An additional load (mass = 5% of subject's body weight) was fixed to the pendulum at its lower end.

Fig 1: A schematic showing the experimental set-up.

The width of the padded hitting surface of the pendulum was adjusted to match the subject's shoulder width. The pendulum was positioned at an initial angle of 30° to the vertical (distance of 0.6 m from the body) and released by an experimenter. Perturbations consisted of unidirectional forces applied by the pendulum on the shoulders of the subjects. The subjects were instructed to look straight towards a target attached to the pendulum at eye level and maintain their balance after the perturbation. A chalk was used to mark the subject's foot position on the top of the force platform at the start of the experiment. This foot position was checked by the experimenter throughout the experimental conditions. The magnitude and direction of the pendulum perturbations were kept constant throughout the study.

In addition, no advance warning of the impending perturbation was provided. The subjects wore wireless headphones playing music throughout all of the conditions to mask any kind of auditory information, which may alert them about the moment of release of the pendulum. For safety purposes during all of the experimental conditions the participants were provided with a harness with two straps attached to the ceiling. The subjects performed two to three practice trials in each experimental condition prior to the start of data collection. Five trials each of 5 s in duration were performed in each experimental condition and the order of the conditions was randomized.

2.2 Instrumentation

Electrical activity of muscles (EMGs) was recorded unilaterally (right side) from the trunk, thigh and leg muscles. The selected groups of muscles are involved in control of vertical posture while dealing with symmetrical perturbations induced in the sagittal plane and were previously used to study anticipatory and compensatory control of posture (e.g. (Latash et al. 1995; Aruin and Latash 1996)). After the skin area was cleaned with alcohol wipes, disposable electrodes (Red Dot 3M) were attached to the muscle belly of each of the muscles, based on recommendations reported in the 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 subject's proximal clavicle; its signal was used to record the moment of pendulum impact. The forces, moments of forces, EMG and accelerometer signals were digitized with a 16 bit resolution at 1000 Hz by means of a customized LabVIEW 8.6.1 software (National Instruments, Austin, TX, USA).

2.3 Data Processing

The data were analyzed off-line using the MATLAB (Math Works, Natick, MA) program. First, the accelerometer signal was corrected for offset, and 'time-zero' ($T_0 = 0$, the moment of pendulum impact) was acquired by a computer algorithm as a point in time at which the signal exceeded 5% of the maximum acceleration. This value was confirmed through visual inspection by an experienced researcher. Then, all the trials were aligned to T_0. EMG signals were then rectified and filtered with a 50 Hz low-pass, 2nd order, zero-lag Butterworth filter, while the reaction forces and moments were filtered with a 20 Hz low-pass, 2nd order, zero-lag Butterworth filter. Data in the range from −1000 ms (before T_0) to +1000 ms (after T_0) were selected for further analysis. Processed trials within each condition were averaged for each subject. Integrals of EMG, muscle latencies, and center of pressure displacements were calculated.

2.3.1. Integrals of the Electromyography

The average EMG signals for each muscle and each subject were integrated (Int_{EMGi}) with 150 ms time windows for a total of 6 time windows representing the −400 ms to + 500 ms of the data. Each of the time windows were further corrected by the averaged 150 ms baseline activity time window of the corresponding EMG integral from −1000 ms to −850 ms in relation to T_0.

(1)

$$Int_{EMG_i} = \int_{150}^{0} EMG - \left(\int_{-1000}^{-850} EMG \right)$$

In Eq. (1), Int_{EMGi} is the integral of EMG activity of muscles inside each 150 ms interval, which was corrected, by the baseline activity. Then the integrals of EMG for each muscle for each subject were normalized to maximal magnitude across all of the conditions (Eq. (2)).

(2)

$$IEMG_{NORM} = \frac{Int_{EMG_i}}{IEMG_{\max}}$$

Due to the normalization, all of the $IEMG_{NORM}$ values were within the range from +1 to −1. Four epochs were selected (each of 150 ms in duration) in relation to T_0.

The four epochs were: (1) from −250 ms to −100 ms (anticipatory, APA1); (2) from -100 ms to + 50 ms (anticipatory, APA2); (3) from +50 ms to +200 ms (compensatory reactions, CPA1); and (4) +200 ms to +350 ms (late compensatory reactions, CPA2) (Santos et al. 2010b; Santos et al. 2010a).

2.3.2. Muscle latencies

Muscle latencies were detected in a time window from −250 ms to +250 ms in relation to T_0 by a combination of a computer algorithm and visual inspection of the individual trials for each muscle. To identify the baseline, mean and standard deviation (SD) of the EMG signal were calculated from −500 ms to −400 ms before T_0. 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 the baseline.

2.3.3. Center of Pressure calculation

Time-varying COP_{AP} displacements were calculated using the following approximation (Winter et al. 1996):

(3)

$$COP_{AP} = \frac{Mx - (Fy * dz)}{F_Z}$$

where, M_x is the moment in the sagittal plane, F_z and F_y are the vertical and anterior–posterior components of the ground reaction force, and dz is the distance from the origin of the force platform to the surface (0.038 m). Since the perturbations were induced symmetrically, only COP displacements in the anterior-posterior direction (Y-axis according to our experimental set-up) will be reported. The COP_{AP} signals were averaged with 50 ms time windows for a total of 20 time windows representing the −450 ms to +550 ms of the data and corrected by its respective baseline (averaged COP baseline activity from −950 ms to −800 ms in relation to T_0). The COP data windows were shifted 50 ms forward to account for the electro-mechanical delay (Cavanagh and Komi 1979; Howatson et al. 2009). We calculated the peak magnitude of the COP, the time of the peak magnitude, and the magnitude of COP_{AP} at the moment of perturbation (T_0).

The methods described above have been repeatedly used over the last two decades by many investigators both from our lab and others.

CHAPTER III

CONTROL OF POSTURE: REDUCED ACUITY

Data presented in this chapter have been published as: Mohapatra S, Krishnan V, Aruin AS (2011). The effect of decreased visual acuity on control of posture. Clin Neurophysiol 123: 173-182.

3.1 Background

Postural stability depends not only on the functionality of the visual system but also on the distance (Le and Kapoula 2006) and illumination of the visual targets (Straube et al. 1990). Moreover, past posturo-graphic experiments have revealed increased postural instability in conditions with reduced visual acuity induced by semitransparent foils (Paulus et al. 1984) and increased postural sway area in the elderly with poor near vision acuity (Lichtenstein et al. 1988). It was also reported that if poor visual acuity and contrast sensitivity are combined with insufficient proprioceptive information associated with standing on a compliant surface, postural sway escalates, thus increasing the risk of falls (Lord and Webster 1990; Lord et al. 1991b; Elliott and Chapman 2010). Additionally, it was demonstrated that motion in the peripheral visual field and changes in stereo acuity and depth perception, that result in blurring vision, can affect control of posture (Previc and Neel 1995) and might increase risk for falls (Dhital et al. 2010). Furthermore, poor vision is an established risk factor for falls in the elderly (Harwood 2001; Lord 2006). It was also reported that older people who wear glasses with outdated prescriptions or no glasses at all are more prone to falls (Jack et al. 1995). Moreover, the rate of falls in the elderly who use multifocal glasses is increased and the incidence of falls in this population could be minimized by usage of single lens glasses (Haran et al. 2010).

The role of acuity of vision in control of posture being crucial; it also matters how the different acuity conditions affects the two major components of postural control: APAs and CPAs. It was demonstrated recently that CPAs are reduced in the presence of APAs and that they are increased when no APAs are generated (Santos et al. 2010a). The described relationship between APAs and CPAs was established in experiments where subjects were perturbed by a pendulum impact in conditions with either full vision (APAs are generated) or while being blindfolded (no APAs are generated). While these extreme visual conditions demonstrate the importance of visual information in generation of feedforward postural adjustments, it is unknown how other visual conditions affect the interplay between APAs and CPAs. Moreover, to the best of our knowledge no data exists on the effect of eyeglasses in generation of APAs and CPAs.

3.2 Subjects

Ten subjects (3 males and 7 females) without any known neurological or musculoskeletal disorders participated in the experiment. The mean age of the subjects was 25.2 ± 2.5 years; mean body mass 62.6 ± 13 kg; and a mean height of 1.67 ± 0.08 m. All of the subjects had normal vision and signed an informed consent approved by the Institution Review Board of the University of Illinois at Chicago.

3.3 Procedure

The subjects were instructed to look straight towards a target attached to the pendulum at eye level and maintain their balance after the perturbation. The four experimental conditions were: (1) eyes open with no eye glasses (no glasses); (2) eyes open with eye glasses of +10 Dioptre (positive); (3) eyes open with eye glasses of −6.0 Dioptre (negative); and (4) eyes closed (no vision) (Fig 2). Wearing positive glasses (convex lens) forms the image in front of the retina, causing the image to appear blurred; looking through negative glasses (concave lens) forms the image behind the retina causing the object to appear clear at first but become blurrier as the object gets closer (Pedrotti and Pedrotti 1998). As such, the positive powered eye glasses blurred and magnified the image of the pendulum, and the negative powered eye glasses blurred and diminished the size of the pendulum as seen by the subject.

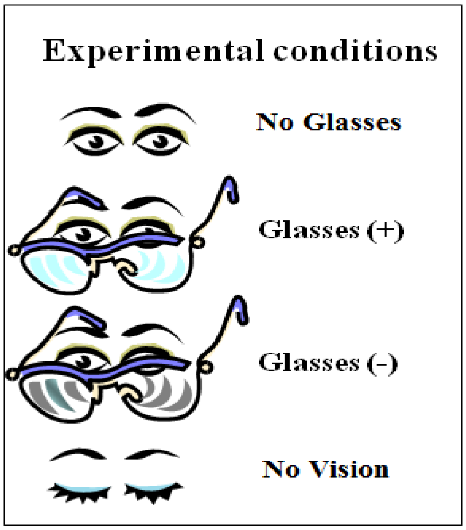


Fig 2: A schematic showing the various visual acuity conditions.

In the no-vision condition, the subjects did not see a pendulum at all and were therefore not aware of the moment of its release. The magnitude and direction of the pendulum perturbations were kept constant throughout the study. Electrical activity of muscles (EMGs) was recorded unilaterally (right side) from the following muscles: tibialis anterior (TA), soleus (Sol), biceps femoris (BF), rectus femoris (RF), gluteus medius (GMED), rectus abdominis (RA), external oblique (EOb) and erector spinae (ES).

3.4 Statistical Analysis

Multiple repeated measures ANOVAs were performed with two within subject factors: visual condition (no glasses, negative, positive and no vision) and epochs (APA1, APA2, CPA1 and CPA2). Subsequent multiple repeated measures ANOVAs were performed with three visual conditions and four epochs. The vision conditions were (a) normal-negative, (b) normal-positive, and (c) positive–negative. The dependent variables were $IEMG_{NORM}$, latency of trunk and leg muscles, peak magnitude of the COP_{AP}, time of the peak magnitude, and magnitude of COP_{AP} at the moment of perturbation (T_0). A post hoc analysis with Bonferroni correction was further done to compare between conditions, epochs and their interactions. In case the Mauchly's test of sphericity was not met, the Greenhouse–Geisser correction was used. For all tests, statistical significance was set at $p < 0.05$. Statistical analysis was performed in SPSS 17 for Windows 7 (SPSS Inc., Chicago, USA).

3.5 Results

3.5.1 Electromyography profiles

Fig. 3 shows EMG traces obtained from the anterior (TA) and the posterior (Sol) muscles of a representative subject performing the experimental task under four different visual conditions. Anticipatory activity seen as bursts (TA) and inhibition (Sol) of the background EMG activity was present in the three conditions with vision available. Quite to the contrary, anticipatory activity was negligible in the no vision condition. As a result, larger compensatory EMG activity was observed in conditions with no vision as compared to other visual conditions.

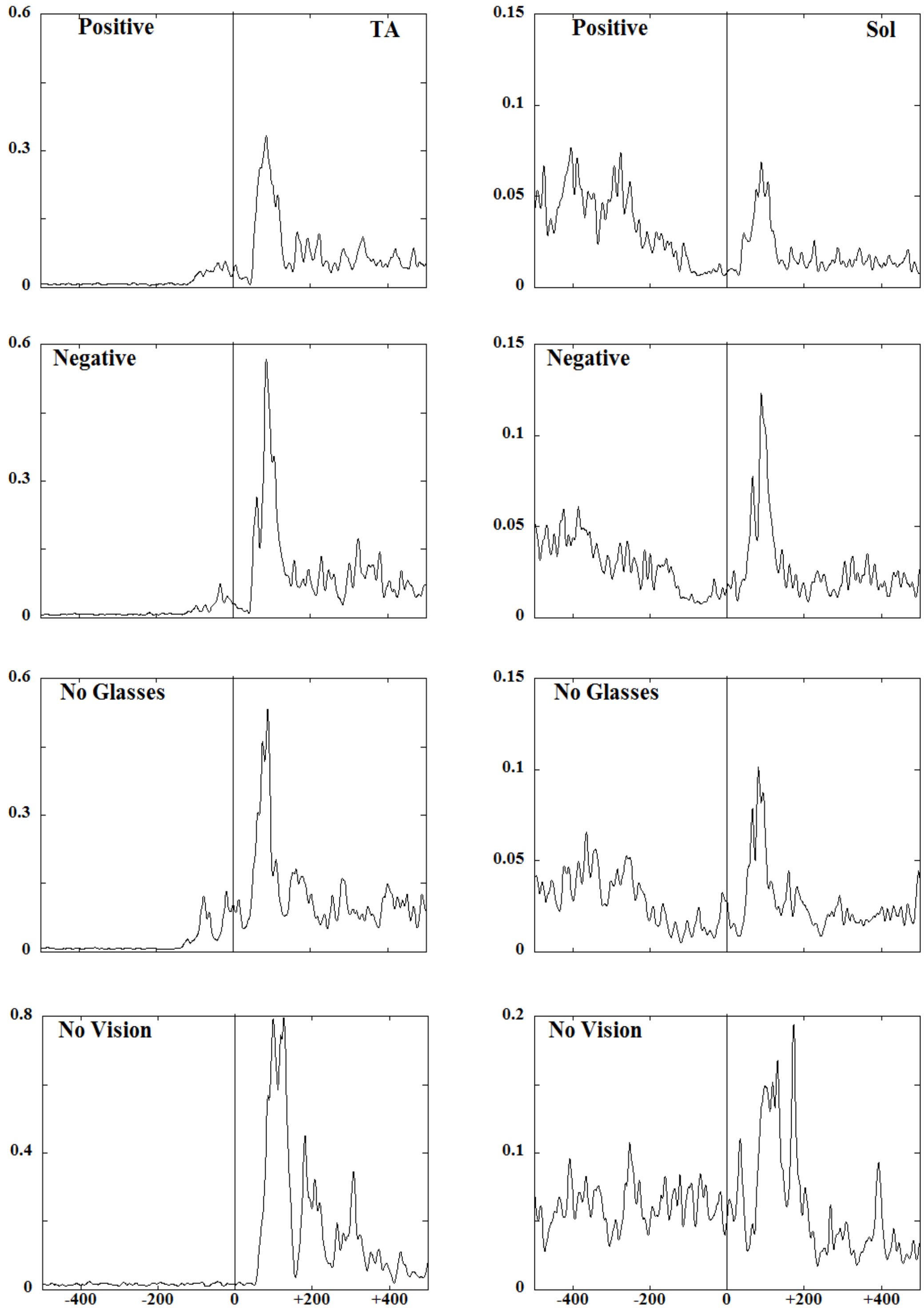


Fig.3. EMG patterns (averaged across 5 trials) for a representative subject for the anterior (TA) and the posterior (Sol) muscles of the right side are presented across all the visual acuity conditions.

3.5.2 Integrals of Electromyography activity

Fig. 4 shows anticipatory $IEMG_{NORM}$ of the trunk and leg muscles averaged across subjects. In general, the anticipatory integrals of EMG (APA1 and APA2) are seen in all conditions with vision available. On the contrary, anticipatory integrals of EMG for the no vision condition were negligible in the three anterior muscles (RA, RF, and TA). Moreover, the magnitudes of the CPA integrals, especially the CPA1, were the largest in the no vision condition.

Comparatively, the existence of anticipatory activity of the anterior muscles in the conditions with no glasses and with differently powered glasses was associated with smaller integrals of EMG during the CPA1 and CPA2 intervals as compared to the no vision condition. Table I shows the repeated measures ANOVA results for conditions, epochs and their interaction. The statistical analysis revealed that there was a significant effect of the conditions, epochs and their interactions. Post hoc analysis showed the no vision condition to be significantly different from conditions with no glasses and conditions in which subjects wore positive eye glasses in the TA ($p < 0.05$). Post hoc analysis also showed that the APA1 and APA2 were significantly different from CPA1 across all anterior muscles ($p < 0.01$). Moreover, the $IEMG_{NORM}$ for TA showed a trend in which the CPA1 magnitude was the highest followed by CPA2, APA2 and APA1.

The posterior muscles (ES and Sol, with the exception of BF) showed inhibition during the APA1 and APA2 epochs in all conditions involving vision (Fig. 4). ES, BF, and Sol $IEMG_{NORM}$ calculated during the APA epochs were negligible in the no vision condition, but were, however, very large during the CPA1 epoch across all muscles.

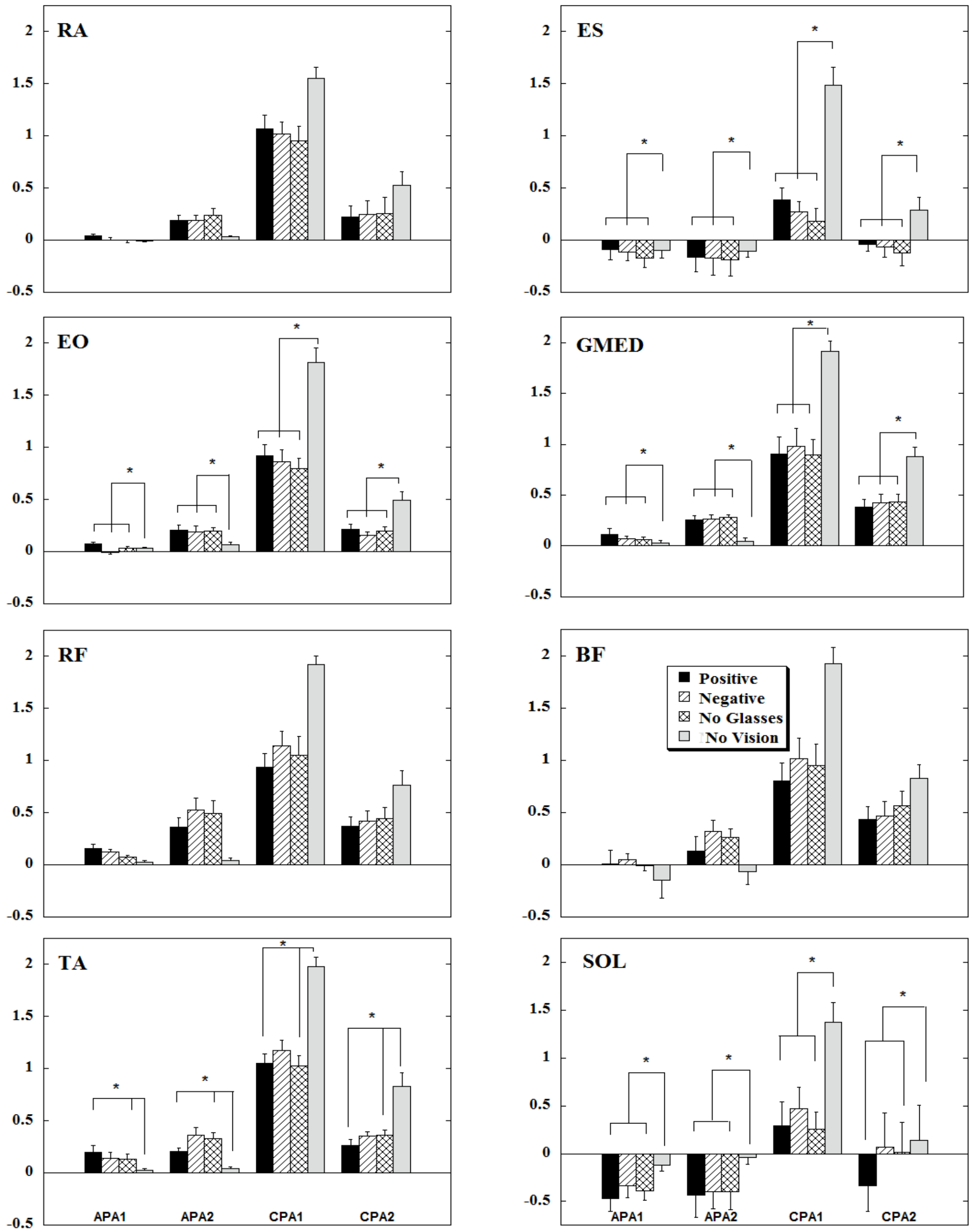


Fig 4. Mean EMG integrals during the four visual acuity conditions across ten subjects. Each column represents the $IEMG_{NORM}$ for 150 ms epochs (APA1, APA2, CPA1 and CPA2) with its standard error bars. * Indicates statistical significance between visual conditions at $p < 0.05$.

Muscles	Conditions		Epochs		Conditions X Epochs	
	F (3,27)	p	F (3,27)	p	F (9,81)	p
RA	3.49	0.03	49.19	<0.0001	7.75	<0.0001
RF	4.92	0.007	99.63	<0.0001	25.87	<0.0001
TA	10.55	<0.0001	163.90	<0.0001	19.75	<0.0001
ES	21.13	<0.0001	35.94	<0.0001	15.69	<0.0001
BF	3.82	0.06	35.84	<0.0001	25.26	<0.0001
SOL	10.41	<0.0001	13.25	<0.0001	3.89	<0.0001
EOb	16.82	<0.0001	177.35	<0.0001	19.33	<0.0001
GMED	14.14	<0.0001	79.52	<0.0001	23.62	<0.0001

Table I. Repeated measures ANOVA of $IEMG_{NORM}$ for conditions, epochs and their interaction. The results are shown for the four experimental conditions: no glasses, positive and negative glasses and no vision and four epochs: APA1, APA2, CPA1 and CPA2.

The results of statistical analysis revealed that the epochs and their interactions were significant across all muscles. Additionally, the effect of conditions was significant for the ES and SOL muscles. Post hoc analysis showed the no vision condition to be significantly different from other visual acuity conditions in ES ($p < 0.01$). Moreover, $IEMG_{NORM}$ in the SOL during the no vision condition were significantly different from integrals calculated in conditions with no glasses and in conditions with positive eye glasses ($p < 0.05$). The APA1 and APA2 epochs were significantly different from the CPA1 epoch in all posterior muscles ($p < 0.01$).

The anticipatory integrals of EMGs for the lateral muscles (EOb, GMED) were also observed in conditions with vision available, and the APA integrals were negligible in the no vision conditions (Fig. 4). The absence of APAs in the no vision conditions resulted in large $IEMG_{NORM}$ during the CPA epochs. Statistical analysis revealed significant effects of conditions, epochs and their interaction. Post hoc analysis showed that the no vision condition to be significantly different from other visual acuity conditions for both the EOb and GMed muscles ($p < 0.05$). The integrals for the APA 1 and APA 2 epochs were significantly different from $IEMG_{NORM}$ during the CPA 1 and CPA 2 epochs in both of these muscles ($p < 0.01$). Post hoc analysis of the epochs for the EOb and GMed showed a trend in which CPA1 magnitude was the highest followed by CPA2, APA2 and APA1.

When statistical analysis was performed comparing the three visual conditions, the results revealed a significant effect for BF: main effect of vision ($F_{2,18} = 3.19$; $p = 0.058$) and main effect of epochs ($F_{3,27} = 15.67$; $p < 0.01$) but no interaction. Pair wise analysis of $IEMG_{NORM}$ between conditions with positive and negative glasses showed that the difference was approaching the level of statistical significance ($p = 0.058$). Post hoc analysis of the epochs for all the studied muscles showed that CPA1 epoch was significantly greater than APA2 epoch.

Additional statistical analyses were performed to assess the effect of blurred vision. Thus, there was a significant main effect of condition (positive and negative glasses) in BF ($F_{1,9} = 8.09$, $p = 0.02$), Sol ($F_{1,9} = 7.13$, $p = 0.026$), RF ($F_{1,9} = 5.23$, $p = 0.048$) and it was close to the level of statistical significance in EOb ($F_{1,9} = 4.06$, $p = 0.07$). There were conditions-epochs interactions observed in RF (positive–negative glasses, $F_{3,27} = 3.94$, $p = 0.019$ and no glasses-positive glasses $F_{3,27} = 3.51$, $p = 0.029$). The visual conditions (no glasses-positive glasses) × epochs interactions revealed that positive glasses resulted in increased magnitudes of RF $IEMG_{NORM}$ in the APA1 whereas $IEMG_{NORM}$ decreased during the CPA1. In addition, visual conditions (negative glasses-positive glasses) × epochs interactions revealed lesser $IEMG_{NORM}$ in APA1 in conditions with negative glasses which resulted in larger $IEMG_{NORM}$ in CPA1 epoch.

3.5.3 Onsets of Electromyography activity

The onsets of EMG activity of all studied muscles for each of the four experimental conditions are presented in Fig. 5. In all conditions with vision available (no glasses, positive and negative glasses) a distal to proximal pattern of activation or inhibition of muscles (with the exception of ES) could be noticed. Thus, in the no glasses condition the distal muscles showed anticipatory activation (e.g. TA at −142.1 ± 12.3 ms) followed by the activation of intermediate muscles (e.g. RF at −135.4 ± 7.2 ms). The proximal muscles were the last to activate (e.g. RA at −56.8 ± 6.7 ms). When the subjects wore positive glasses, a similar distal to proximal pattern was seen (TA at −166.7 ± 10.6 ms, RF at −141.6 ± 10.4 ms, and RA at −81.3 ± 10.3 ms). This pattern was also preserved in conditions with negative glasses (TA at −133.2 ± 11.6 ms, RF at −127.4 ± 12.2 ms, and RA at −63.03 ± 8.1 ms). In the no vision condition, muscles were active only after the perturbation (e.g. TA at 49.9 ± 1.6, RF at 49.4 ± 1.6, and RA at 48.8 ± 2.2) and did not follow any specific pattern of activation or inhibition.

In general, in conditions with positive glasses, latencies of all muscles were the earliest when compared to other experimental conditions. The latencies recorded in conditions with negative glasses and no glasses at all followed the latencies in the conditions with positive glasses. This could be best observed in Sol, BF, RA, and ES (negative glasses) and in TA, RF, GMED and EOb (no glasses).

The results of statistical analysis comparing the four experimental conditions are presented in Table II.

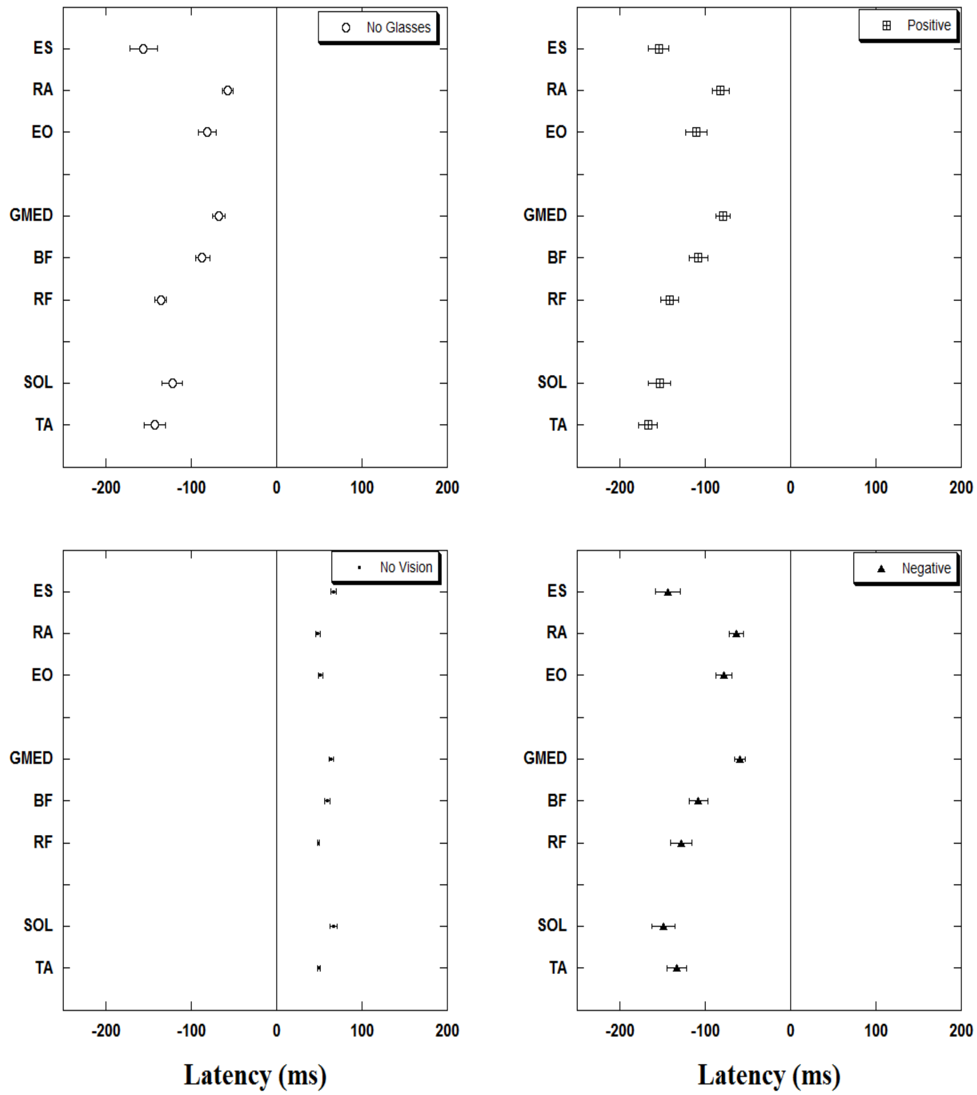


Fig 5. Muscle latencies for the four experimental conditions. Note that in the no vision conditions the onset of activity for all studied muscles is after the perturbation (T_0). The onsets of activity of muscles in conditions with no glasses, positive and negative eyeglasses are before the perturbation impact (T_0). Latencies are grouped for proximal, intermediate and distal muscles.

Pair-wise analysis revealed that significantly different results for all the muscles were only found for the no vision condition when compared with all other visual conditions ($p < 0.05$) as well as between the positive and no glasses conditions ($p < 0.05$).

Muscles	RA	RF	TA	ES	BF	Sol	EOb	GMED
$F_{3,120}$	60.07	123.52	333.62	83.89	89.38	103.06	82.09	110.95
p	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Table II. Repeated measures ANOVA of latencies for all the muscles. The results are shown for the four experimental conditions: no glasses, positive and negative glasses and no vision.

Additional statistical analysis comparing the latencies in the three visual conditions (no glasses, positive and negative glasses) revealed a main effect of conditions for TA ($F_{2,78} = 3.85$, $p = 0.03$), Sol ($F_{2,78} = 3.05$,$p = 0.05$), and EOb ($F_{2,78} = 4.46$, $p = 0.02$). Pair wise comparison revealed differences between the positive and negative glasses conditions in TA ($p = 0.02$) while differences approached the level of significance in EOb ($p = 0.05$). In addition, differences between the positive and no glasses conditions were near the level of statistical significance for EOb ($p = 0.05$) and Sol ($p = 0.07$) muscles.

3.5.4 Changes in the Center of Pressure displacement

The CoP displacements were all in the backward direction irrespective of the visual condition. The statistical analysis comparing all the four conditions showed main effect of conditions for displacement of CoP ($F_{3,27} = 24.28$, $p < 0.0001$) and for the peak CoP displacement after perturbation ($F_{3,27} = 24.43$, $p < 0.0001$). The displacement of CoP at the moment of perturbation (T_0) in the no vision condition was the smallest ($p < 0.01$) (Fig. 6A).

Although not statistically significant, the time at which CoP displacement reached its peak after the perturbation was the shortest in experiments with positive glasses. It was slightly longer in conditions with negative glasses and no glasses. In the no vision condition the time at which CoP displacement reached its peak was the longest among all four conditions (Fig. 6B).

The peak CoP displacement (measured after the perturbation) was significantly higher ($p < 0.01$) for the no vision condition when compared to the other conditions in which vision was available (Fig. 6C). However, when statistical analysis was performed for the three vision conditions, no statistical significant results were found.

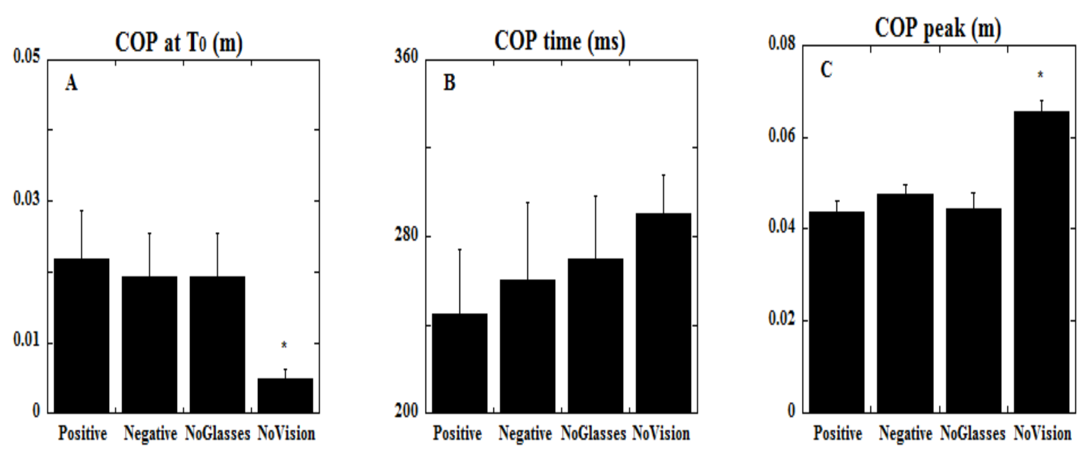


Fig 6. The magnitude of CoP displacement at T_0 (A), the time of the CoP peak (B) and the magnitude of peak CoP displacement (C) are shown as mean with standard errors. CoP positive values correspond to displacements in the direction opposite to the perturbation. Note that, CoP displacements in conditions of standing with no vision are larger than in conditions with no glasses and when wearing positive or negative eyeglasses. * Indicates statistical significant differences at $p<0.05$

3.6 Discussion

The current study was designed to investigate how the changes in visual acuity, induced by wearing differently powered glasses, influence APAs and CPAs in terms of muscular activity and COP displacements. The outcome of the experiments demonstrated that the subjects were able to generate APAs in conditions with blurred vision, thus, partially disputing the hypotheses that blurred vision induced by wearing differently powered eye glasses will affect the generation of APAs. The second hypothesis, that blurred vision influences the relationship between APAs and CPAs, however, was supported as we observed vision condition-related changes in CPAs.

3.6.1 Role of full vision

The role of vision in minimizing body sway has been reported earlier (Paulus et al. 1984; Wade and Jones 1997). However, the literature on the effect of vision in generation of APAs is scarce. This is partially due to the fact that APAs were mostly studied using self-initiated body perturbations such as fast arm (Belenkiy et al. 1967; Friedli et al. 1984) or leg (Nardone and Schieppati 1988) movements. Since the parameters of the self-induced body perturbation became available to the subject's CNS even with no vision, APAs could be expected even in conditions with no vision. Moreover, previously used approaches included voluntary movements, such as arm lifts (used to study APAs and CPAs) or application of unexpected external perturbations, such as movement of the platform on which the subjects stood (to study CPAs) (Hughey and Fung 2005; Gage et al. 2007). However, due to the difference in nature of the perturbations applied, the control processes differed and the outcomes could not be compared. The pendulum-impact paradigm that we used in the current study allows us to apply the same magnitude of whole-body external perturbation (the nature of which does not change during the experiments) to human upright posture, thereby allowing both APAs and CPAs and their interaction to be studied.

The results of the current study reveal that in conditions with vision available, strong APAs (seen as bursts of activity in the majority of muscles and inhibition of activity in ES and Sol) were observed. However, when vision was not available, no APAs were called into play since no information on the moment of the pendulum release was available. Hence, large compensatory postural adjustments were used in order to restore balance (Fig. 6). This result is in accordance with the recent literature that reported a lack of APAs and large CPAs in blindfolded conditions (Santos et al. 2010a). Thus, the outcome of the current study further supports previous data on the importance of full vision in the generation of anticipatory postural adjustments and subsequent minimization of compensatory corrections.

3.6.2 Role of blurred vision

It has been described in the literature that blurred vision affects how humans control their posture. For example, it was reported that blurred vision was responsible for the increased postural instability in healthy subjects when somatosensory and vestibular inputs were disrupted (Anand et al. 2002). Moreover, there was a 25% increase in postural instability in individuals with myopia when they did not wear glasses (Paulus et al. 1984). Visual loss can also be associated with age related macular degeneration (Szabo et al. 2008), or diseases such as glaucoma, cataract, diabetes mellitus (Dhital et al. 2010) and multiple sclerosis (Regan et al. 1981). It was also reported that subjects took

11% longer to execute a stepping task when their vision was blurred by cataract simulation (Heasley et al. 2004).

Blurred vision in the current study was induced by wearing eyeglasses with positive or negative lenses which affected the perception of the pendulum impact. When compared to the perception of the pendulum in the no glasses condition, negative glasses caused the pendulum to appear clear but farther away at the moment of its release, while positive glasses caused the pendulum to appear blurred and closer at the moment of its release.

The observed differences in latencies of anticipatory EMGs as well as $IEMG_{NORM}$ for certain conditions (i.e., negative glasses and positive glasses) were associated with differences between eyeglasses. For example, it appears as though positive lenses create a perception that the pendulum is going to hit the body sooner than in conditions with no glasses. This perception might result in the CNS selecting a strategy of an earlier and larger anticipatory activation of certain postural muscles to prevent body destabilization. On the other hand, negative lenses cause the object to be perceived as positioned farther away, thus delaying and reducing the anticipatory preparation needed to handle the forthcoming perturbation. Indeed, the latency analysis revealed that anticipatory activation of muscles was seen early in conditions with positive glasses as compared to negative glasses or no glasses conditions. Hence, we can assume that the glasses-related differences in perception of the pendulum affect the timing and magnitude of anticipatory muscle activation. Furthermore, we observed that the vision-related changes in APAs translated to differences in the magnitude and timing of CPAs. Thus, peak COP_{AP} displacement was the earliest for the positive glasses condition, followed by conditions with negative glasses, while the no vision condition showed peak displacement the latest. The magnitude of the CPA, measured as the peak COP_{AP} displacement, was the largest for the no vision condition. This result is in agreement with the literature that shows that while standing quietly, COP_{AP} displacements are significantly higher when the visual target is positioned at a far distance (200 cm), compared to the target located at a near distance (40 cm) (Le and Kapoula 2006).

3.6.3 Relationship between Anticipatory and Compensatory Postural Adjustments

The existence of a relationship between the anticipatory and the compensatory components of postural control has been described in experiments with full vision and when visual information about the upcoming body perturbation was not available (Santos et al. 2010b; Santos et al. 2010a). However, there are conditions when vision is partially obstructed or diminished due to, for example, dim light or health issues. In addition, studies have shown that using inappropriate eye glasses, especially in older people, creates a significant risk factor for falls (Lord 2006). Therefore, it is important to gain knowledge on whether changes in the generation of APAs that are due to modified vision translate into changes of the compensatory component of postural control.

The results of this experiment suggest that modifying vision conditions by using differently powered glasses alters the generation of APAs, and as a result, affects CPAs. Thus, anticipatory $IEMG_{NORM}$ in RF, GMED, and TA were larger in the positive glasses condition when compared to the negative glasses condition. This resulted in small $IEMG_{NORM}$ in conditions with positive glasses during the compensatory phase. Such an eyeglasses-related alteration in the electrical activity of muscles was accompanied by small changes in the magnitude of the COP peak displacement during the CPA periods:

COP peaks were larger while wearing negatively powered glasses and smaller while wearing positively powered glasses. Thus, it seems as though the existence of APAs in conditions with differently powered glasses was a primary reason for the diminishing CPAs. Moreover, information about the forthcoming perturbation was available to the CNS even in conditions with altered vision (wearing positive and negative glasses). As a result, APAs were generated and subsequent CPAs were smaller compared to conditions with no vision. This suggests that (1) even with altered vision the CNS could successfully utilize feed forward postural control and (2) CPAs are still influenced by APAs even when vision is modified with differently powered glasses. Indeed, earlier and larger anticipatory activation of certain postural muscles in the condition with positive glasses resulted in lesser magnitudes of compensatory corrections as compared to the condition with negative glasses.

3.7 Conclusion

The study outcome revealed that vision plays an important role in the generation of anticipatory and compensatory corrections while maintaining posture. It was also demonstrated that changes in visual acuity induced by differently powered glasses affect the way anticipatory postural adjustments are utilized, which in turn affects the compensatory control of posture. Hence, the role of differently powered glasses in postural control should not be underestimated.

CHAPTER IV

CONTROL OF POSTURE: ALTERED VISUAL CUES

Data presented in this chapter has been published as: Mohapatra S and Aruin AS (2012). Static and dynamic visual cues in feed-forward postural control, Exp Brain Res (Oct, 14 2012, EPub Ahead of Print).

4.1 Background

While the contribution of somatosensory and vestibular systems to postural control is well documented in the literature, the role of the visual system in control of balance is less understood, despite its importance (Wade and Jones 1997). One of the reasons is the way that visual information is obtained and processed is affected by many factors within human beings themselves, the environment, and the interaction between the two. For example, visual acuity, contrast sensitivity, and depth perception play a significant role in how humans themselves can see the object with clarity. Environmental factors such as lighting in the room also affect the way the individuals see the surrounding. For example, previous literature has shown humans demonstrate diminished ability to control posture in conditions with dimmed lights (Owsley and Sloane 1987; Lord and Menz 2000).

It has also been shown that vision plays an important role in generation of APAs (Krishnan and Aruin 2011; Mohapatra et al. 2011). In particular, APAs associated with catching a load were seen when the subjects watched the upcoming object, but they were absent when the eyes of the subjects were closed (Lacquaniti and Maioli 1989). Similar results were obtained in a series of experiments involving external perturbations induced by a pendulum impact (Santos et al. 2010a). Furthermore, when healthy subjects were catching a falling load onto a tray attached to their trunk and were able to see the load during the first 10 cm of its trajectory (which was approximately 140 ms after the object was unexpectedly released by an experimenter), APAs timed appropriately with respect to the moment of load impact were generated (Aruin et al. 2001). Overall, the outcomes of the previous studies suggest that when adequate visual information for an accurate prediction of the impact time is available, strong APAs can be generated. At the same time, it was shown that diminished visual acuity (induced by differently powered glasses) affected the ability of subjects to predict the impending external perturbation and as such the generation of APAs (Mohapatra et al. 2011). While the previous studies provided important information on the role of vision in the control of posture using anticipatory postural adjustments, in most of the cases they did not study the effect of different visual cues upon APAs.

There are two types of visual cues described in the literature: static cues and dynamic cues. When an object is visible throughout the whole length of time it is moving (this can only be possible when the subject has full vision and can see the object during its whole path), the visual information is obtained using dynamic visual cues. The spatiotemporal relation between the subject and surrounding environmental objects is thus provided by dynamic information from the retina that is mainly generated by the observer’s self motion (Sun et al. 2004) as well as the motion of the objects in the environment (Sun and Frost 1998). When the individual is able to see the object at specific intervals of time but not through the entire length of time, the visual information is obtained via static visual cues. For example, static cues are available when in a dark environment a light exposes the object for a fraction of a second. It is important to note that when objects are seen for a short period of time, (i.e. when the frequency of light on the object is low) the visual information about the movement of the object is inaccurate. At the same time, when the frequency of light on the object increases, the visual information becomes more accurate (Bull et al. 2003).

The issue of relying on visual information becomes even more important when one has to maintain vertical posture that might be affected by external perturbations applied to the body. In such a case, precise visual information about the approaching object could significantly increase the efficacy of postural control. However, the extent to which available visual information about the impending perturbation affects the control of posture has not been fully investigated. In particular, it is not known how different visual cues are utilized in generation of APAs. Thus, the aim of the current study was to investigate the role of static and dynamic visual cues in the generation of the anticipatory postural adjustments. We hypothesized that when healthy subjects are provided with static visual cues about the forthcoming perturbation, they will demonstrate diminished ability to generate anticipatory postural adjustments as compared to conditions where they are provided with dynamic visual cues.

4.2 Subjects

Ten healthy young subjects (6 females and 4 males, mean age of 26.8±1 years, a mean weight of 65.7±4.6 kg and height of 1.67±0.3m) participated in the study. All the study participants had 6/6 visual acuity; they had no musculoskeletal, neurological or balance disorders. The subjects signed an informed consent approved by the Institution Review Board.

4.3 Procedure

The perturbations were induced in conditions with different availability of visual cues. The experimental conditions were dynamic visual cues: full vision (FV) and high frequency (66.67 Hz) strobe light condition (HFS), static cues: low frequency (5.83 Hz) strobe light condition (LFS) , and a control condition: no cues provided at all and the subjects' eyes were open while the room was completely dark (EOD) (Fig 7). In all the conditions the time the pendulum moved from the moment of its release till perturbing the body was the same. However, the subject was able to see the pendulum during its path more frequently in HFS than in LFS.

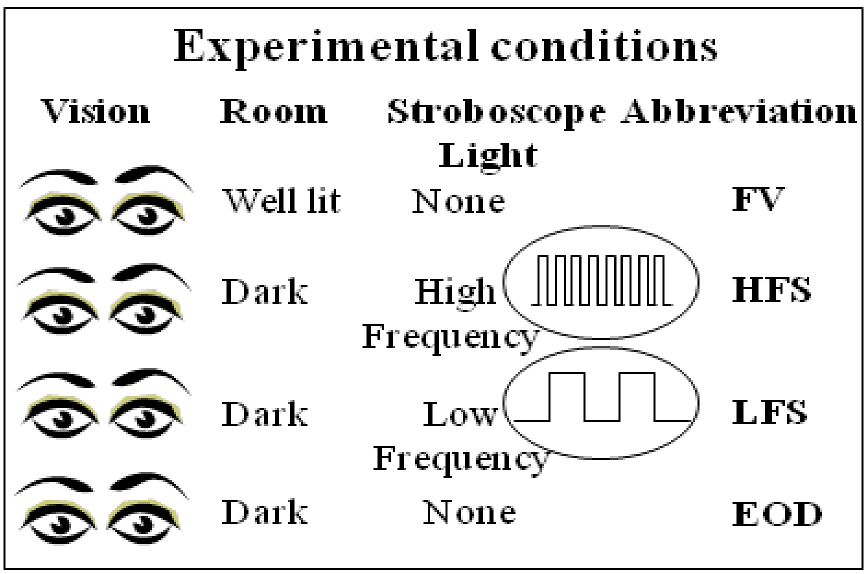


Fig 7 Schematic shows the various cue conditions.

The strobe light was flashed on the pendulum by a Stroboscope (Model: GenRad1531-AB STROBOTAC) and was turned on a few seconds before the pendulum release, while keeping it on during data collection. A range switch on the Stroboscope controlled the strobe light frequency. The lengths of light and dark phases were of equal durations for a particular frequency. Thus the duration for which the flash was either on or off for HFS condition was about 8.5 ms whereas for LFS it was about 85 ms. The intensity of the flash was about 0.16 million beam candles for LFS and 1 million beam candles for HFS. The subjects were always instructed to keep their eyes open and look at the oncoming pendulum. In the EOD condition, the room was made completely dark and the experimenter ensured that the subject did not see the pendulum while keeping their eyes open. In all the conditions the time the pendulum moved from the moment of its release till perturbing the body was the same. However, the subject was able to see the pendulum during its path more frequently in HFS than in LFS.

Electrical activity of the following nine muscles on the right side of the body were recorded: Tibialis anterior (TA), Semitendinosus (ST), Medial gastronemius (MG), Biceps femoris (BF), Rectus femoris (RF), Gluteus medius (GM), External oblique (EOb), Rectus abdominis (RA) and Erector spinae (ES). Principal component analysis (PCA) was applied to correlation matrices of muscles latencies data of all the subjects. The PCs were further subjected to Oblimin with Kaiser Normalization rotation with factor extraction.

4.4 Statistical analysis

Repeated-measures ANOVAs were performed with two within-subject factors: conditions (FV, HFS, LFS, and EOD) and epochs (APA1 and APA2). The dependent variables were $IEMG_{NORM}$s, latency of trunk and leg muscles, magnitude of CoP at the moment of perturbation (T_0), and peak magnitude of the CoP.

Further comparison between conditions, epochs, and their interactions was done by a post hoc analysis using appropriate Bonferroni corrections. For all the above measures, statistical significance was set at $p < 0.05$. SPSS 17 for Windows 7 (SPSS Inc., Chicago, USA) was used to conduct the statistical analysis. Data are presented in the text and figures as means and standard errors.

4.5 Results

4.5.1 Electromyography patterns

Fig. 8 shows EMG patterns for a representative subject for the Tibialis anterior (TA) and Biceps femoris (BF) muscles recorded during all the experimental conditions. Anticipatory activation of TA and BF was seen in the full vision (FV) and high frequency strobe light (HFS) conditions. At the same time, activation of muscles was delayed in the low frequency (LFS) strobe light and eyes open in dark (EOD) conditions.

4.5.2 Onset of muscular activity

The muscle onset times calculated for all the subjects are shown in Fig.9. In the dynamic cue conditions (FV and HFS) almost all the muscles showed anticipatory activity. The earliest activity in the FV condition was seen as an inhibitory response in the ES muscle at 98±47 ms before perturbation whereas in HFS condition the earliest activity was noticed in the RF muscle at 89±34 ms before T_0.

In the static cue condition (LFS) the majority of the muscles showed activity only after T_0 with the exceptions of BF and RF, which were inhibited at (9±21ms) or activated at (15±20ms) respectively before the perturbation.

In the condition where no external visual cues were available (EOD) all the muscles showed activity only after the perturbation onset with the ES muscle showing the most delayed activity at 98±13ms after T_0.

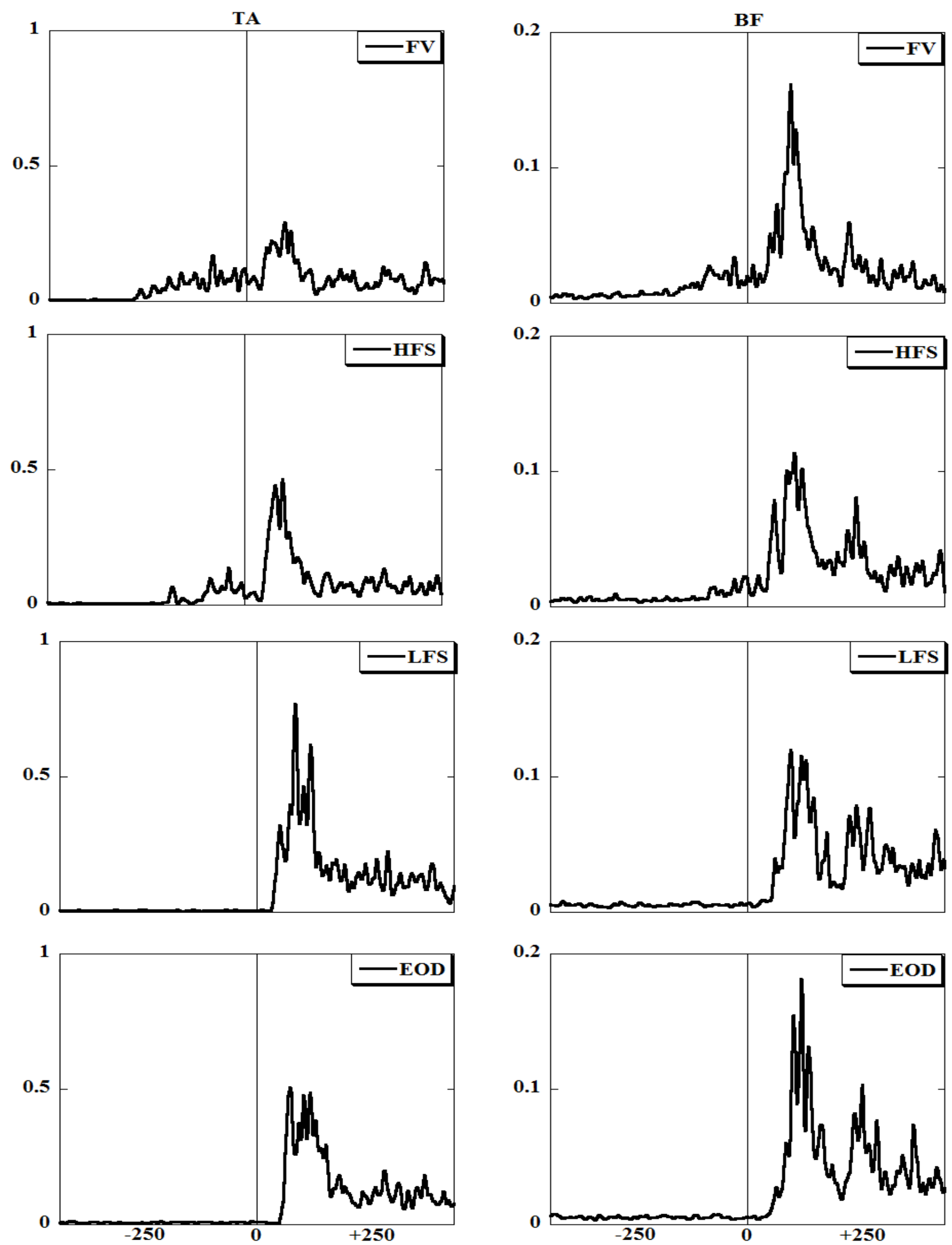


Fig 8. EMG patterns (averaged across 3 trials) for a representative subject for the TA and BF muscles of the right side are presented across all the visual cues conditions. Vertical line at T_0 indicates the moment of pendulum impact. EMG is in arbitrary units. Time is in ms.

PCA validity was confirmed by visual inspections of the scree plots. On an average, three principal components (PCs) (Table III) accounted for 79 % of the total variance in the muscle activation space in the HFS condition and 77 % of the total variance in the FV condition. The first PC in the HFS condition showed high loading values for ES, ST, RF, BF and GM. Whereas in FV condition the first PC was significantly loaded by TA, EOb, MG and RA muscles. The second PC in HFS condition showed high loading values for the muscle onsets of RF, BF, EOb, TA and MG. Whereas in FV condition the second PC was loaded mainly by BF, ES and RA. The third PC was loaded significantly higher in HFS condition by BF, RA and GM muscles but by ST, RF and GM in FV condition.

Muscles	Components (FV)			Components (HFS)		
	1	2	3	1	2	3
TA	**.938**	.314	.166	-.071	**.774**	.009
EOb	**.857**	-.247	-.168	.282	**.793**	.162
MG	**.605**	.035	-.010	-.268	**.681**	-.347
BF	-.135	**.887**	-.068	-.583	**.547**	.457
ES	.341	**.807**	-.082	**.884**	.076	.272
RA	**.617**	-.630	.040	-.246	-.017	**.945**
ST	.255	-.058	**.928**	**.891**	-.109	-.093
RF	-.389	.386	**.754**	**.622**	**.573**	-.398
GM	-.042	-.289	**.620**	.460	-.067	**.772**

Table III. PC analyses for muscle onsets for the FV and HFS conditions are shown. Loading factors are presented for the first three PCs. Loadings over 0.5 are shown in bold.

It is important to note that a co-contraction pattern was seen in especially in the second and third components. A co-contraction is defined as a pattern with significant loading coefficients on the same PC with the same sign (positive or negative) for two muscles with opposing actions at a particular joint (ankle, knee or hip) (Krishnan et al. 2012).

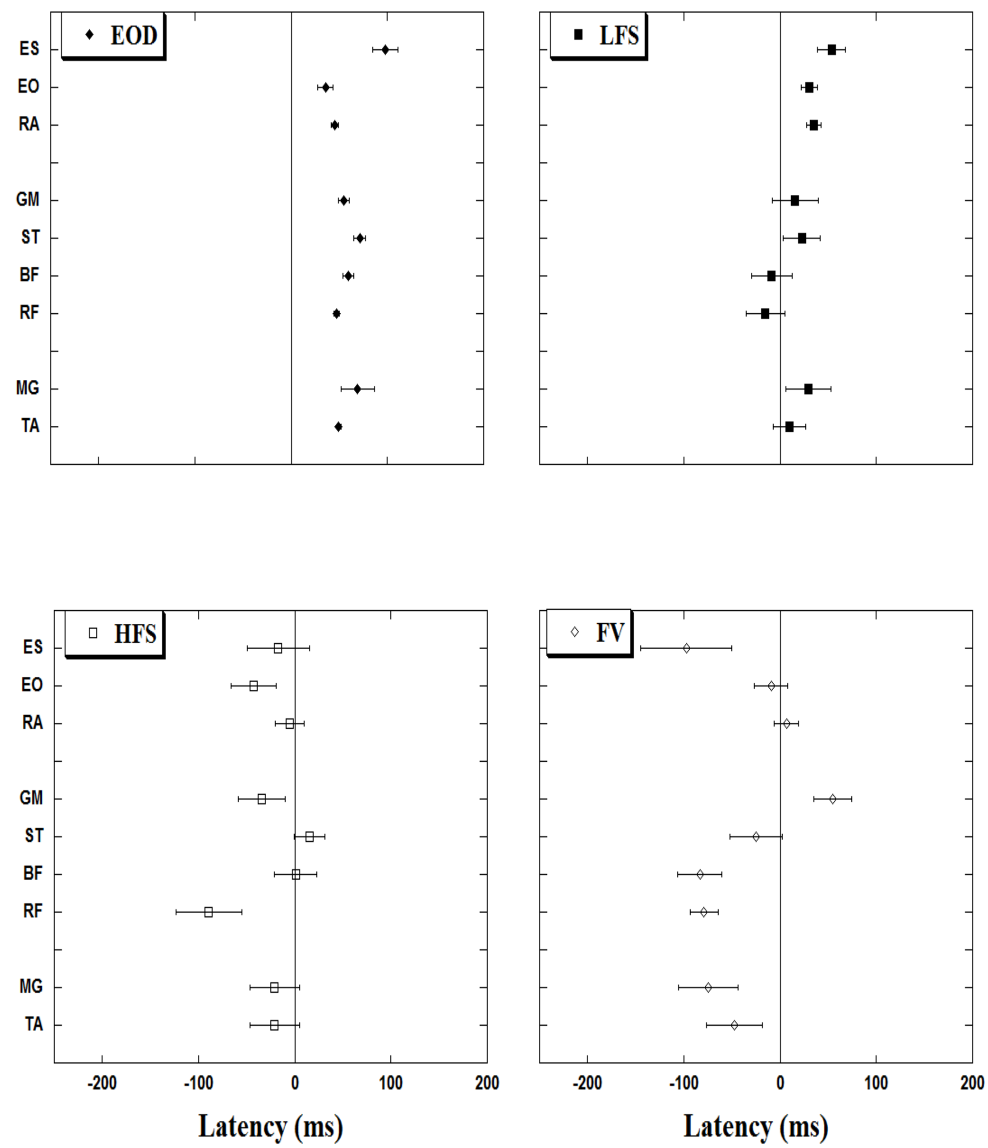


Fig 9**.** Muscle latencies for the four experimental conditions. Note that for the EOD and LFS conditions the onset of activity for all studied muscles is after the perturbation (*T_0*). The onsets of activity of muscles in conditions with FV and HFS are before the perturbation impact (*T_0*).

4.5.3 Electromyography integrals

Integrals of EMG for the four experimental conditions are shown in Fig 10. EMG integrals were larger in the dynamic cues conditions (FV and HFS) than in the static cues (LFS) and no cues (EOD) conditions. A main effect of conditions (Table IV) was seen in GM ($F_{3, 27}$=8.24, p<0.0001), TA ($F_{3, 27}$=9.49, p<0.0001) and RF ($F_{3, 27}$=6.45, p=0.002). Further analysis revealed that this effect was primarily due to significant differences between the dynamic cues (FV and HFS) and no cue (EOD) conditions. Thus, significantly larger EMG integrals in GM (p=0.01 and p=0.04)) and TA (p=0.015 and p=0.001)) were observed in the dynamic cue conditions (FV and HFS respectively) when compared to the no cue condition (EOD).

Muscles	Conditions		Epochs		Conditions * Epochs	
	[$F_{3,27}$]	p	[$F_{1,9}$]	p	[$F_{3,27}$]	p
TA	9.487*	<0.0001	11.935*	0.007	4.771*	0.009
MG	2.325	0.097	1.513	0.25	0.303	0,823
RF	6.454*	0.002	20.019*	0.002	7.805*	0.001
BF	0.596	0.623	0.54	0.481	4.296*	0.013
ST	0.417	0.742	2.155	0.176	0.134	0.939
GM	8.238*	<0.0001	17.702*	0.002	6.755*	0.002
RA	1.684	0.194	12.256*	0.007	5.724*	0.004
EOb	1.733	0.184	17.786*	0.002	5.576*	0.004
ES	1.053	0.385	9.034*	0.015	1.089	0.37

Table IV. Repeated measures ANOVA of $IEMG_{NORMS}$ for conditions, epochs and their interactions. The results are shown for the four experimental conditions: FV, EOD, LFS, HFS and AP1 and APA2 epochs.

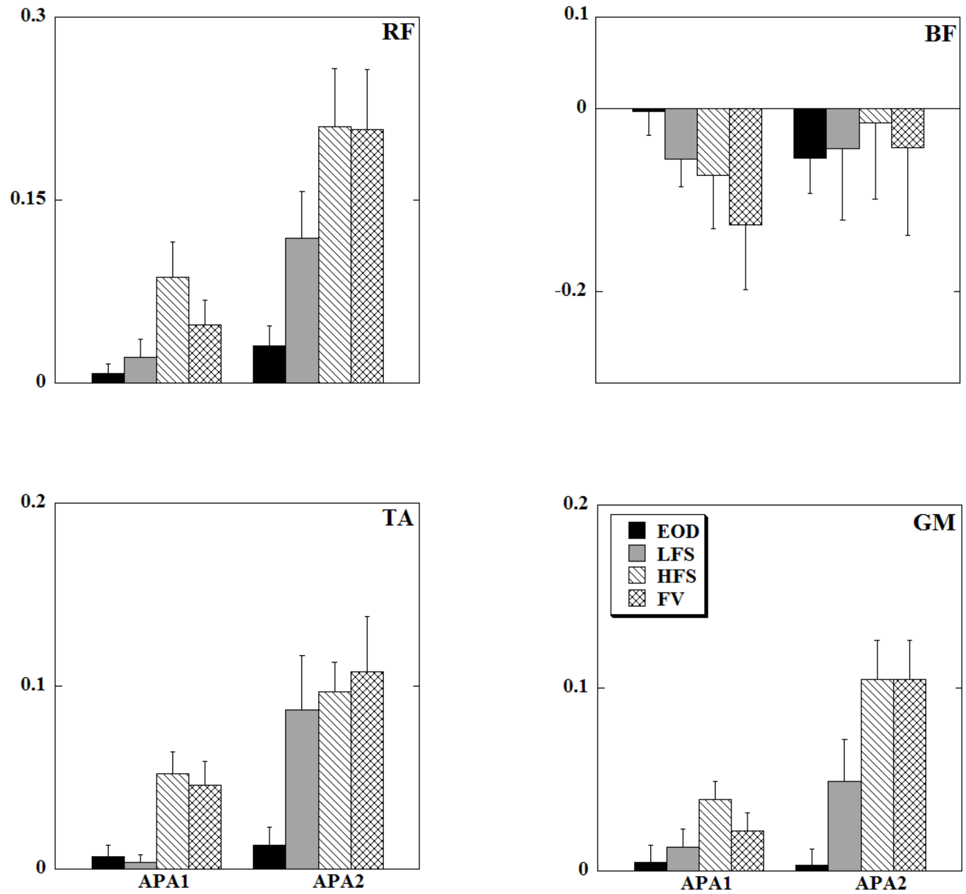


Fig 10. Mean normalized EMG integrals of GM, BF, RF and TA during the four visual conditions for all subjects. Each column represents the $IEMG_{NORM}$s for 150 ms of the APA1 and APA2 epochs with its standard error bars.

There were notable significant differences in the EMG integrals between the various epochs (Table IV). Overall, when epochs were compared, APA2 epoch showed larger muscle activity than APA1 epoch. Significantly ($p<0.05$) larger EMG activity in APA2 epoch was recorded for EOb, ES, GM , RA , RF and TA . There were statistically significant ($p<0.05$) interactions between epochs and conditions for TA, RF, BF, GM, RA and EOb.

4.5.4 Center of Pressure displacements

Fig. 11 shows changes in the position of the CoP in all experimental conditions. Early backward CoP displacements could be seen in FV and HFS conditions. The CoP displacement at the moment of perturbation (CoP T_0), reflecting anticipatory changes in the body position, revealed a significant main effect of cue conditions on APAs ($F_{3, 27}=14.29$, $p<0.0001$).

The displacement at T_0 was the smallest (0.003±0.001m) in the no cue condition (EOD), being significantly smaller than the CoP displacement observed in the dynamic cue conditions, FV (0.014±0.002m, p=0.006) and HFS (0.018±0.002m, p=0.001). Although the anticipatory CoP displacement in the static cue condition (LFS) was smaller (0.008±0.002m) in comparison to the dynamic cue conditions, the difference was not statistically significant.

The magnitudes of the CoP peak for FV, HFS, LFS and EOD were 0.04±0.003m, 0.04±0.003m, 0.05±0.004m and 0.06±0.003m respectively. The peak of the CoP change recorded after perturbation (that is compensatory) showed a significant main effect of various cue conditions ($F_{3, 27}=40.04$, $p<0.0001$).

Further pair-wise comparison revealed that when the subjects were provided with dynamic cues (FV and HFS), the CoP peaks were significantly smaller when compared with static cues (p=0.014 & p=0.003 respectively) and no cues (EOD) (p<0.0001 for both). In addition, the CoP peak for the no cue condition showed significantly larger displacement than static cue condition (p=0.011).

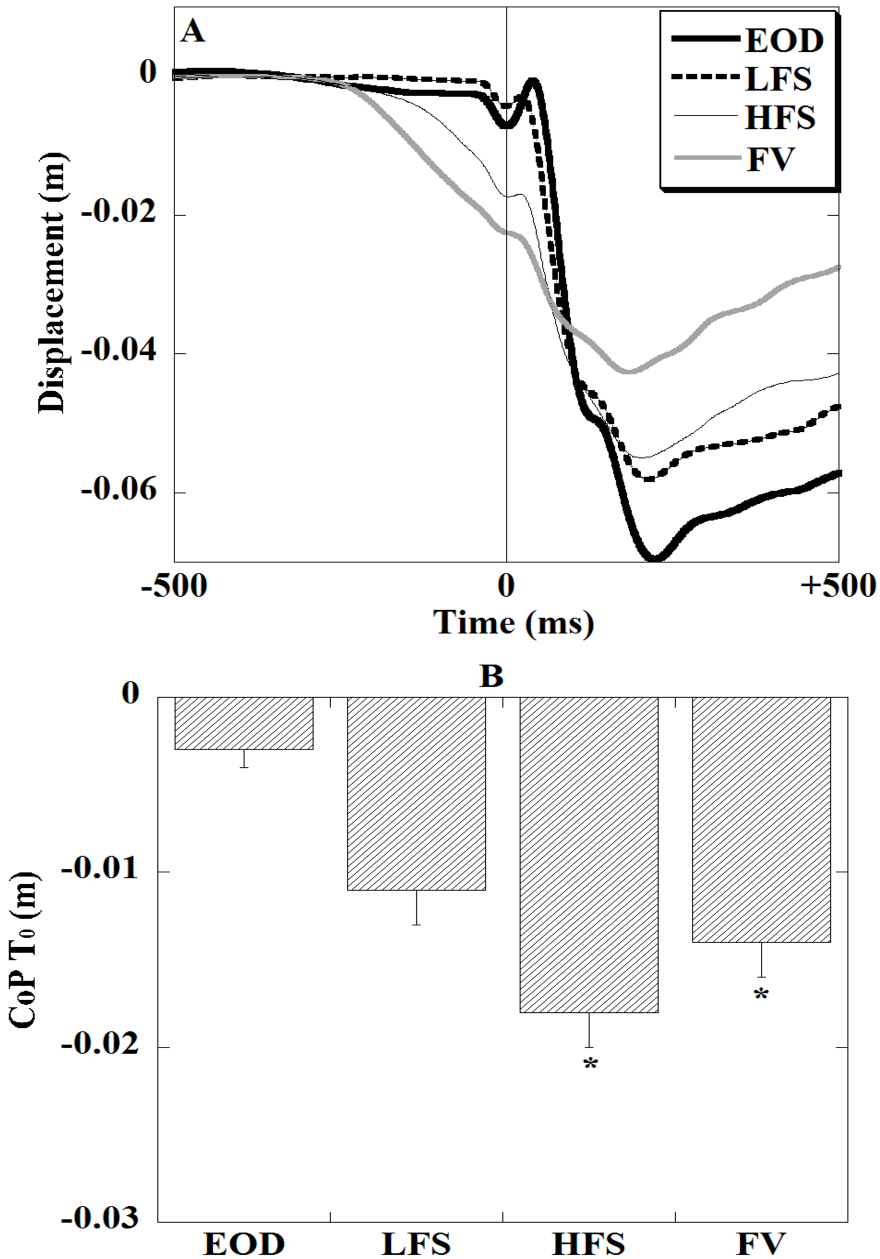


Fig 11. (A) CoP traces for a representative subject are presented across all the visual cues conditions. Vertical line at T_0 indicates the moment of pendulum impact. (B) Mean CoP displacement at T_0 are shown as mean with standard errors. CoP negative values correspond to backward displacements. * indicates statistical significance at $p<0.05$ in comparison with EOD condition.

4.6 Discussion

The results of the experiment reinforce previous findings on the importance of vision in control of vertical posture and provide evidence that feed-forward postural control in standing is modified due to the presence of different visual cues. In particular, the outcome of the study revealed that the availability of the dynamic visual cues was associated with considerable anticipatory activation of muscles producing large anticipatory CoP displacements. However, when static visual cues were provided, the anticipatory activation of muscles and CoP displacements were reduced significantly. Finally, when no visual cues were available there was a complete absence of APAs. Thus, our hypothesis that the ability to generate anticipatory postural adjustments is reduced in conditions with static as compared to dynamic cues was supported.

4.6.1Role of vision in counteracting external perturbations

The role of vision in providing the CNS with continuously updated information regarding the position and movements of the body's segments and its relationship with the environment while maintaining balance is well documented. Thus, when people stand with their eyes closed, the postural sway increases by 20–70% as compared to standing with eyes open (Paulus et al. 1984; Magnusson et al. 1990; Lord et al. 1991a). Moreover, it was demonstrated that modifying visual information by moving visual fields induces a powerful sense of self motion resulting in significant increases in body sway (Wei et al. 2010). In addition, previous research provides a plethora of evidence about the importance of visual information in restoring vertical posture after external perturbation is applied to the body (Clement et al. 1985; Bardy et al. 1999; Schmid et al. 2007).

At the same time, the literature on the role of vision in generation of APAs is limited. This is partially due to the fact that the vast majority of previous APA studies were based on utilizing self-initiated movements to induce body perturbations (Aruin and Latash 1995; Strang and Berg 2007; Klous et al. 2011). However, visual information is not required to generate APAs in response to self-initiated movements of the body segments for example, arm movements. Therefore, to a large extent studies involving self-induced perturbations cannot provide information on the role of vision in the generation of APAs. On the contrary, using a method involving external body perturbations allows the assessment of the role of vision in the generation of APAs and sub sequentially, CPAs. Thus, it was shown in experiments with a load catch that no APAs are produced when vision was not available. However, when visual information about the moment of the load release was available, the subjects were able to generate APAs (Aruin et al. 2001). Moreover, it was recently shown that when vision was available, strong APAs were present which implied that the CNS was aware of the forthcoming body perturbation and had already activated the postural muscles for any adverse effects and the generated CPAs were smaller in magnitude. However, when visual information about the onset of the external perturbation was not known to the subjects (they were standing with eyes closed), the CNS failed to generate APAs and thus the CPAs were massive in magnitude (Santos et al. 2010b; Santos et al. 2010a).

The outcome of the current experiment with full vision also demonstrates the importance of vision in the generation of APAs in relation to the predicted external perturbation: when the subjects were able to see the pendulum they showed strong APAs evidenced by large anticipatory activation of muscles and substantial CoP displacements before the onset of the external perturbation. The generation of strong APAs resulted in more efficient maintenance of vertical posture confirmed by smaller magnitudes of CoP displacement after the perturbation.

4.6.2 Role of quality of visual information in generation of Anticipatory Postural Adjustments

The current study demonstrated that not only availability of visual information *per se* affects generation of APAs in the case of external body perturbations, but also the quality of the available visual information is an important element in maintenance of vertical posture. In particular, the outcome of the study revealed that certain visual cues allow an individual to utilize strong anticipatory postural adjustments needed for efficient control of vertical posture. Thus, when visual cues were dynamic (full vision, FV and high frequency strobe light condition, HFS), APAs were generated. Quite the opposite, when static cues were provided (low frequency, LFS strobe light condition), APAs were significantly diminished.

The differences in the APA generation could be explained by the alterations in the quality of visual information about the pendulum release. Thus, the results of the PC analysis support those different visual cues are associated with different loading responses in the studied muscles. Different loading responses could explain that the cues were qualitatively different. For example in FV the PC1 was significantly loaded for lower leg and trunk muscles while in the HFS it was loaded with trunk and thigh muscles (Table IV). PCA also demonstrates that there were differences in the co-contraction of muscles between the conditions: in FV it was observed in the muscles around the ankle joint whereas in HFS it was around the knee joint.

Temporal parameters of visual cues are also crucial for generation of APAs. Thus, when dynamic visual cues are available continuously either in a well lit environment or when a strobe light is set at high frequency, precise information about the moment of the pendulum release becomes available which results in the generation of strong APAs. In our study, dynamic visual cues were available in the full vision (FV) and high frequency (66.67 Hz) strobe light (HFS) conditions allowing the subjects to see the pendulum either continuously (FV) or intermittently (HFS) during its entire movement until the pendulum hit the body. The existence of APAs in FV conditions is supported by the outcome of numerous previous experiments (Latash et al. 1995; Benvenuti et al. 1997; Toussaint et al. 1998; Yiou et al. 2009), while the current study demonstrated that dynamic cues allow the generation of decent APAs. In particular, visual cues available during the FV as well as HFS conditions provided sufficient information about the moment of the pendulum release thus enabling generation of APAs.

On the contrary, when the strobe light is set at the frequency less than 9Hz (e.g. 5.83 Hz as it was in the current experiment), utilization of such static cues could produce errors in detecting movements of objects as described by (Cian et al. 1997). As such, in the LFS condition the particular moment of the pendulum release might not be known to the subjects thus resulting in diminished ability to predict the consequences of the perturbation and generate strong APAs.

It is known that the CNS generates APAs by releasing a program that is time-locked to the expected body perturbation; such an ability to generate APAs is learned during childhood (Schmitz et al. 1999; Hadders-Algra 2005) and is used by healthy individuals throughout their life. In the current study the subjects knew the moment of the perturbation in HFS, which makes it possible for them to estimate the time –to-contact with his/her body. As such, it is not surprising that obtaining precise information about the pendulum release resulted in healthy young subjects being able to generate strong APAs: In addition previous experiments suggest that when the subjects could see the object during the first 10 cm of its trajectory (which was approximately 140 ms after the object was unexpectedly released by an experimenter), APAs timed appropriately with respect to the moment of load impact were generated (Aruin et al. 2001). Furthermore, kinematics of the falling object is taken into account by the CNS to estimate the time before contact with that object (Zago et al. 2004). Thus, the ability to see the pendulum path helps in obtaining information needed for generating APAs.

When visual cues about the moment of the pendulum release are provided by LFS, the time the subjects were able to see the moving pendulum after it was released was about 85 ms. It appears that this was not enough time to obtain precise information about the pendulum release and to trigger APAs. This conclusion is in line with the literature describing that the "time pressure" conditions (induced by the instructions to perform arm lifts under a simple reaction-time instruction) were associated with the inability of the subjects to generate the regular pattern of APAs (De Wolf et al. 1998).

There are some study limitations, which should be taken into consideration. First, we performed experiments in a dark room. While walking in a poorly lit room is a common task for many activities of daily living, dealing with external perturbations in a completely dark room is not very common. As such, while the study outcome provides an insight into the use of visual information in the control of vertical posture, additional studies performed in a room with some light are needed. Second, while we were able to investigate the role of static and dynamic cues in control of posture, only two frequencies of the stroboscope light were used suggesting a need to further investigate the effect of visual cues at different frequencies. Thus, a separate study to understand how different frequencies of static (<9Hz) and dynamic (>9Hz) cues affect APAs can be investigated in the future. Moreover, the Stroboscope needs to be synchronized with the moment of the release of the pendulum so that the light and dark phases of the flashes are better controlled. Third, since the stroboscope induced continuous change in the lighting conditions, it is not known how APAs are generated when only a single light of certain duration is provided.

4.7 Conclusion

In our experiment we altered visual cues to investigate their role in control of vertical posture in humans. The outcome of the study revealed that when dynamic cues are available it is easier for the CNS to predict the upcoming perturbation and generate APAs than when static cues are available. This conclusion is supported by the corresponding changes in the EMG activity and CoP displacements. The outcome of the study will help understand how different visual cues can enhance generation of APAs and thus enhance control of vertical posture.

CHAPTER V

CONTROL OF POSTURE: ACHILLES TENDON VIBRATION

Data presented in this chapter have been published as: Mohapatra S, Krishnan V, Aruin AS (2012). Postural control in response to an external perturbation: effect of altered proprioceptive information. Exp Brain Res 217: 197-208.

5.1 Background

A number of techniques are used to alter proprioception while studying control of posture. Among them are a local anesthesia (Kjaergard et al. 1984), cuff compression (Mauritz and Dietz 1980; Demura et al. 2008) or lower legs cooling (Fujiwara et al. 2003; Stal et al. 2003). Another relatively easy-to-implement way of altering proprioception involves vibrating the muscle tendons (Roll et al. 1993; Gurfinkel and Kireeva 1995; Gurfinkel et al. 1996). For example, the effect of a vibratory stimulus has been studied by vibrating the neck (Courtine et al. 2003), trunk (Schmid et al. 2005), or ankle tendons (Thompson et al. 2007). It had been demonstrated that vibration applied to the ankle muscles produces body tilts in stance without any effect on gait (Ivanenko et al. 2000; Courtine et al. 2001; Verschueren et al. 2002). Such a vibration, if applied at the proper frequency and amplitude, activates mainly the muscle spindles connected to the primary Ia afferents. The CNS interprets this vibration as a stretching of that muscle (Burke et al. 1976; Roll and Vedel 1982; Roll et al. 1989). This results in an interpretation of proprioceptive information which does not match with the actual body position. Consequently, the body starts tilting in the direction of the vibrated muscles (Hayashi et al. 1981) which is accompanied by the increased body sway (Eklund 1973; Gurfinkel and

Kireeva 1995). Such a vibration has been shown to change spatial body orientation very fast (Roll et al. 1989; Ceyte et al. 2007; Thompson et al. 2007) resulting in a postural response known as a ‘vibration-induced falling’ (Eklund 1973; Hayashi et al. 1981). It was shown that if the effect of vibration-induced changes in proprioception is combined with erroneous signals from visual and/or vestibular systems, the control of vertical posture becomes yet more complex. Thus, it was reported that bilateral Achilles tendon vibration applied in the absence of vision resulted in the backward lean of the body with trunk extension, posterior pelvic tilt and flexion of hips and knees (Thompson et al. 2007). When vibration was applied to the Soleus muscles simultaneously with a moving visual scene which compromised visual information, the angles of “body –tilt” that were induced by the vibration were modulated by the motion of the visual scene (Adamcova and Hlavacka 2007). In contrast to this, it has been shown that body instability diminishes the effect of vibration applied to the Achilles tendon (Ivanenko et al. 1999) or tensor fascia latae muscles (Gurfinkel et al. 1996). Based on the outcome of these studies it was suggested that when tendon vibration is combined with body instability, the vibration-induced artificial afferent flow is blocked (Ivanenko et al. 1999). At the same time, it was demonstrated that increased body stability, produced by a back support combined with the vibration-induced changes in proprioception, did not affect the body tilt induced by the Achilles tendon vibration (Talis and Solopova 2000). Information on the role of altered proprioception or proprioceptive stimulation on anticipatory and compensatory components of postural control is limited. Nevertheless, it was reported that vibration of Achilles tendons induced an increase in APAs in rectus femoris, biceps femoris and erector spinae muscles prior to the fast arm movements and load release (Slijper and Latash 2004). It was also demonstrated that the latency of the anticipatory activation of biceps femoris in the experiments with the fast arm flexion movement is modulated depending upon the application of the vibratory stimuli. When vibration was applied to Tibialis anterior, early activation of Biceps femoris was elicited 30 ms earlier than when applied to the Soleus muscle (Kasai et al. 2002). The outcome of our recent experiments with altered vision (wearing glasses with negative lenses) revealed that activation of the trunk and leg muscles observed prior to the body perturbation induced by a swinging pendulum is delayed and reduced as the pendulum was perceived positioned further away. However, it is still unknown if the backward body lean induced by vibration of Achilles tendons (that might lead to the pendulum being perceived as positioned further away) would associated with similar delayed and reduced APAs.

Studies of the effect of altered proprioceptive information on compensatory postural control revealed that bilateral Achilles tendon vibration affects body kinematics and COM and COP displacements (Thompson et al. 2011). At the same time it has been shown that the patterns of adaptation to the rotational movements of the support surface were not affected by the application of bilateral Achilles tendon vibration (Hatzitaki et al. 2004).

Sensory deficit is a well-known consequence of many neurological disorders. While sensory deficit is commonly seen in the entire limb, still there are cases of patchy and localized loss of proprioception (Lephart et al. 1997; Ducic et al. 2004; Harati Y 2008; Eun et al. 2011). As such investigating the effect of altered proprioceptive information in control of posture has the potential to help enhance balance rehabilitation. Moreover, little is known about how changes in proprioceptive information affect the generation of anticipatory and compensatory corrections used to maintain balance before and after an external perturbation. In addition, it is virtually unknown how changes in proprioceptive information combined with changes in visual information modify the relationship between anticipatory and compensatory components of postural control. These deficits in the research limit the development of rehabilitation approaches that are centered on APA-based interventions that seek to restore balance abilities in individuals with altered proprioception.

In this study we aimed to investigate how changes in proprioception, induced by a vibration applied to Achilles tendons in condition with and without vision influence the APAs and CPAs. We hypothesized that: 1) APA patterns will be different between conditions with intact and altered proprioception. In particular, due to the backward body tilt and increased sway we expect to see delays in the anticipatory activation of muscles. 2) In conditions with altered proprioception, CPA patterns will differ when compared to conditions with intact proprioception irrespective of the availability of vision.

5.2 Subjects

Nine healthy subjects (3 males and 6 females) without any known neurological, musculoskeletal or balance disorders participated in the experiment. The mean age of the subjects was 25 ± 0.9 years; mean body mass 64.2 ± 4 kg; and mean height 1.67 ± 0.03 m. They all signed a written informed consent approved by the Institutional Review Board.

5.3 Procedure

The subjects were instructed to maintain their balance after the perturbation. The four experimental conditions were: (1) eyes open (EO), (2) eyes open with tendon vibration (VEO), (3) eyes closed (EC), and (4) eyes closed with tendon vibration (VEC) (Fig 12).

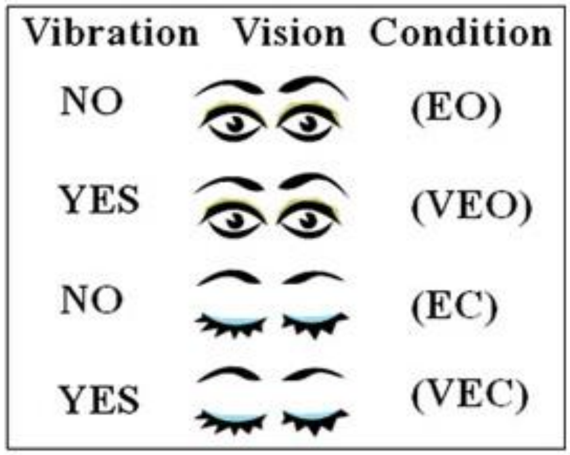


Fig.12. A schematic showing the various experimental conditions.

In eyes closed conditions the subjects were wearing an eye mask. A chalk was used to mark the subject's foot position on the top of the force platform at the start of the experiment. The experimenter throughout the experimental conditions checked this foot position. The subjects stood with their arms at their sides, and the pendulum impact was on their shoulders while proprioception and visual conditions were manipulated. Two custom-built miniature tendon vibrators were securely strapped bilaterally to the Achilles tendons of the subject. The vibrator produced a vibration at the frequency of 90 Hz with 1 mm amplitude. The vibrators were switched on one minute prior and were kept on throughout the five trials in each of the two conditions involving tendon vibration. The results of a pilot experiment involving two subjects demonstrated that vibration induces a small backward body tilt however; both the subjects were able to keep their balance throughout the experimental condition that lasted for about 30 s. After the recording, the subjects were required to open their eyes and vibrators were turned off for at least one minute. During this time the subjects performed dynamic movements of ankle (for example, walking in place.) to minimize the effect of vibration (Thompson et al. 2007). Electrical activity of muscles (EMGs) were recorded unilaterally (right side) from the following muscles: tibialis anterior (TA), Soleus (SOL), biceps femoris (BF), rectus femoris (RF), gluteus medius (GMed), rectus abdominis (RA), external oblique (EOb) and erector spinae (ES).

5.4 Statistical Analysis

Multiple repeated measures ANOVAs were performed with two within subject factors: visual conditions (EO, VEO, EC and VEC) and epochs (APA1, APA2, CPA1 and CPA2). The dependent variables were $IEMG_{NORM}$s, latency of trunk and leg muscles, peak magnitude of the COP, time of the COP peak magnitude, and magnitude of COP at the moment of perturbation (T_0). A post hoc analysis with Bonferroni correction was further done to compare between conditions, epochs and their interactions. For all tests, statistical significance was set at $p < 0.05$. Statistical analysis was performed in SPSS 17 for Windows 7 (SPSS Inc., Chicago, USA).

5.5 Results

<u>5.5.1 Electromyography Profiles</u>

Fig. 13 shows EMG traces obtained from the anterior (RF) and the posterior (BF) muscles of a representative subject performing the experimental task under four different conditions. Anticipatory activity, seen as bursts in the background EMG activity, was present in the two conditions with eyes open. Quite to the contrary, anticipatory activity was negligible in the no vision conditions. Moreover, in conditions with tendon vibration the activation of RF and BF were delayed in the eyes open conditions. EMG activity after the perturbation was larger in EC condition as compared to EO condition where anticipatory activity was present. In addition, peaks of EMG activity during the compensatory period were smaller in conditions with tendon vibration (VEO and VEC).

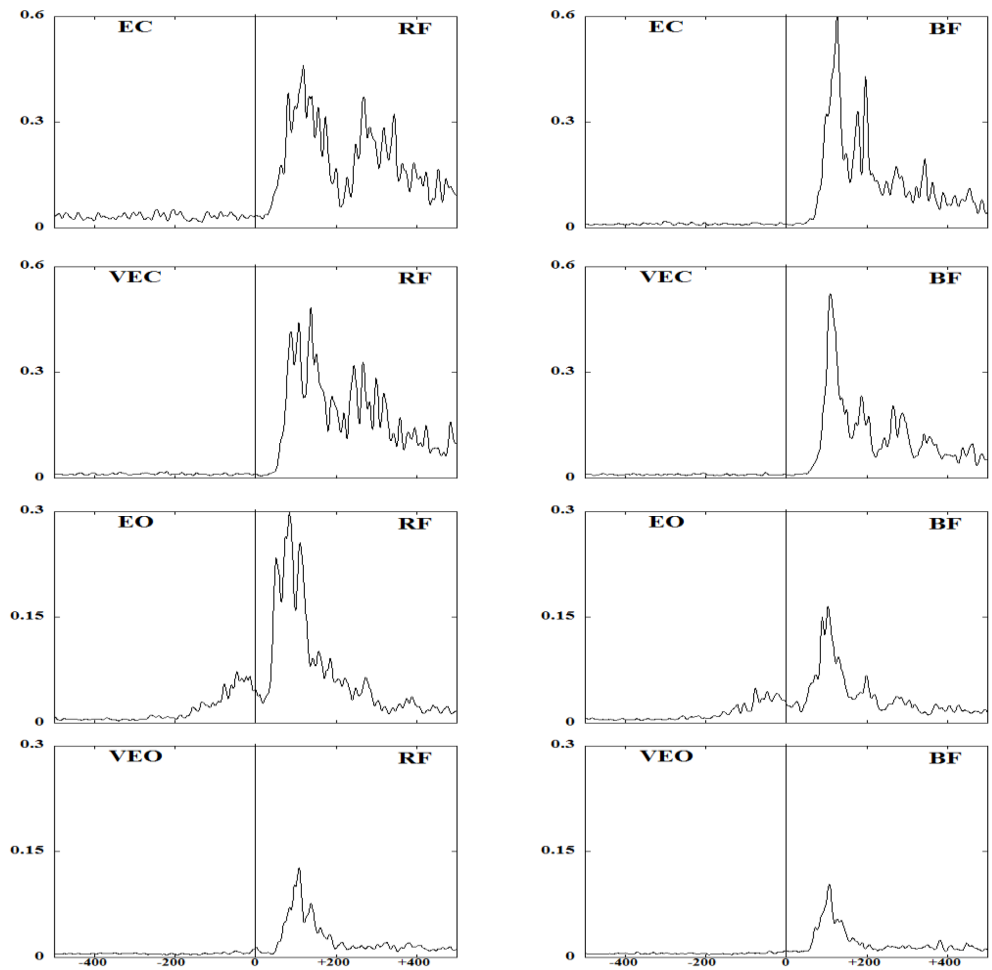


Fig 13. EMG patterns (averaged across 5 trials) for a representative subject for the rectus femoris (RF) and biceps femoris (BF) muscles are presented across all the experimental conditions. Vertical line at T_0 indicates the moment of pendulum impact.

5.5.2 Integrals of Electromyography activity

The anticipatory and compensatory $IEMG_{NORM}$ of the trunk and leg muscles averaged across subjects are shown in Fig 14. In general, the anticipatory integrals of EMG (APA1 and APA2) are seen in all anterior muscles, (RA, RF, and TA) in the conditions where vision was available. In VEO condition, the anticipatory integrals of EMG across all anterior muscles stayed relatively the same as in the EO condition whereas the compensatory integrals of EMG were reduced in the VEO as compared to EO condition. Anticipatory integrals of EMG for these muscles were absent or negligible in conditions when eyes were closed (EC and VEC). As a result, compensatory $IEMG_{NORM}$ in the two blindfolded conditions were larger compared to eyes open conditions. When tendon vibration was applied in the conditions with eyes closed, compensatory $IEMG_{NORM}$ were smaller compared to the eyes closed condition with no tendon vibration. Overall, the largest $IEMG_{NORM}$ for all anterior muscles during the CPA1 were seen in the EC, followed by VEC, EO and VEO conditions. Table V shows the repeated measures ANOVA results for conditions, epochs and their interaction. The statistical analysis revealed a significant effect of the conditions, epochs and their interactions. Pair wise comparisons of conditions showed that RA $IEMG_{NORM}$ calculated for the EC-EO and VEO-VEC conditions were significantly different ($p<0.05$). Moreover, TA $IEMG_{NORM}$ for the, EO-EC, EO-VEC, EC-VEO and VEO-VEC pairs were statistically significant ($p<0.05$). Pair wise comparisons of epochs showed that APA1-CPA1, APA1-CPA2, APA2-CPA1 and CPA1-CPA2 pairs to be significantly different ($p<0.05$) in all the anterior muscles. The interactions revealed that $IEMG_{NORM}$ were smaller with application of vibration in both the CPA1 and CPA2 epochs for both EO and EC conditions.

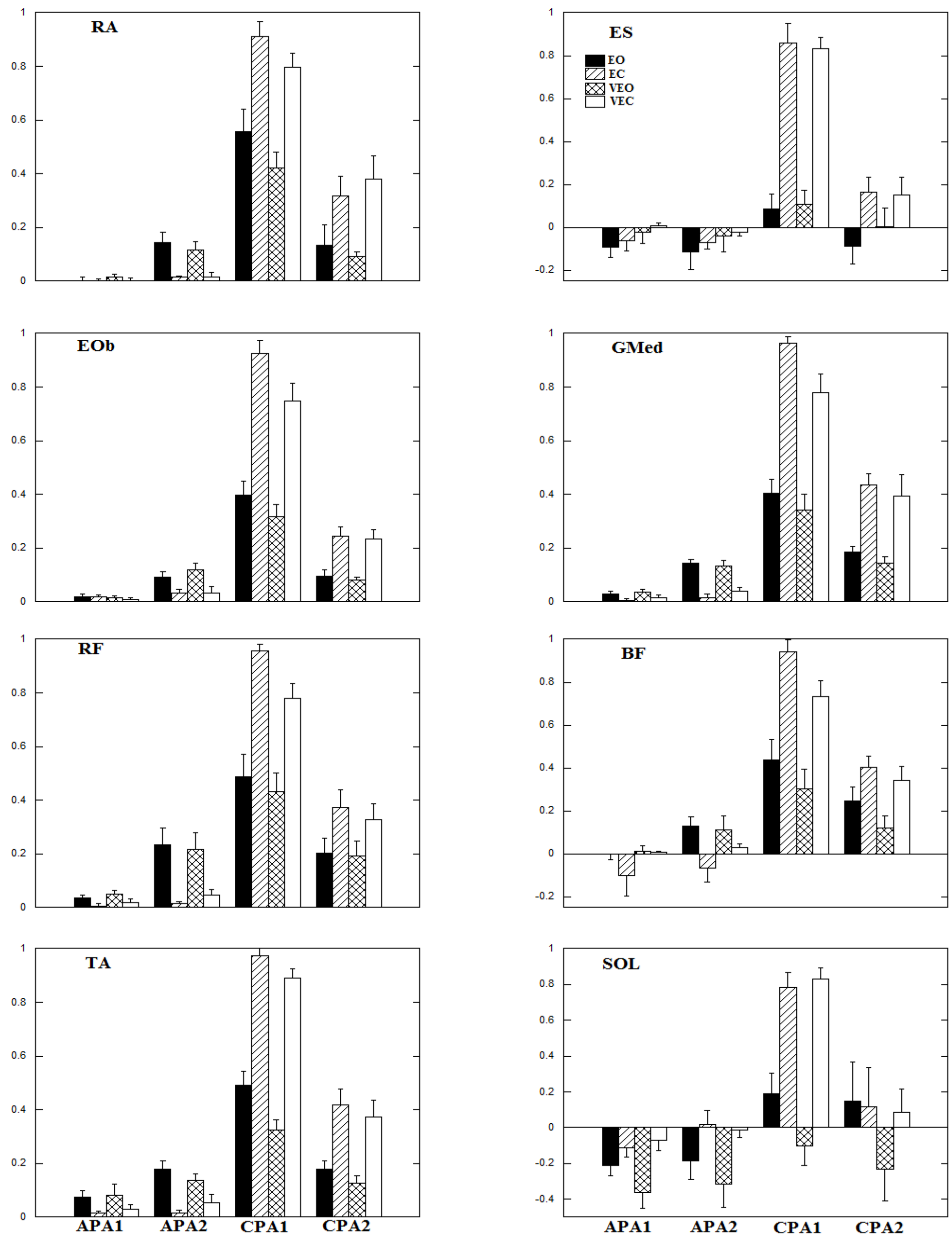


Fig 14. Mean EMG integrals during the four experimental conditions across subjects. Each column represents the Int_{EMGi} for 150 ms epochs (APA1, APA2, CPA1 and CPA2) with its standard error bars.

Muscles	Conditions		Epochs		Conditions * Epochs	
	$[F_{3,24}]$	p	$[F_{3,24}]$	p	$[F_{9,72}]$	p
TA	16.83	<0.0001	203.33	<0.0001	41.55	<0.0001
SOL	17.13	<0.0001	16.05	<0.0001	6.99	<0.0001
RF	3.60	0.03	141.48	<0.0001	23.74	<0.0001
BF	3.04	0.04	76.27	<0.0001	33.61	<0.0001
GMed	16.34	<0.0001	184.72	<0.0001	28.93	<0.0001
EOb	18.89	<0.0001	257.41	<0.0001	27.60	<0.0001
RA	8.43	0.001	72.17	<0.0001	13.07	<0.0001
ES	17.03	<0.0001	78.55	<0.0001	22.69	<0.0001

Table V. Repeated measures ANOVA of $IEMG_{NORM}$ for conditions, epochs and their interactions. The results are shown for the four experimental conditions: EO, EC, VEO, VEC and four epochs: APA1, APA2, CPA1 and CPA2.

The anticipatory activity (APA1 and APA2) represented by integrals of EMG is also seen in all posterior muscles (ES, BF, and SOL) in conditions with vision available. In the VEO condition, the compensatory integrals of EMG were reduced when compared to EO condition for all posterior muscles except ES. Anticipatory integrals of EMG for these muscles were absent or negligible in conditions when eyes were closed (EC, VEC). As a result, compensatory $IEMG_{NORM}$ in the two blindfolded conditions were larger compared to eyes open conditions. However, in conditions with the tendon vibration (VEC) the compensatory $IEMG_{NORM}$ in all posterior muscles with the exception of SOL were smaller compared to EC condition. The repeated measures ANOVA results revealed a significant effect of the conditions, epochs and their interactions (Table V). Pairwise comparisons of conditions discovered that ES $IEMG_{NORM}$ were statistically significant for the following conditions: EO-EC, EO-VEC, EC-VEO and VEO-VEC ($p<0.05$). Moreover, the SOL $IEMG_{NORM}$ were statistically significant between the EO-VEO, EC-VEO, and VEO-VEC conditions ($p<0.05$). Pairwise comparisons of epochs showed APA1-CPA1 and APA2-CPA1 pairs to be significantly different ($p<0.05$) in all the posterior muscles. $IEMG_{NORM}$ were smaller with application of vibration in both the CPA1 and CPA2 epochs for both EO and EC conditions which is supported by significant interactions.

The anticipatory integrals of EMG (APA1 and APA2) are seen in both the lateral muscles (GMed and EOb) in conditions with vision available. On the contrary, anticipatory integrals of EMG for these muscles were absent or negligible in conditions when eyes were closed. When tendon vibration was present in VEO condition, the anticipatory integrals of EMG stayed relatively the same as in the EO condition whereas the compensatory integrals of EMG were reduced in the VEO condition in both the lateral muscles. Similar pattern was also seen in these muscles when VEC and EC conditions were compared. Overall, the largest $IEMG_{NORM}$ during CPA1 was seen in the EC, followed by VEC, EO and VEO conditions for both the lateral muscles. Table V shows the repeated measures ANOVA results for conditions, epochs and their interaction. The statistical analysis revealed that there was a significant effect of the conditions, epochs and their interactions. Pairwise comparisons of conditions discovered that GMed $IEMG_{NORM}$ during EO-EC, EO-VEC and EC-VEO conditions were significantly different ($p<0.05$). Moreover, EOb $IEMG_{NORM}$ during EO-EC, EO-VEC, EC-VEO and VEO-VEC conditions pairs were statistically significant ($p<0.05$). Pairwise comparisons of epochs showed all the pairs to be significantly different ($p<0.05$) from each other for both the muscles. The interactions revealed that $IEMG_{NORM}$ were smaller with application of vibration in both the CPA1 and CPA2 epochs for both EO and EC conditions.

5.5.3 Onset of Electromyography activity

The onset of EMG activity of all studied muscles for each of the four experimental conditions is presented in Fig 15. In the EO condition all the muscles showed anticipatory activation, with SOL and ES showing inhibition before the perturbation. When tendon vibration was induced in the VEO condition, the onset of all leg and trunk muscles was significantly delayed ($p<0.0001$). It is interesting to note that when tendon vibration was applied in conditions with full vision, the onset of the lateral (GMed and EOb) and trunk (RA and ES) muscle activity was further delayed so the muscles became active only after the perturbation. Thus, in the EO condition TA became active first at −140 ± 12 ms followed by BF (−85 ± 8 ms), GMed (−61 ± 6 ms) and RA (−47 ± 7 ms) before the perturbation. In VEO condition TA was active at −33 ± 13 ms followed by BF (−8 ± 11 ms) before the perturbation whereas, GMed and RA were active +17 ± 8 ms and +12 ± 8 ms respectively after perturbation.

In both the EC and VEC conditions the onset of muscle activity for all muscles was seen only after perturbation. ANOVA revealed no difference between the onset of muscle activation involving the EC and VEC conditions.

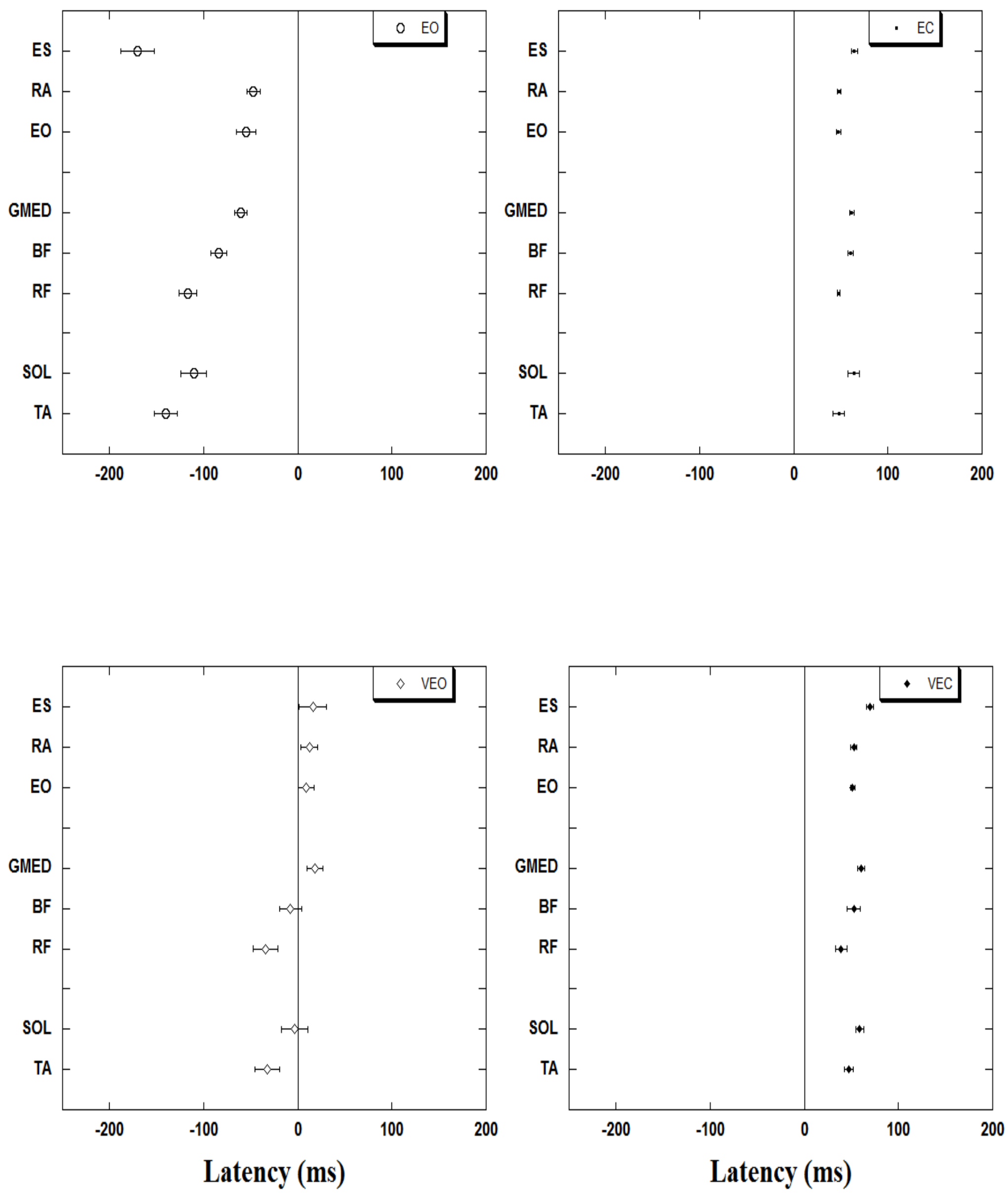


Fig 15. Muscle latencies with standard error bars are represented for the four experimental conditions. Note the delay of muscle activation in VEO.

5.5.4 Changes in the Center of Pressure displacement

The perturbation-related CoP displacements were all in the backward direction irrespective of the condition. The anticipatory displacement of CoP at the moment of perturbation (T_0) was the smallest for the EC followed by VEC, EO and was the largest for the VEO condition (Fig. 16). Statistically significant differences ($p<0.01$) were found for the anticipatory CoP displacement (at T_0) between EO-EC, EO-VEC, EC-VEO and VEO-VEC conditions.

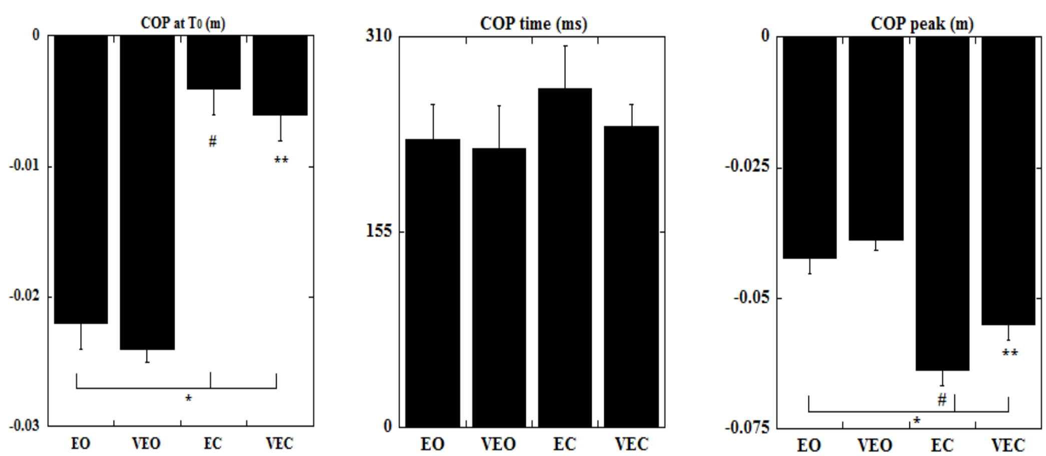


Fig 16. The magnitude of COP displacement at T_0, the time of the COP peak and the magnitude of peak COP displacement are shown as mean with standard errors. COP positive values correspond to displacements in the direction opposite to the perturbation. * Indicates statistical significance at $p<0.05$

The time to the peak COP (Fig. 16) was reduced in conditions with vibration (VEO and VEC). The COP peak was seen earliest in VEO followed by EO and VEC whereas it was most delayed in the EC condition. This difference in time however was not statistically significant. The magnitude of the COP displacement after perturbation (Fig. 16) was the highest for the EC followed by VEC, EO and it was the smallest for the VEO condition. Statistically significant differences were found between EO-EC, EO-VEC, EC-VEO and VEO-VEC conditions ($p<0.05$).

5.6 Discussion

This study was designed to investigate how the changes in proprioception, induced by vibratory stimuli to the Achilles tendon, influence APAs and CPAs in terms of muscular activity and COP displacements. The outcome of the experiments supports the first hypothesis that the alteration of the lower leg proprioception in the presence of vision resulted in significant delays of anticipatory activation of muscles (APA). The results of the experiments also support the second hypothesis because they demonstrated that irrespective of the availability of vision, altered proprioception was associated with a reduction of compensatory (CPA) activity of muscles and lesser COP displacements after the perturbation. Moreover, vibration-related changes in CPAs were larger when vision was not available.

5.6.1 The effect of altered proprioception

The important role of proprioceptive information in control of posture is well documented. For example, it is reported that in a well-lit environment with a firm base of support, healthy individuals rely on a combination of somatosensory (70%), vision (10%) and vestibular (20%) information in order to maintain their upright posture (Peterka 2002). Furthermore, intact muscles around the ankle joint have traditionally been considered the source of muscle proprioceptive information, responsible for signaling changes in body position (Nakagawa et al. 1993; Barbieri et al. 2008). Thus, changes in the accuracy of proprioceptive information could affect the ability of an individual to control his posture (Barbieri et al. 2008).

The role of altered proprioceptive information in control of perturbed posture is of a special interest because many individuals with neurological conditions have diminished proprioceptive information and are frequently exposed to external perturbations. For example, it was shown that diminished proprioceptive information in individuals with diabetic neuropathy leads to greater body sway around equilibrium point than in healthy adults (Nardone and Schieppati 2004). It has been established by epidemiological studies that a reduction of leg proprioception sense is a risk factor for falls in the elderly and patients with peripheral neuropathy (Richardson et al. 1992; Lord et al. 1996).

Alterations in the proprioceptive information in the current study were induced by bilateral vibration of the Achilles tendons which produced body tilt in the direction of the vibrated tendon which is in line with the literature (Polonyova and Hlavacka 2001; Ceyte et al. 2007). Such a vibration resulted in delayed anticipatory activity of the leg and trunk muscles in VEO as compared to EO (no vibration condition). There are several possible explanations for this observation. First, given the fact that somatosensory information is a driving force in balance control (Peterka 2002) and that vibration of muscles or their tendons induces powerful discharge of muscle spindle primary afferents (Bove et al. 2003), it is not surprising that alterations in the proprioceptive input clearly affected muscle activation patterns and COP displacements even in the presence of vision. This outcome is in line with previous literature (Kasai et al. 2002; Slijper and Latash 2004). Second, a delay in the activation of the leg and trunk muscles could be explained by changes in the position of the body with application of vibration. Indeed, like what is described in previous literature (Ceyte et al. 2007; Thompson et al. 2007), application of vibratory stimuli to the Achilles tendon induces tilt of the body backwards. The subjects in the current study also exhibited a leaning backward, moving away from the pendulum. As such, the time from the pendulum release (which was known by the subjects since their vision was not obstructed) until the pendulum hits the body, should increase. We speculate that based on the expectation of a delayed perturbation impact, the CNS selected a strategy of delayed APAs. Given the fact that the subjects were healthy adults, capable of fast changes in the strategy if needed, it may suggest that delays in APAs were a way the CNS dealt with erroneous signals from ankle proprioceptors. It is important to note that vibration-induced alteration in the proprioceptive information induces body tilt and increased body sway (Eklund 1973; Gurfinkel and Kireeva 1995), however it is difficult to distinguish between the body lean and increased body sway without assessing the body kinematics. Another explanation could be that altered proprioceptive information did not allow the regular pattern of APAs to be triggered in a timely manner resulting in the delays of muscle activation. The possibility of the delays in triggering of APAs has been previously described in studies with simple reaction time instructions (De Wolf et al. 1998). Differences in the baseline activity of the postural muscles between conditions with no vibration and with vibration (that is associated with body tilt) could be another reason for the observed dissimilarity in the anticipatory EMG activity. We believe this was not the case since the baseline activity from −600 ms to −450 ms for both with and without vibration conditions was subtracted from the EMG signal prior to its integration. As such, the reported changes in the EMG patterns represent changes in the anticipatory activation of muscles associated with the altered proprioceptive information and not the body tilt.

Tendon vibration in the current study resulted in decreased compensatory EMG activity in all the trunk and leg muscles which resulted in smaller compensatory COP displacements. Such a decrease in compensatory $IEMG_{NORM}$ could be explained by the increase of the anticipatory $IEMG_{NORM}$ as was shown previously (Santos et al. 2010a; Mohapatra et al. 2011). However, no difference in the anticipatory $IEMG_{NORM}$ was observed between EO and VEO conditions in the current study. This suggests that the decrease in compensatory EMG activity is due to the effect of tendon vibration rather than the effect of APAs on CPAs.

5.6.2 The effect of vision

The significance of visual information in postural control is well recognized. It has been documented that body sway around equilibrium point is increased with decrease in visual acuity; and sway is maximal in blindfolded conditions (Uchiyama and Demura 2008). It has also been demonstrated that peripheral rather than central vision contributes to maintaining a stable standing posture, with postural sway being influenced more in the direction of stimulus observation, or head/gaze direction, than in the direction of trunk orientation (Berencsi et al. 2005).

The results of the current study indicate that when vision is not available, APAs are not generated. A lack of robust anticipatory postural adjustments in blindfolded conditions relates to massive compensatory postural adjustments seen in increased EMG activity and COP displacements after the perturbation, indicating a decreased postural stability. These results are in line both with the previously reported fact that when a perturbation is unpredictable, APAs are diminished leading to huge CPAs (Santos et al. 2010b; Santos et al. 2010a) as well as with the outcome of our recent study which revealed that altering visual acuity using differently powered glasses results in diminished APAs and increased CPAs (Mohapatra et al. 2011).

5.6.3 Combined effect of altered proprioceptive and visual information

When proprioceptive information was altered simultaneously with the altering of visual information (VEC), $IEMG_{NORM}$ calculated during both CPA1 and CPA2 epochs were smaller in the majority of the studied muscles when compared to blindfolded conditions with no altered proprioception (EC). Such a decrease in the activation of muscles resulted in smaller compensatory COP displacements after the perturbation.

These results are consistent with the conclusion of previous studies that focused on the individual as well as the combined effect of the alteration of two sources of information in control of posture. When one system is challenged in two different ways (proprioception altered by Achilles tendon vibration and by reduced postural stability), the effect of Achilles tendon vibration diminishes (Gurfinkel et al. 1996; Ivanenko et al. 1999). Moreover, when information from somatosensory and vestibular systems was altered separately, postural movement strategies were appropriately selected for their environmental contexts (Horak et al. 1990). Furthermore, when proprioceptive information was altered in vestibular-loss individuals there were delays in the activation of the paraspinalis muscles and decrease in the magnitude of quadriceps muscle activity (Allum and Honegger 1998).

In our study information from two sensory systems, vision and proprioception, was altered before applying external perturbations to the upper body of the subjects. The findings revealed that in conditions with altered proprioception and a lack of vision there were smaller activation of muscles and smaller COP displacements during the CPA epochs. There are two possible explanations to such a reduction in activity of muscles and COP displacement during the CPA. First is based on the outcome of previous studies that show that generation of optimal APAs could significantly minimize CPAs (muscle activation after a perturbation) (Santos et al. 2010b; Santos et al. 2010a). However, no substantial change in APAs was observed in no vision conditions with tendon vibration suggesting that variation in the magnitude of APAs between the no vibration and vibration conditions could not explain the decreased EMG activity during the CPA epochs. The second explanation relates to the effect of a backward lean of the body as a result of the application of Achilles tendon vibration. In the VEC condition, the backward displacement of the COP measured at 500 ms before T_0 was about 20% of the backward shift of the COP at T_0. As such, smaller EMG activity and COP displacements observed during the restoration of posture after the perturbation onset could be a result of the tendon vibration-related backward body lean.

There are study limitations that should be considered. First, the Achilles tendon vibration induces backward body lean as well as body sway and instability. As such the delayed and decreased APAs observed in the current study during the Achilles tendon vibration reveal the combined effect of the lean of the body and the increased body instability. Future studies are needed to estimate the contribution of each element in the postural control. Second, when a tendon vibrator is used tonic vibratory reflex may complicate the way we have interpreted our findings, as such a reflex may lead to a sustained muscle contraction. Third, since the study was conducted on healthy young subjects with altered proprioception induced by vibratory stimulation, its outcome could not be directly applied to individuals with impaired proprioception. As such additional studies involving individuals with deficient proprioception are needed.

5.7 Conclusion

Altered proprioceptive information from the ankle joints resulted in delayed generation of anticipatory postural adjustments prior to the external perturbation and the diminished compensatory postural adjustments. The outcome of the study sheds light on the interplay between APAs and CPAs in healthy individuals in the presence of altered proprioception.

CHAPTER VI

CONTROL OF POSTURE: DIFFERENT SUPPORTING SURFACES

6.1 Background

The somatosensory system comprises of a variety of sensors including plantar cutaneous mechanoreceptors and joint and muscle receptors (Kandel et al. 1991). It is believed that important afferent information that is necessary to maintain posture comes from the two types of specialized mechanoreceptors located on the sole of the feet (Magnusson et al. 1990). Slowly adapting mechanoreceptors provide spatial information about the pressure distribution between the feet and the ground whereas rapidly adapting mechanoreceptors provide information about the amplitude and changes in the pressure distribution (Kavounoudias et al. 1999). Also, it is important to note that such mechanoreceptors not only supply information about surface contact pressures (Vallbo and Johansson 1984) but also help sensing small but continuous changes of posture.

Individuals with diabetic neuropathy, elderly individuals with peripheral neuropathy, or traumatic injury which may involve one of the nerves of the lower extremity, commonly have diminished ability to utilize somatosensory information (Greene DA 1990; van Deursen and Simoneau 1999). A number of clinical tests of balance evaluating how patients utilize the somatosensory information are performed when patients or elderly stand on a force platform (Duncan et al. 1990; Maki et al. 1994). However, using a firm force platform might not be sensitive enough to test individuals with balance disorders (Johansson and Magnusson 1991). Thus, balance assessment techniques frequently include standing on foam, a more compliant supporting surface positioned on the top of the force platform (Allum et al. 2002; NeuroCom 2010) or keeping the surface similar in texture but altering its stability by using a wobbling board (Burton 1986).

Standing on a compliant surface such as foam induces body instability in both sagittal and frontal planes and also alters inputs to both joint receptors and cutaneous mechanoreceptors in the sole. Thus, while standing on the foam inputs from the plantar cutaneous mechanoreceptors are altered however the stimulation of stretched muscle is not affected (Chiang and Wu 1997). Moreover whereas the short latency reflexes are not affected by changes in plantar pressure, both medium and long latency reflexes are delayed when the subjects stands on foam (Wu and Chiang 1997). It has been also shown that foam surface density and compressibility to a known force are significantly related to stability (Patel et al. 2008a; Patel et al. 2008b). Thus, past studies have shown that standing on foam results in a significant challenge to postural control resulting in the increased body sway in both, antero-posterior and lateral directions in the both low (<0.1 Hz) and high frequency (>0.1 Hz) ranges (Patel et al. 2011). Standing on foam is considered to be a more complex balance task than pitch controlled ankle-sway referencing (Allum et al. 2002). The destabilizing effects of standing on foam have been investigated in several other studies as well (Blackburn et al. 2003; Jeka et al. 2004; Vrancken et al. 2005).

In contrast, wobble board induces body instability in one plane which is orthogonal to the axis of its rotation. Furthermore, since the texture of surface in contact with the sole is firm, somatosensory inputs from the foot (Roll et al. 2002) are different compared to those obtained while standing on foam that is soft. It is known that standing on a wobble board simulates activity of lower limb musculatures as well as lumbar erector spinae

(Burton 1986). Activity in these muscles primarily depends on the dimensions (a specific diameter and a specific height) of the wobble board. While standing on wobble board equilibrium is maintained by changes in the ankle joint angle (ankle joint strategy) wherein the center of gravity (CG) is not moving. To maintain equilibrium, an individual shifts the point of contact of the wobble board with the floor by tilting the board back and forth so the CG position is always inside the base of support (BOS). This task however, could not be performed by some patients especially those with cognitive deficit as it was shown that difficulty in maintaining balance on wobble board increases with addition of cognitive tasks (Dault et al. 2001).

Both foam and wobble board distort the normal proprioceptive inputs from the lower extremity. Hence, maintaining posture on such surfaces can be challenging and needs a crucial role of CNS for a fast action to restore the imbalance. It is known that maintenance of vertical posture is regulated by two different strategies utilized by the CNS: (1) feed forward control, which is the anticipatory postural adjustments (APA) prior to the expected body perturbations (Belen'kii et al. 1967; Massion 1992) feedback control, which is the compensatory postural adjustments (CPA) that are initiated by the sensory feedback signals after the perturbations (Horak et al. 1996; Park et al. 2004; Alexandrov et al. 2005). Whereas, APAs serve to minimize the displacement of the body’s COM prior to a perturbation (Bouisset and Zattara 1987; Aruin and Latash 1995), CPAs serve as a mechanism for restoration of the position of COM after a perturbation has already occurred (Macpherson et al. 1989; Maki et al. 1996).

The way both the components of postural control are used could be affected by changes in the stability of the supporting surface and associated changes in the available somatosensory information. Thus, it was reported that subjects standing on unstable surfaces increase their postural sway (Ivanenko et al. 1997), enhance reflex excitability thus increasing the role of stretch reflex (Dietz et al. 1980), and change the strategy for maintaining upright posture while adapting to the new environmental conditions (Horak and Nashner 1986). In experiments involving fast arm movements while standing on a wobble board APAs were still present but they were earlier and smaller in magnitude especially for BF muscle as compared to standing on a stationary surface (Gantchev and Dimitrova 1996). Furthermore, APAs associated with voluntary movements were attenuated when body posture was unstable due to unilateral stance (Nouillot et al. 1992) as well as when it was very stable (Nardone and Schieppati 1988). APAs (e.g. EMGs of calf muscle) were also reduced when subjects performed backward bending while standing on a narrow support (Pedotti et al. 1989). Instability of supporting surface also affects the feedback component of postural control. Thus, standing on a narrow beam (Horak and Nashner 1986; Gatev et al. 1999) or on one leg (Tropp and Odenrick 1988) results in subjects utilizing primarily hip strategy while recovering from a perturbation induced by the moving support. Moreover, increase in the amplitude of EMG activity of leg and trunk muscles was observed while subjects wore unstable foot wear (Sousa et al. 2010), while standing on foam (Fransson et al. 2007) and while standing on a wobble board (Burton 1986).

While the effect of standing on foam or wobbling board was investigated individually, no studies were conducted to evaluate the effect of both supports in control of vertical posture in the presence of an external perturbation. Thus, to study the role of different surfaces upon APAs and CPAs we designed the current experiment where subjects stood either on stable or unstable surfaces (foam, wobble board) while being exposed to similar perturbations induced at the shoulder level. We hypothesize that: a) APAs will be reduced in conditions with diminished stability, and b) CPAs will be different between the two unstable conditions with greater EMG activity in the most unstable condition that is foam.

6.2 Subjects

Nine healthy participants (4 males and 5 females) with no history of lower extremity injury within last 6 months, chronic ankle instability or clinically diagnosed balance disorder participated in the study. Mean age, height and weight of the participants were 23±0.5 years, 1.7±0.02 m and 67±5.8 kg respectively. The protocol was approved by the University's Institutional Review Board prior to participant recruitment and all participants provided written informed consent prior taking part in the experimental procedures.

6.3 Procedure

The subjects were instructed to stand on different surfaces and maintain standing balance while being subjected to upper extremity perturbation at the shoulder level by an aluminum pendulum (Mohapatra et al. 2011; Mohapatra et al. 2012). The supporting surface was either just kept firm by making the subject stand on the force platform (FIRM), on foam (thickness 12.7cm, FOAM) or on a customized wooden see saw (7.6cm in height), which can rotate around a medio-lateral axis, thus creating instability in the sagittal plane (WOBBLE). The foam and see saw were positioned on the top of the force platform. The subjects stood on these surfaces while keeping eyes open or closed. The experimenter made sure that the feet position in relation to the center of the force platform was the same across all the conditions.

Electrical activity of muscles (EMGs) was recorded unilaterally (right side) from the following muscles: tibialis anterior (TA), biceps femoris (BF), semitendinosus (ST), vastus lateralis (VL), vastus medialis (VM), lateral gastrocnemius (GL), medial gastrocnemius (GM), rectus femoris (RF), rectus abdominis (RA), and erector spinae (ES).

6.4 Statistical Analysis

Two separate multiple repeated-measures ANOVAs were performed. First analysis was focused on the feed forward postural control, which included two within subject factors: conditions (REO, FEO and WEO) and epochs (APA1 and APA2). Second analysis was focused on the feedback postural control that included two within subject factors: conditions (REC, FEC and WEC) and epochs (CPA1 and CPA2). The dependent variables were $IEMG_{NORM}$s, latency of trunk and leg muscles, peak magnitude of the COP, and magnitude of COP at the moment of perturbation (T_0). A post hoc analysis (pair-wise t-test) with Bonferroni correction was further done to compare between conditions and epochs. For all the tests, statistical significance was set at $p < 0.05$. Statistical analysis was performed in SPSS 17 for Windows 7 (SPSS Inc., Chicago, USA).

6.5 Results

<u>6.5.1Feedforward control</u>

Electromyography patterns

Anticipatory postural adjustments were seen in conditions with full vision: the majority of muscles showed activity prior to the perturbation (T_0) (Fig 17). Overall all the anterior muscles showed earlier activity in FOAM than WOBBLE (Table VIII). GL was the only muscle to show activity after perturbation in all surface conditions even when eyes were open. Moreover, irrespective of the nature of instability and somatosensory inputs, the first muscle to show activity in these conditions (FOAM or WOBBLE) was RF (115±26 ms before T_0 for FOAM and 62±37 ms before T_0 for WOBBLE).

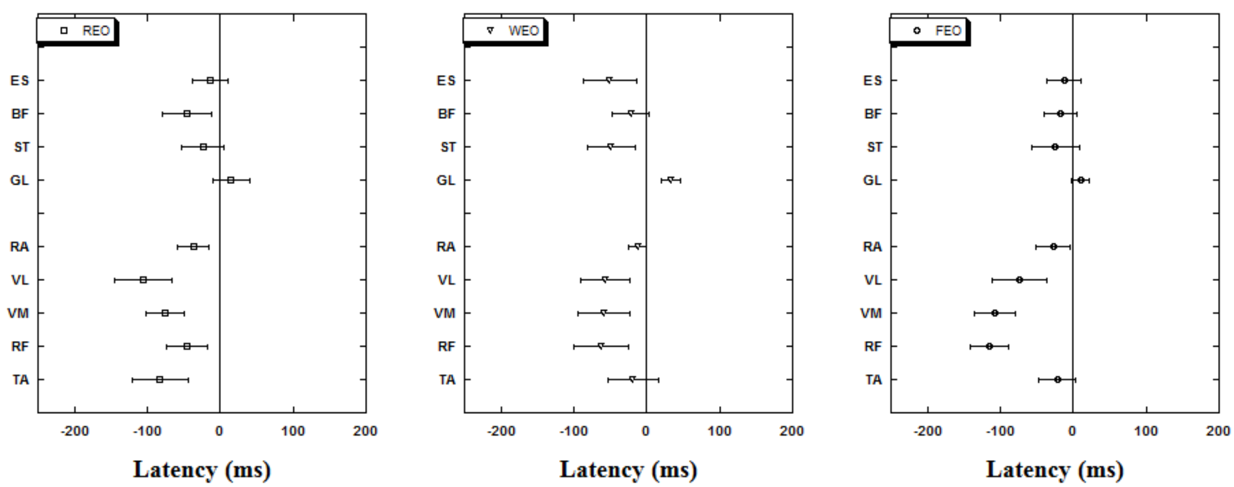


Fig 17. Onsets of muscle activity with SE for EO conditions on the different supporting surfaces

It is interesting to note that the subsequent muscles that showed activity for the unstable conditions were mainly the intermediate (thigh) muscles (VM and VL). Thus, VM was active at 108±28 ms and 59±36 ms before perturbation when the subjects stood on foam and wobble board respectively. VL showed activity at 74±37 ms and 57±33 ms before perturbation for FOAM and WOBBLE conditions respectively.

Principle Component Analysis

PCA validity was confirmed by visual inspections of the scree plots. On an average, two principal components (PCs) (Table VI) accounted for the 75% total variance in the muscle activation space in the REO, 72 % in FEO, and 76 % of the total variance in the WEO conditions. The first PC in the REO showed significantly high loading values for BF, VL, ES, RF, ST and VM. In FEO however, the loading patterns for the first PC was significantly higher for VL, RF, ST, RA, VM and TA. Furthermore, when the subjects stood on the wobble board (WEO) the muscles which showed highest loading in the PC1 were VL, ES, RF, VM and TA. The second PC in the REO showed significantly high loading values for ES, RA, TA and GL. In FEO however, the loading patterns for the second PC was significantly higher for BF, ES, ST, TA and GL. Furthermore, when the subjects stood on the wobble board (WEO) the muscles which showed highest loading in the PC2 were BF, ST and GL.

It is important to note that a co-contraction pattern for the thigh muscles was seen especially in the PC1 component for FEO and REO conditions. In addition, REO also showed co-contraction for both the trunk and leg muscles in the PC2 component. A co-contraction is defined as a pattern with significant loading coefficients on the same PC with the same sign (positive or negative) for two muscles with opposing actions at a particular joint (ankle, knee or hip) (Krishnan et al. 2012).

Muscles	Components (REO)		Components (WEO)		Components (FEO)	
	1	2	1	2	1	2
BF	**.894**	-.158	.279	**.910**	.002	**-.955**
VL	**.886**	.137	**.950**	.316	**.726**	-.063
ES	**.544**	**.543**	**.694**	-.426	-.157	**-.927**
RF	**.845**	-.035	**.928**	.177	**.827**	.124
ST	**.836**	.016	-.353	**.799**	**.773**	**-.506**
RA	-.337	**.870**	.341	-.434	**.592**	.310
VM	**.807**	-.105	**.989**	.120	**.967**	.099
TA	.019	**.933**	**.679**	-.180	**.520**	**-.555**
GL	.492	**.619**	-.261	**-.889**	.078	**.765**

Table VI. PC analyses for muscle onsets for the eyes open conditions for various supporting surfaces are shown. Loading factors are presented for the first two PCs. Loadings over 0.5 are shown in bold.

Electromyography integrals

Anticipatory integrals of EMG (*iEMGs*) calculated for all the muscles and conditions are shown in Fig 18. The only muscle to show a significant main effect of the surfaces was TA ($F_{2, 16}$=4.95, p=0.021) (Table VII). In general, seven out of the ten muscles (ES, GL, GM, RF, TA, VL and VM) showed highest anticipatory activity especially in the APA2 epoch in the FOAM condition. Furthermore five of these seven muscles (ES, GL, RF, VL and VM) showed the least muscular activity especially in the APA2 epoch for the WOBBLE condition.

Five muscles (RA, RF, TA, VL, and VM) showed a significant main effect of the two APA epochs analyzed (Table VII). When the APA1 and APA2 epochs were compared across conditions, *iEMGs* were larger during the APA2 epoch as compared to the APA1 in all the muscles. The difference was statistically significant in RA (p=0.001), RF (p=0.001), TA (p=0.05), VM (p=0.002) and VL (p=0.005) muscles.

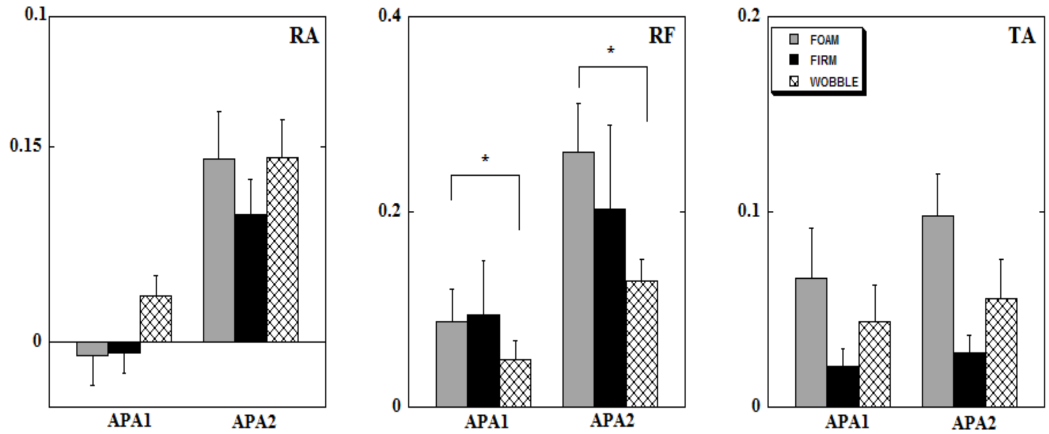


Fig 18. Normalized iEMG with SE shown for the APA epochs. * implies statistical significant ($p<0.05$) differences between FOAM and WOBBLE conditions.

Displacements of Center of Pressure

In EO conditions the subjects demonstrated almost equal CoP T_0 displacements (0.014±0.002 m) in the backward direction in all the different surface conditions. While being positioned on different supports with eyes open (EO) the peak displacements of CoP were much smaller: 0.028±0.003 m on FOAM followed by WOBBLE (0.030±0.006 m) and 0.033±0.004 m for FIRM conditions.

Muscles	Conditions		Epochs		Conditions * Epochs	
	[$F_{2,16}$]	p	[$F_{1,8}$]	p	[$F_{2,16}$]	p
TA	4.948*	0.021	4.983	0.056	1.420	0.271
VL	1.747	0.206	14.943*	0.005	2.736	0.095
VM	1.701	0.214	22.108*	0.002	5.113*	0.019
RF	1.660	0.221	23.602*	0.001	3.154	0.070
RA	3.272	0.064	24.108*	0.001	0.892	0.429
GL	1.399	0.275	0.115	0.743	0.039	0.962
ST	2.112	0.153	1.717	0.226	1.934	0.177
BF	0.903	0.420	0.222	0.065	1.923	0.178
ES	0.403	0.675	2.032	0.192	1.528	0.247

Table VII. Repeated measures ANOVA of $IEMG_{NORM}$ for conditions, epochs and their interactions. * indicates statistically significant differences ($p<0.05$).

6.5.2 Feedback control

Electromyography patterns

There was no anticipatory activity in any muscle in conditions with eyes closed (EC): instead all the muscles (Fig. 19) became active only after the perturbation onset (T_0). A group of muscles (TA, VL, ST and BF) showed earliest activity in the WOBBLE followed by FOAM and FIRM conditions. Another group of muscles (VM and GL) showed a different pattern with earliest activation seen in the FOAM followed by WOBBLE and last in FIRM. It is interesting to note that irrespective of the supporting surface the pattern of activation of muscles was similar based on their location on the body (anterior or posterior). Thus, the anterior muscles were the first to show activity followed by the posterior muscles (Table VIII).

Muscles	EO			EC		
Anterior	FOAM	FIRM	WOBBLE	FOAM	FIRM	WOBBLE
TA	-22±25	-82±39	-19±35	46±3	60±6	35±8
VL	-74±37	-105±39	-57±33	42±4	50±4	28±10
VM	-108±28	-75±26	-59±36	42±4	47±4	44±9
RF	-115±26	-45±28	-62±37	39±3	44±3	39±3
RA	-27±23	-37±21	-12±12	24±11	29±6	34±6
Posterior						
GL	10±12	15±25	33±13	51±11	62±9	56±7
ST	-24±32	-24±29	-49±33	56±13	64±5	54±11
BF	-17±25	-46±34	-22±26	62±11	75±12	61±11
ES	-12±23	-14±25	-51±36	79±9	68±7	56±20

Table VIII. Muscle onsets with S.E for all the muscles for both eyes open and eyes closed conditions for various supporting surfaces.

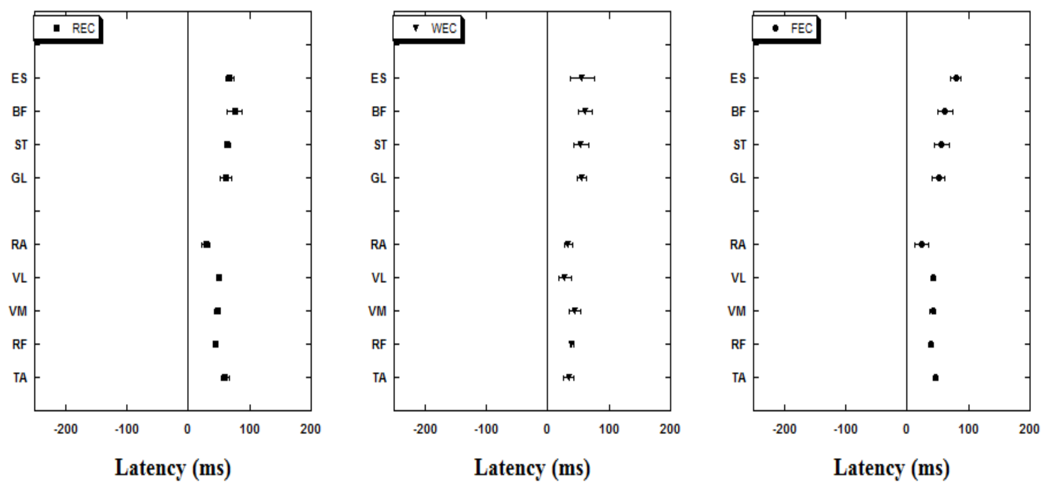


Fig 19. Onsets of muscle activity with SE for EC conditions on the different supporting surfaces

Principle Component Analysis

PCA validity was confirmed by visual inspections of the scree plots. On an average, two principal components (PCs) (Table IX) accounted for the 74% total variance in the muscle activation space in the REC, 73 % in FEC, and 70 % of the total variance in the WEC conditions.

Muscles	**Components (REC)**		**Components (WEC)**		**Components (FEC)**	
	1	**2**	**1**	**2**	**1**	**2**
BF	-.364	**-.939**	**.771**	.147	.099	**.946**
VL	**.626**	**-.564**	.041	**.914**	**.883**	.117
ES	-.167	**.616**	.300	-.259	**.760**	.161
RF	**.686**	**-.536**	**.913**	.074	**.910**	.098
ST	**.653**	-.476	**.679**	-.447	-.022	**.973**
RA	.263	.107	**.670**	.291	.498	.100
VM	**.942**	-.154	**.531**	**-.716**	**.960**	-.257
TA	**.985**	.083	.280	**.963**	**.933**	.071
GL	.085	**-.873**	**.854**	-.188	**.549**	-.129

Table IX. PC analyses for muscle onsets for the eyes closed conditions for various supporting surfaces are shown. Loading factors are presented for the first two PCs. Loadings over 0.5 are shown in bold.

The first PC in the REC showed high loading values (Table IX) for VL, RF, ST, VM and TA. In FEC however, the loading patterns for the first PC was significantly higher for VL, ES, RF, VM, TA and GL. Furthermore, when the subjects stood on the wobble board (WEC) the muscles which showed highest loading in the PC1 were BF, RF, ST, RA, VM and GL. The second PC in the REC showed high loading values for BF, VL, RF and GL.

In FEC however, the loading patterns for the second PC was significantly higher for BF and ST. Furthermore, when the subjects stood on the wobble board (WEC) the muscles which showed highest loading in the PC2 were VL, VM and TA.

A co-contraction pattern was seen in the thigh muscles especially in the PC1 and PC2 components for WEC condition and just the PC1 of the WEC. In addition, FEC also showed co-contraction for leg muscles in the PC1 component.

Electromyography integrals

Compensatory integrals of EMG (*iEMGs*) of TA, VL and GL calculated for all the conditions (Integrals shown in Fig 20). There was a significant main effect of the support surface (Table X) in GL, RF, TA, VL and VM. Thus, compensatory iEMGs were significantly larger in BF ($p=0.028$), GL ($p<0.0001$) and TA ($p<0.0001$) for FOAM when compared with the condition when the subject stood on the force-platform (FIRM). Additionally, compensatory iEMGs were significantly larger in RF ($p=0.022$), VL ($p=0.05$), TA ($p=0.031$) and VM ($p=0.05$) while standing on FOAM when compared to WOBBLE. The comparison of the epochs revealed that CPA1 was significantly larger ($p<0.01$) than CPA2 for all the muscles (Table X).

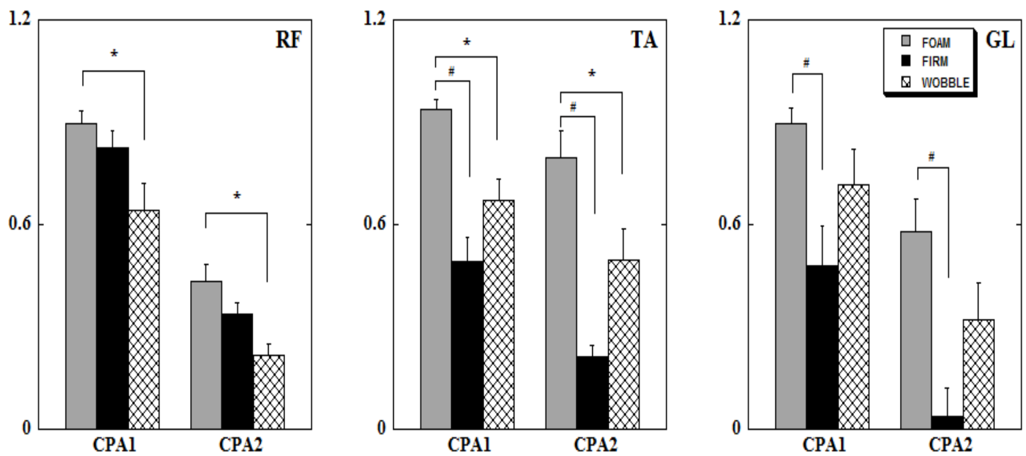


Fig 20. Normalized iEMG with SE shown for the CPA epochs. * implies statistical significant (p<0.05) differences between FOAM and WOBBLE conditions and # between FOAM and FIRM conditions.

Muscles	Conditions $[F_{2,16}]$	p	Epochs $[F_{1,8}]$	p	Conditions * Epochs $[F_{2,16}]$	p
TA	19.614#	<0.0001	13.456#	0.006	2.269	0.136
VL	6.938#	0.007	56.686#	<0.0001	1.889	0.184
VM	5.748*	0.013	46.141#	<0.0001	2.257	0.137
RF	8.934#	0.002	131.454#	<0.0001	0.281	0.759
RA	1.088	0.361	134.46#	<0.0001	1.092	0.359
GL	10.123#	0.001	26.901#	0.001	0.437	0.653
ST	2.380	0.124	12.261#	0.008	2.295	0.133
BF	2.887	0.085	23.040#	0.001	2.714	0.097
ES	1.841	0.191	61.840#	<0.0001	1.003	0.389

Table X. Repeated measures ANOVA of $IEMG_{NORM}$ for conditions, epochs and their interactions. * indicates statistically significant differences (p<0.05).

Displacements of Center of Pressure

When subjects stood on the force-platform (FIRM) with eyes closed, their maximum CoP displacement was (0.055±0.003 m), followed by WOBBLE (0.053±0.004 m) and FOAM (0.052±0.004 m) surface.

6.6 Discussion

The results provide evidence on the role of body instability and deficient proprioceptive and somatosensory inputs in generation of APAs and CPAs.. Moreover, this investigation revealed that both APAs and CPAs were larger in conditions with increased body instability. Thus, standing on foam that created instability in both sagittal and frontal planes as well as reduced somatosensory inputs, was associated with greater APAs as well as CPAs compared to the wobble board condition, which just destabilized the body in the sagittal plane with no major reduction in the somatosensory inputs. Hence our first hypothesis that there will be reduction in APAs with increase in instability was rejected but the second hypothesis was supported as there was an increase in CPAs with increase in instability.

6.6.1 Role of support instability on feedforward postural control

While positioning on foam various parameters of normal standing are compromised or altered. First, foam induces instability in both, the sagittal and also in frontal planes. Second, the somatosensory inputs from the sole of the feet are distorted due to the altered texture of the supporting surface. Hence while standing on foam an individual deals with both, greater instability and unreliable somatosensory information. As a result, such an increase in threat to stability is associated with the co-contraction in the thigh muscles (confirmed by the PC analysis) which results in overall increase of the activity of the postural muscles during the anticipatory epochs. This outcome contrasts previous literature (Pedotti et al. 1989; Aruin et al. 1998) reporting decreased APAs when posture was unstable. The differences in the outcomes can be explained by the use of unstable posture or board in the former studies and foam in the current study to make the supporting surface unstable. Foam not only affects the stability but also alters somatosensory information which changes due to its compliant nature. Hence, we can suggest that when both stability and sensory information are altered we may not see the previously described reduction of APAs.

When subjects stood on the wobble board although the surface in contact with the feet was unyielding as in the FIRM condition and the board was unstable in the sagittal plane. Most of the muscles showed smaller APAs in the WOBBLE condition. Thus this result is in agreement with the previous literature (Pedotti et al. 1989; Aruin et al. 1998) suggesting that when surface is unstable the CNS uses a strategy to generate smaller APAs thus avoiding additional destabilization of body equilibrium. Furthermore past studies (Gantchev and Dimitrova 1996) reported that when a subject stands on a board unstable in the sagittal plane (i.e. on a see-saw) the anticipatory EMG activity of BF and SOL muscles is observed earlier compared to the stable condition. However, in our study although reduced APAs were noticed when the subjects stood on a wobble board with the intermediate muscles (around the knee joint) showeing the least activity across all conditions. Moreover, the intermediate muscles (RF, BF) were not activated early when the subjects were positioned on a wobble board. The differences in the study outcomes could be due to the dissimilarity of the self-initiated perturbations (Gantchev and Dimitrova 1996) and external perturbation used in the current study.

It is interesting to note that although the anticipatory activity varied between different surface conditions, almost similar anticipatory CoP displacements were seen in experimental conditions with different stability of the supporting surface. We can speculate that the support-related changes in the EMG activity was not realized in significant changes in the body position as the CNS modulated anticipatory activity of the trunk and leg muscles maintaining the CoP relatively motionless. It is also important to note that anticipatory activation was seen as co-activation of muscles which might be responsible for a cancellation of the effect of muscle activation on the CoP displacement. This suggestion is supported by the outcome of a study involving self-initiated releases of a load from extended arms while standing on an unstable board (Aruin et al. 1998) that also reported a lack of clear attenuation in the CoP displacement that depended on the direction of instability.

6.6.2 Role of support instability on feedback postural control

Surface-dependent order of activation of the trunk and leg muscles in response to the translation or tilts of the support surface was described in the literature (Keshner et al. 1988; Nardone et al. 1990). When postural responses to lateral and antero-posterior surface translations were compared, the kinematic patterns in response to such translations were similar thus showing sequential displacement and reversal of the shank/thigh and then trunk segments (Henry et al. 1998a). It was suggested that neither a simple reflex mechanism nor a fixed muscle synergy organization is adequate to explain the muscle activation patterns observed in response to a multidirectional surface translations (Henry et al. 1998b). In the current study irrespective of the nature of instability of the supporting surface after the perturbation all anterior muscles were activated first followed by the activation of posterior muscles. This further corroborates the finding as reported earlier that a flexible continuum of muscles synergies is task-dependent. The differences in the order of activation of muscles in the current study and the former one could be explained by a different type of perturbation and its point of application. While past studies mainly used a support surface translation movements, our study utilized perturbations delivered to the shoulders.

Past studies have also suggested that the body CoM was displaced equally in response to lateral and antero-posterior translations, redistributing the vertical forces and changing the shear forces exerted against the support surface necessary for maintaining equilibrium (Henry et al. 1998a). In our investigation we found slightly larger displacements of CoP after perturbation in the stable (FIRM) conditions when compared to unstable conditions (FOAM or WOBBLE). This can be explained by the support-related differences in the ability to apply forces to the ground. When the supporting surface was the most compliant and unstable (FOAM) the subjects might had difficulties in generating forces needed for efficient balance restoration after the perturbation. This finding is in line with past studies reporting that when subjects were positioned on compliant surface smaller peak pressure amplitudes were recorded in the fore-foot and rear-foot .

CHAPTER VII

CONCLUSIONS AND DIRECTIONS FOR FUTURE RESEARCH

7.1 Conclusions

The purpose of this thesis was to investigate how altering vision and proprioception will affect the feedforward (APAs) and feedback (CPAs) control of posture in young healthy individuals.

In the first chapter we presented an overview of how various systems play a role in controlling vertical posture. Further, we went on describing the crucial role that APAs and CPAs play in the maintenance of posture. The second chapter described the methods used in all the experiments presented in the thesis.

Our research findings were presented in Chapters Three, Four, Five and Six. The first study (Chapter Three) provided crucial information necessary to understand how changes in visual acuity will affect the generation of APAs and thus subsequently affect the CPAs. The study outcome revealed that vision plays an important role in the generation of anticipatory and compensatory corrections while maintaining posture. It was also demonstrated that changes in visual acuity induced by differently powered glasses affect the way anticipatory postural adjustments are utilized, which in turn affects the compensatory control of posture. Hence, the role of glasses of different powers should be taken into consideration when studying APAs and CPAs in relation to posture studies.

The second study (Chapter Four) investigates how different visual cues affect the generation of APAs. In this study we used a stroboscope that produced both static as well as dynamic visual cues. The outcome of the study revealed that when dynamic cues are available it is easier for the CNS to predict the upcoming perturbation and generate APAs than when static cues are present. This conclusion is supported by the corresponding changes in the EMG activity and CoP displacements. This outcome helps to understand how different visual cues can enhance generation of APAs and thus play a role in control of vertical posture.

The third study (Chapter Five) was done with a focus to understand the role of proprioception in control of vertical posture and how it affects APAs and CPAs. Using a miniature customized tendon vibrator around the Achilles tendon, proprioceptive information from the ankle joints was altered. The outcome of the study reveled a delayed generation of APAs prior to the external perturbation and the diminished CPAs. Thus this study sheds light on the interplay between APAs and CPAs in healthy individuals in the presence of altered proprioception.

The fourth and the final study (Chapter Six) examined how different supporting surfaces such as a foam or wobbling board affect feedforward and feedback control of posture. The outcome of the study revealed a region specific control of posture based on the type of supporting surface. Thus, APAs were most reduced for distal muscles in foam, intermediate muscles in wobbling board condition and a mix of proximal and distal muscles when the supporting surface was just flat and rigid. Also, the CoP peak after perturbation was the maximum when the surface was most stable and least when it was very unstable. This information should be taken into consideration in planning rehabilitation interventions focused on improvement of balance in patients.

7.2 Directions for future research

From all of our studies we could establish the role of APAs and CPAs in control of vertical posture while being subjected to altered vision or proprioceptive inputs. The studies were done only on healthy individuals because we had to first understand how these senses when altered affect the normal control of posture for which we designed the above set of studies.

Future studies could extrapolate the knowledge gained from these set of studies to patient populations. Thus, the first study (Chapter Three) could be modified to understand how different aspects of control of posture are affected in individuals with low vision either due to age (elderly) or disease (myopia, hyperopia, diabetic retinopathy etc.). Understanding the control of vertical posture in such individuals will not only help us constantly monitor posture and thus prevent instability leading to falls in these populations, but also it will be an important point to consider while developing balance rehabilitation protocols for such individuals.

The second study (Chapter Four) could be shaped further from a lab setting to more of a practical usage. For example, understanding how frequency of visual cues affect the way we perceive an approaching object could help better design vehicles and subsequently lighting on the streets to make our walking and driving much safer. As we could relate the fact that knowledge of cues is important for the generation of feedforward control of posture, we can speculate this will also alter the way we perceive an approaching threat and thus keep the driver more alert. Not only in driving, but also in clinical settings different frequencies of light could be used to challenge and train individuals so that they can better perceive and react to an incoming threat and thus improve their balance by better controlling their posture.

The subject of the third study (Chapter Five) can be further investigated in individuals with loss of proprioception due to age (elderly) or disease (diabetic neuropathy etc.). A better knowledge of how these individuals control their posture can help rehabilitation professionals to design balance rehabilitation tools that can be customized to the need of such individuals. Moreover, additional strategies could also be developed to counteract this lost or altered proprioception that will ultimately help these individuals to lead a better life.

The outcome of the fourth and the final study (Chapter Six) can be applied to individuals who show instability due to loss of both proprioceptive as well as somatosensory inputs. This loss of sensations can either be due to age (elderly), disease (neuropathies) or trauma (nerve injuries). Furthermore, training such individuals on unstable surfaces such as foam or a wobbling board would better prepare them to deal with instability during day-to-day life and thus avoid loss of balance.

Although the outcomes from our studies lay a foundation to better understand postural control, lots still need to be done to further explore the role of feed-forward and feedback control on posture in patient populations. Future experiments can focus on development of balance training techniques for rehabilitation of individuals with impaired postural control.

CITED LITERATURE

Adamcova N, Hlavacka F (2007) Modification of human postural responses to soleus muscle vibration by rotation of visual scene. Gait Posture 25: 99-105

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

Allum JH (1983) Organization of stabilizing reflex responses in tibialis anterior muscles following ankle flexion perturbations of standing man. Brain Res 264: 297-301

Allum JH, Honegger F (1998) Interactions between vestibular and proprioceptive inputs triggering and modulating human balance-correcting responses differ across muscles. Exp Brain Res 121: 478-494

Allum JH, Zamani F, Adkin AL, Ernst A (2002) Differences between trunk sway characteristics on a foam support surface and on the Equitest ankle-sway-referenced support surface. Gait Posture 16: 264-270

Allum JHJ, Keshner EA (1986) Vestibular and proprioceptive control of sway stabilization. In: Bles W, Brandt T (eds) Disorders of Posture and Gait. Elsevier, Amsterdam, pp 19-39

Anand V, Buckley J, Scally A, Elliott DB (2002) The effect of refractive blur on postural stability. Ophthalmic Physiol Opt 22: 528-534

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 (1995) 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

Barbieri G, Gissot AS, Fouque F, Casillas JM, Pozzo T, Perennou D (2008) Does proprioception contribute to the sense of verticality? Exp Brain Res 185: 545-552

Bardy BG, Warren WH, Jr., Kay BA (1999) The role of central and peripheral vision in postural control during walking. Percept Psychophys 61: 1356-1368

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

Belen'kii VE, Gurfinkel VS, Pal'tsev EI (1967) [Control elements of voluntary movements]. Biofizika 12: 135-141

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

Benvenuti F, Stanhope SJ, Thomas SL, Panzer VP, Hallett M (1997) Flexibility of anticipatory postural adjustments revealed by self-paced and reaction-time arm movements. Brain Res 761: 59-70

Berencsi A, Ishihara M, Imanaka K (2005) The functional role of central and peripheral vision in the control of posture. Hum Mov Sci 24: 689-709

Blackburn JT, Riemann BL, Myers JB, Lephart SM (2003) Kinematic analysis of the hip and trunk during bilateral stance on firm, foam, and multiaxial support surfaces. Clin Biomech (Bristol, Avon) 18: 655-661

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

Bove M, Nardone A, Schieppati M (2003) Effects of leg muscle tendon vibration on group Ia and group II reflex responses to stance perturbation in humans. J Physiol 550: 617-630

Brandt T, Paulus W, Straube A (1986) Vision and posture. In: Bles W, Brandt T (eds) Disorders of Posture and Gait. Elsevier Science Publishers BV (Biomedical Division), Amsterdam, pp 157-175

Bronstein AM (1986) Suppression of visually evoked postural responses. Exp Brain Res 63: 655-658

Bull NJ, Hunter M, Finlay DC (2003) Cue gradient and cue density interact in the detection and recognition of objects defined by motion, contrast, or texture. Perception 32: 29-39

Burke D, Hagbarth KE, Lofstedt L, Wallin BG (1976) The responses of human muscle spindle endings to vibration of non-contracting muscles. J Physiol 261: 673-693

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

Burton AK (1986) Trunk muscle activity induced by three sizes of wobble (balance) boards. J Orthop Sports Phys Ther 8: 27-29

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

Ceyte H, Cian C, Zory R, Barraud PA, Roux A, Guerraz M (2007) Effect of Achilles tendon vibration on postural orientation. Neurosci Lett 416: 71-75

Chiang J-H, Wu G (1997) The influence of foam surfaces on biomechanical variables contributing to postural control. Gait & Posture: 239-245

Cian C, Esquivie D, Barraud PA, Raphel C, Ohlmann T (1997) Strobe frequency in the rod and frame effect. Percept Mot Skills 85: 43-50

Clement G, Gurfinkel VS, Lestienne F, Lipshits MI, Popov KE (1985) Changes of posture during transient perturbations in microgravity. Aviat Space Environ Med 56: 666-671

Courtine G, Papaxanthis C, Laroche D, Pozzo T (2003) Gait-dependent integration of neck muscle afferent input. Neuroreport 14: 2365-2368

Courtine G, Pozzo T, Lucas B, Schieppati M (2001) Continuous, bilateral Achilles' tendon vibration is not detrimental to human walk. Brain Res Bull 55: 107-115

Dault MC, Geurts AC, Mulder TW, Duysens J (2001) Postural control and cognitive task performance in healthy participants while balancing on different support-surface configurations. Gait Posture 14: 248-255

De Wolf S, Slijper H, Latash ML (1998) Anticipatory postural adjustments during self-paced and reaction-time movements. Exp Brain Res 121: 7-19

Demura S, Yamaji S, Kitabayashi T, Yamada T, Uchiyama M (2008) Attention of postural control on foot somatosensor disturbance caused by the compression of blood vessels. J Hum Ergol (Tokyo) 37: 91-102

Dhital A, Pey T, Stanford MR (2010) Visual loss and falls: a review. Eye (Lond) 24: 1437-1446

Dietz V, Mauritz KH, Dichgans J (1980) Body oscillations in balancing due to segmental stretch reflex activity. Exp Brain Res 40: 89-95

Dijkstra TM, Schoner G, Gielen CC (1994) Temporal stability of the action-perception cycle for postural control in a moving visual environment. Exp Brain Res 97: 477-486

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

Ducic I, Short KW, Dellon AL (2004) Relationship between loss of pedal sensibility, balance, and falls in patients with peripheral neuropathy. Ann Plast Surg 52: 535-540

Duncan PW, Weiner DK, Chandler J, Studenski S (1990) Functional reach: a new clinical measure of balance. J Gerontol 45: M192-197

Eklund G (1973) Further studies of vibration-induced effects on balance. Ups J Med Sci 78: 65-72

Elliott DB, Chapman GJ (2010) Adaptive gait changes due to spectacle magnification and dioptric blur in older people. Invest Ophthalmol Vis Sci 51: 718-722

Enbom H (1990) Vestibular and somatosensory contribution to postural control. In. University of Lund, Lund

Enoka RM (2008) Neuromechanics of Human Movement

Era P, Schroll M, Ytting H, Gause-Nilsson I, Heikkinen E, Steen B (1996) Postural balance and its sensory-motor correlates in 75-year-old men and women: a cross-national comparative study. J Gerontol A Biol Sci Med Sci 51: M53-63

Eun MY, Kang CH, Kim BJ (2011) Tibial neuropathy associated with Behcet's disease. Am J Phys Med Rehabil 90: 432-433

Fransson PA, Gomez S, Patel M, Johansson L (2007) Changes in multi-segmented body movements and EMG activity while standing on firm and foam support surfaces. Eur J Appl Physiol 101: 81-89

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

Fujiwara K, Asai H, Miyaguchi A, Toyama H, Kunita K, Inoue K (2003) Perceived standing position after reduction of foot-pressure sensation by cooling the sole. Percept Mot Skills 96: 381-399

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

Gatev P, Thomas S, Kepple T, Hallett M (1999) Feedforward ankle strategy of balance during quiet stance in adults. J Physiol 514 (Pt 3): 915-928

Greene DA SA, Albers JW, Pfeifer MA (1990) Diabetic neuropathy. Elsevier, New York

Gurfinkel VS, Kireeva TB (1995) [Maintenance of vertical posture during simultaneous vibration of the calf and anterior tibial muscles]. Fiziol Cheloveka 21: 106-120

Gurfinkel VS, Kireeva TB, Lebik Iu S (1996) [Effect of postural muscle vibration on equilibrium maintenance in the frontal plane at various levels of stability]. Fiziol Cheloveka 22: 83-92

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

Haran MJ, Cameron ID, Ivers RQ, Simpson JM, Lee BB, Tanzer M, Porwal M, Kwan MM, Severino C, Lord SR (2010) Effect on falls of providing single lens distance vision glasses to multifocal glasses wearers: VISIBLE randomised controlled trial. BMJ 340: c2265

Harati Y BE (ed) (2008) Disorders of peripheral nerves. Butterworth-Heinemann Elsevier, Philadelphia

Harwood RH (2001) Visual problems and falls. Age Ageing 30 Suppl 4: 13-18

Hatzitaki V, Pavlou M, Bronstein AM (2004) The integration of multiple proprioceptive information: effect of ankle tendon vibration on postural responses to platform tilt. Exp Brain Res 154: 345-354

Hayashi R, Miyake A, Jijiwa H, Watanabe S (1981) Postural readjustment to body sway induced by vibration in man. Exp Brain Res 43: 217-225

Heasley K, Buckley JG, Scally A, Twigg P, Elliott DB (2004) Stepping up to a new level: effects of blurring vision in the elderly. Invest Ophthalmol Vis Sci 45: 2122-2128

Henry SM, Fung J, Horak FB (1998a) Control of stance during lateral and anterior/posterior surface translations. IEEE Trans Rehabil Eng 6: 32-42

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

Hlavacka F, Njiokiktjien C (1985) Postural responses evoked by sinusoidal galvanic stimulation of the labyrinth. Influence of head position. Acta Otolaryngol 99: 107-112

Horak FB, MacPherson JM, Peterson BW (1996) Postural orientation and equilibrium. Published for the American Physiological Society by Oxford University Press, New York

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

Horak FB, Nashner LM, Diener HC (1990) Postural strategies associated with somatosensory and vestibular loss. Exp Brain Res 82: 167-177

Howatson G, Glaister M, Brouner J, van Someren KA (2009) The reliability of electromechanical delay and torque during isometric and concentric isokinetic contractions. J Electromyogr Kinesiol 19: 975-979

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

Ivanenko YP, Grasso R, Lacquaniti F (2000) Influence of leg muscle vibration on human walking. J Neurophysiol 84: 1737-1747

Ivanenko YP, Levik YS, Talis VL, Gurfinkel VS (1997) Human equilibrium on unstable support: the importance of feet-support interaction. Neurosci Lett 235: 109-112

Ivanenko YP, Talis VL, Kazennikov OV (1999) Support stability influences postural responses to muscle vibration in humans. Eur J Neurosci 11: 647-654

Jack CI, Smith T, Neoh C, Lye M, McGalliard JN (1995) Prevalence of low vision in elderly patients admitted to an acute geriatric unit in Liverpool: elderly people who fall are more likely to have low vision. Gerontology 41: 280-285

Jeka J, Kiemel T, Creath R, Horak F, Peterka R (2004) Controlling human upright posture: velocity information is more accurate than position or acceleration. J Neurophysiol 92: 2368-2379

Johansson R, Magnusson M (1991) Human postural dynamics. Crit Rev Biomed Eng 18: 413-437

Johansson RS, Vallbo AB (1980) Spatial properties of the population of mechanoreceptive units in the glabrous skin of the human hand. Brain Res 184: 353-366

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

Kandel ER, Schwartz JH, Jesselell TM (1991) Principles of neural science. Appleton & Lange, Norwalk, Connecticut

Kasai T, Yahagi S, Shimura K (2002) Effect of vibration-induced postural illusion on anticipatory postural adjustment of voluntary arm movement in standing humans. Gait Posture 15: 94-100

Kavounoudias A, Gilhodes JC, Roll R, Roll JP (1999) From balance regulation to body orientation: two goals for muscle proprioceptive information processing? Exp Brain Res 124: 80-88

Keshner EA, Woollacott MH, Debu B (1988) Neck, trunk and limb muscle responses during postural perturbations in humans. Exp Brain Res 71: 455-466

Kjaergard H, Korsgaard Larsen T, Rasmussen PS, Brondum L (1984) Impairment of postural stability following perivascular axillary block with mepivacaine. Acta Anaesthesiol Scand 28: 508-510

Klous M, Mikulic P, Latash ML (2011) Two aspects of feedforward postural control: anticipatory postural adjustments and anticipatory synergy adjustments. J Neurophysiol 105: 2275-2288

Krishnan V, Aruin AS (2011) Postural control in response to a perturbation: role of vision and additional support. Exp Brain Res 212: 385-397

Krishnan V, Latash ML, Aruin AS (2012) Early and late components of feed-forward postural adjustments to predictable perturbations. Clin Neurophysiol 123: 1016-1026

Lacquaniti F, Maioli C (1987) Anticipatory and reflex coactivation of antagonist muscles in catching. Brain Res 406: 373-378

Lacquaniti F, Maioli C (1989) The role of preparation in tuning anticipatory and reflex responses during catching. J Neurosci 9: 134-148

Latash ML (1998) 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

Le TT, Kapoula Z (2006) Distance impairs postural stability only under binocular viewing. Vision Res 46: 3586-3593

Lee DN, Aronson E (1974) Visual proprioceptive control of standing in human infants. Attention, Perception & Psychophysics 15: 4

Leibowitz HW, Rodemer CS, Dichgans J (1979) The independence of dynamic spatial orientation from luminance and refractive error. Percept Psychophys 25: 75-79

Lephart SM, Pincivero DM, Giraldo JL, Fu FH (1997) The role of proprioception in the management and rehabilitation of athletic injuries. Am J Sports Med 25: 130-137

Lichtenstein MJ, Shields SL, Shiavi RG, Burger MC (1988) Clinical determinants of biomechanics platform measures of balance in aged women. J Am Geriatr Soc 36: 996-1002

Lord SR (2006) Visual risk factors for falls in older people. Age Ageing 35 Suppl 2: ii42-ii45

Lord SR, Clark RD, Webster IW (1991a) Postural stability and associated physiological factors in a population of aged persons. J Gerontol 46: M69-76

Lord SR, Clark RD, Webster IW (1991b) Visual acuity and contrast sensitivity in relation to falls in an elderly population. Age Ageing 20: 175-181

Lord SR, Lloyd DG, Li SK (1996) Sensori-motor function, gait patterns and falls in community-dwelling women. Age Ageing 25: 292-299

Lord SR, Menz HB (2000) Visual contributions to postural stability in older adults. Gerontology 46: 306-310

Lord SR, Webster IW (1990) Visual field dependence in elderly fallers and non-fallers. Int J Aging Hum Dev 31: 267-277

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

Magnusson M, Enbom H, Johansson R, Pyykko I (1990) Significance of pressor input from the human feet in anterior-posterior postural control. The effect of hypothermia on vibration-induced body-sway. Acta Otolaryngol 110: 182-188

Maki BE, Holliday PJ, Topper AK (1994) A prospective study of postural balance and risk of falling in an ambulatory and independent elderly population. J Gerontol 49: M72-84

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

Maki BE, McIlroy WE, Perry SD (1996) Influence of lateral destabilization on compensatory stepping responses. J Biomech 29: 343-353

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

Mauritz KH, Dietz V (1980) Characteristics of postural instability induced by ischemic blocking of leg afferents. Exp Brain Res 38: 117-119

McComas A (1996) Skeletal Muscle: Form and Function. In: Human Kinetics, Champaign, IL, pp 230–231

McIlroy WE, Maki BE (1993) Do anticipatory postural adjustments precede compensatory stepping reactions evoked by perturbation? Neurosci Lett 164: 199-202

Mohapatra S, Krishnan V, Aruin AS (2011) The effect of decreased visual acuity on control of posture. Clin Neurophysiol

Mohapatra S, Krishnan V, Aruin AS (2012) Postural control in response to an external perturbation: effect of altered proprioceptive information. Exp Brain Res 217: 197-208

Morasso PG, Schieppati M (1999) Can muscle stiffness alone stabilize upright standing? J Neurophysiol 82: 1622-1626

Nakagawa H, Ohashi N, Watanabe Y, Mizukoshi K (1993) The contribution of proprioception to posture control in normal subjects. Acta Otolaryngol Suppl 504: 112-116

Nardone A, Giordano A, Corra T, Schieppati M (1990) Responses of leg muscles in humans displaced while standing. Effects of types of perturbation and of postural set. Brain 113 (Pt 1): 65-84

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

Nardone A, Schieppati M (2004) Group II spindle fibres and afferent control of stance. Clues from diabetic neuropathy. Clin Neurophysiol 115: 779-789

Nashner LM (1983) Analysis of movement control in man using the movable platform. Adv Neurol 39: 607-619

Nashner LM, Wolfson P (1974) Influence of head position and proprioceptive cues on short latency postural reflexes evoked by galvanic stimulation of the human labyrinth. Brain Res 67: 255-268

NeuroCom (2010) NeuroCom Users Manual for Smart Balance Master. Clackamas, OR

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

Owsley C, Sloane ME (1987) Contrast sensitivity, acuity, and the perception of 'real-world' targets. Br J Ophthalmol 71: 791-796

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

Patel M, Fransson PA, Johansson R, Magnusson M (2011) Foam posturography: standing on foam is not equivalent to standing with decreased rapidly adapting mechanoreceptive sensation. Exp Brain Res 208: 519-527

Patel M, Fransson PA, Lush D, Gomez S (2008a) The effect of foam surface properties on postural stability assessment while standing. Gait Posture 28: 649-656

Patel M, Fransson PA, Lush D, Petersen H, Magnusson M, Johansson R, Gomez S (2008b) The effects of foam surface properties on standing body movement. Acta Otolaryngol 128: 952-960

Paulus WM, Straube A, Brandt T (1984) Visual stabilization of posture. Physiological stimulus characteristics and clinical aspects. Brain 107 (Pt 4): 1143-1163

Pavlik AE, Inglis JT, Lauk M, Oddsson L, Collins JJ (1999) The effects of stochastic galvanic vestibular stimulation on human postural sway. Exp Brain Res 124: 273-280

Pedotti A, Crenna P, Deat A, Frigo C, Massion J (1989) Postural synergies in axial movements: short and long-term adaptation. Exp Brain Res 74: 3-10

Pedrotti L, Pedrotti F (1998) Optics and Vision. Prentice-Hall, New Jersey

Peterka RJ (2002) Sensorimotor integration in human postural control. J Neurophysiol 88: 1097-1118

Pierrot-Deseilligny E, Katz R, Hultborn H (1983) Functional organization of recurrent inhibition in man: changes preceding and accompanying voluntary movements. Adv Neurol 39: 443-457

Polonyova A, Hlavacka F (2001) Human postural responses to different frequency vibrations of lower leg muscles. Physiol Res 50: 405-410

Previc FH, Neel RL (1995) The effects of visual surround eccentricity and size on manual and postural control. J Vestib Res 5: 399-404

Prochazka A, Wand P (1980) Tendon organ discharge during voluntary movements in cats. J Physiol 303: 385-390

Pyykko I, Jantti P, Aalto H (1990) Postural control in elderly subjects. Age Ageing 19: 215-221

Regan D, Raymond J, Ginsburg AP, Murray TJ (1981) Contrast sensitivity, visual acuity and the discrimination of Snellen letters in multiple sclerosis. Brain 104: 333-350

Richardson JK, Ching C, Hurvitz EA (1992) The relationship between electromyographically documented peripheral neuropathy and falls. J Am Geriatr Soc 40: 1008-1012

Roll JP, Popov K, Gurfinkel V, Lipshits M, Andre-Deshays C, Gilhodes JC, Quoniam C (1993) Sensorimotor and perceptual function of muscle proprioception in microgravity. J Vestib Res 3: 259-273

Roll JP, Vedel JP (1982) Kinaesthetic role of muscle afferents in man, studied by tendon vibration and microneurography. Exp Brain Res 47: 177-190

Roll JP, Vedel JP, Ribot E (1989) Alteration of proprioceptive messages induced by tendon vibration in man: a microneurographic study. Exp Brain Res 76: 213-222

Roll R, Kavounoudias A, Roll JP (2002) Cutaneous afferents from human plantar sole contribute to body posture awareness. Neuroreport 13: 1957-1961

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

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

Schmid M, De Nunzio AM, Schieppati M (2005) Trunk muscle proprioceptive input assists steering of locomotion. Neurosci Lett 384: 127-132

Schmid M, Nardone A, De Nunzio AM, Schieppati M (2007) Equilibrium during static and dynamic tasks in blind subjects: no evidence of cross-modal plasticity. Brain 130: 2097-2107

Schmitz C, Martin N, Assaiante C (1999) Development of anticipatory postural adjustments in a bimanual load-lifting task in children. Exp Brain Res 126: 200-204

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

Sousa ASP, Macedo R, Santos R, Tavares JMRS (2010) Influence of an unstable shoe on compensatory postural adjustments: An experimental evaluation. In: TMSi - Sixth International Conference on Technology and Medical Sciences

Spirduso W, Francis K, MacRae P (eds) (2005) Physical Dimensions of Aging. Champaign, IL

Stal F, Fransson PA, Magnusson M, Karlberg M (2003) Effects of hypothermic anesthesia of the feet on vibration-induced body sway and adaptation. J Vestib Res 13: 39-52

Strang AJ, Berg WP (2007) Fatigue-induced adaptive changes of anticipatory postural adjustments. Exp Brain Res 178: 49-61

Straube A, Paulus W, Brandt T (1990) Influence of visual blur on object-motion detection, self-motion detection and postural balance. Behav Brain Res 40: 1-6

Sun H, Frost BJ (1998) Computation of different optical variables of looming objects in pigeon nucleus rotundus neurons. Nat Neurosci 1: 296-303

Sun HJ, Campos JL, Young M, Chan GS, Ellard CG (2004) The contributions of static visual cues, nonvisual cues, and optic flow in distance estimation. Perception 33: 49-65

Szabo SM, Janssen PA, Khan K, Potter MJ, Lord SR (2008) Older women with age-related macular degeneration have a greater risk of falls: a physiological profile assessment study. J Am Geriatr Soc 56: 800-807

Talis VL, Solopova IA (2000) Vibration-induced postural reaction continues after the contact with additional back support. Motor Control 4: 407-419

Thompson C, Belanger M, Fung J (2007) Effects of bilateral Achilles tendon vibration on postural orientation and balance during standing. Clin Neurophysiol 118: 2456-2467

Thompson C, Belanger M, Fung J (2011) Effects of plantar cutaneo-muscular and tendon vibration on posture and balance during quiet and perturbed stance. Hum Mov Sci 30: 153-171

Toussaint HM, Michies YM, Faber MN, Commissaris DA, van Dieen JH (1998) Scaling anticipatory postural adjustments dependent on confidence of load estimation in a bi-manual whole-body lifting task. Exp Brain Res 120: 85-94

Trevarthen CB (1968) Two mechanisms of vision in primates. Psychol Forsch 31: 299-348

Tropp H, Odenrick P (1988) Postural control in single-limb stance. J Orthop Res 6: 833-839

Uchiyama M, Demura S (2008) Low visual acuity is associated with the decrease in postural sway. Tohoku J Exp Med 216: 277-285

Vallbo AB, Johansson RS (1984) Properties of cutaneous mechanoreceptors in the human hand related to touch sensation. Hum Neurobiol 3: 3-14

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 Deursen RW, Simoneau GG (1999) Foot and ankle sensory neuropathy, proprioception, and postural stability. J Orthop Sports Phys Ther 29: 718-726

Verschueren SM, Swinnen SP, Desloovere K, Duysens J (2002) Effects of tendon vibration on the spatiotemporal characteristics of human locomotion. Exp Brain Res 143: 231-239

Vrancken AM, Allum JH, Peller M, Visser JE, Esselink RA, Speelman JD, Siebner HR, Bloem BR (2005) Effect of bilateral subthalamic nucleus stimulation on balance and finger control in Parkinson's disease. J Neurol 252: 1487-1494

Wade MG, Jones G (1997) The role of vision and spatial orientation in the maintenance of posture. Phys Ther 77: 619-628

Wei K, Stevenson IH, Kording KP (2010) The uncertainty associated with visual flow fields and their influence on postural sway: Weber's law suffices to explain the nonlinearity of vection. J Vis 10: 4

Winter DA, Patla AE, Prince F, Ishac M, Gielo-Perczak K (1998) Stiffness control of balance in quiet standing. J Neurophysiol 80: 1211-1221

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

Wu G, Chiang JH (1997) The significance of somatosensory stimulations to the human foot in the control of postural reflexes. Exp Brain Res 114: 163-169

Yiou E, Mezaour M, Le Bozec S (2009) Anticipatory postural adjustments and focal performance during bilateral forward-reach task under different stance conditions. Motor Control 13: 142-160

Zago M, Bosco G, Maffei V, Iosa M, Ivanenko YP, Lacquaniti F (2004) Internal models of target motion: expected dynamics overrides measured kinematics in timing manual interceptions. J Neurophysiol 91: 1620-1634

VITA

Name

Sambit Mohapatra

Education

- **Pre-doctoral Fellow (UIC Chancellors Graduate Research Fellow)**
  University of Illinois at Chicago (UIC) - Department of Kinesiology, Nutrition and Rehabilitation, 2012

- **PhD Candidate (Concentration in Rehabilitation sciences and Neurosciences)**
  University of Illinois at Chicago (UIC) - Department of Kinesiology, Nutrition and Rehabilitation, 2009-2012 (expected)

- **M.S Kinesiology (Concentration in Motor control & Learning)**
  University of Illinois at Chicago (UIC) - Department of Kinesiology & Nutrition, 2007-2009

- **B.Sc (Honors) Physical therapy**
  University of Delhi- Department of Physical therapy, 2002-2007

Research experience & projects

- Graduate research assistant, Knecht Movement science laboratory, Department of Physical therapy, UIC, 2009-present.

- "Compelled Body Weight Shift Therapy in Individuals with Stroke Related Hemi-paresis" with Department of Physical Therapy, UIC and UIC Medical Center, 2008-2011

- "Virtual reality and its role in rehabilitation", in collaboration with Dr Hiro Ida, Jobu University, Japan and Dr Alexander Aruin, Department of Physical Therapy, UIC , 2011-2012.

- "The role of vision in control of human posture", with Knecht Movement science laboratory under the guidance of Dr. Alexander Aruin, Department of Physical Therapy, UIC, 2009-2012.

- "The role of proprioception in control of human posture", with Knecht Movement science laboratory under the guidance of Dr. Alexander Aruin, Department of Physical Therapy, UIC, 2011-2012.

Teaching & administrative experience

- Graduate teaching assistant in Department of Kinesiology & Nutrition, UIC: 2007-2008
  Taught human anatomy, human cadaver dissection & human physiology labs.

- Graduate head teaching assistant in Department of Kinesiology & Nutrition, UIC: 2008-2009
  Taught human anatomy & physiology labs and assisted in cadaver dissection.
  Organized and assigned the departmental TAs' schedules.
  Conducted review sessions for students prior to lecture exams.
  Coordinated course evaluations.

- Senior Administrator at Academic Support and Advising Center, Office of Dean, College of Applied Health Sciences, UIC: 2009-2012.
  Tutored human anatomy, physiology and biomechanics courses to undergraduate students.
  Coordinated co- tutors and employees at the center
  Managed budget and finances of the center

- Graduate teaching assistant in Department of Physical therapy, UIC 2009- 2012.
  Taught DPT 1st year students the following courses:
  Introduction to Physical therapy
  Motor Control
  Applied Kinesiology

Clinical experience

Worked as a Physical Therapy intern in the following institutions:

- Burns, Plastic & Maxillofacial Surgery Department, P.T Unit, Safdarjung Hospital, New Delhi, 2006-2007

- District Disability Rehabilitation Center, Jaisalmer, Rajasthan, 2006-2007

- Pt.Deen Dayal Updhyaya Institute for the physically handicapped, Department of Physical therapy, New Delhi, 2006-2007

Awards & achievements

- **2nd** in poster presentation at**"44th Annual conference of Indian Association of Physiotherapists",** held at Ahmedabad from 6th-8th January 2006.

- **Van Doran** scholarship, Fall, 2008. Amount: $400.
- **Donna K Roach Award** for Spring, 2010, Fall 2011. Amount: $800.
  Award to provide support for the professional development of meritorious students in the Department of Physical Therapy in the areas of education, research and community service.
- **UIC, Graduate Student Council** travel award, Fall 2011. Amount: $300
- **UIC Graduate College** travel award, Fall 2011. Amount: $300.
- **Force and Motion Foundation** travel scholarship Summer 2011. Amount: $500.
- **Chancellors graduate research fellowship** for Spring-Summer, 2012. Amount: $4000.
  Pre-doctoral fellowship, which supports increased multidisciplinary research opportunities and exposure to varied research and creative fields for graduate and professional students.
- **UIC Graduate College** travel award, Summer 2012. Amount: $200.
- **UIC, Graduate Student Council** travel award, Summer 2012. Amount: $300

Publications

- **Mohapatra S**, Krishnan V, Aruin A.S. The effect of decreased visual acuity on control of posture. **Clinical Neurophysiology**, 2012 Jan; 123(1):173-82. Epub 2011 Jul 22.
- **Mohapatra S**, Krishnan V, Aruin A.S. Postural control in response to an external perturbation: effect of altered proprioceptive information. **Experimental Brain Research.** Epub, 2011 Dec 25.
- **Mohapatra S,** Eviota A.C, Ringquist K.L, Muthukrishnan Sri R, Aruin A.S. Compelled body weight shift technique to facilitate rehabilitation of individuals with acute stroke, **International Society of Scholarly Network- Rehabilitation,** May 2012**.**
- **Mohapatra S** and Aruin A.S. Static and dynamic visual cues in feed-forward postural control. **Experimental Brain Research**, Epub, 2012 Oct 14.
- **Mohapatra S** and Aruin A.S. Support-surface related changes in feedforward and feedback control of posture. (In preparation) 2012.

Presentations

- **Mohapatra S**, Krishnan V, Aruin A.S. The effect of decreased visual acuity on control of posture. Poster presented at the 8th Motor control summer school, Pittsburgh, USA, July 9-13, 2011.

- Aruin A.S, Rao N, Sharma A, Chaudhri G, **Mohapatra S**, Eviota A, Ringquist K, Muthukrishnan S.R. Compelled Body weight shift technique to facilitate rehabilitation of individuals with stroke. Presented at 6th International Posture Symposium, Smolenice Castle, Slovakia, September 15-18, 2011.

- **Mohapatra S**, Krishnan V, Aruin A.S. Reduced acuity conditions during control of posture when subjected to external perturbations. Poster presented at the 99th Indian Science Congress, India, January 3rd-7th, 2012.

- **Mohapatra S**, Krishnan V, Aruin A.S. Posture control in response to external perturbation: role of altered proprioception. Poster presented at Clinical Gait & Movement Analysis Society, May 9th-12th, 2012.

- **Mohapatra S**, Aruin A.S. Posture control in response to an external perturbation: role of altered vision and proprioception. Invited talk at National Rehabilitation Hospital & Georgetown University, Washington D.C, May 16th, 2012.