THE SENSORIMOTOR CONTROL OF HUMAN STANDING POSTURE:

AN INVESTIGATION INTO THE RELATIONSHIP AMONG ATTENTION, VISUAL FEEDBACK AND AGE

THE SENSORIMOTOR CONTROL OF HUMAN STANDING POSTURE: AN INVESTIGATION INTO THE RELATIONSHIP AMONG ATTENTION, VISUAL FEEDBACK AND AGE

By TING TING YEH B.Sc. Physiotherapy (Hons)

A Thesis Submitted to the School of Graduate Studies in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy

McMaster University

DOCTOR OF PHILOSOPHY (2013)
(KINESIOLOGY)
McMaster University, Hamilton, ON, Canada

TITLE: The Sensorimotor Control of Human Standing Posture: An Investigation into the Relationship among Attention, Visual Feedback and Age

AUTHOR: Ting-Ting Yeh, B.Sc. Physiotherapy (Hons) (Chung Shan Medical University, Taiwan)

CO-SUPERVISORS: Drs. Timothy D. Lee and James Lyons
NUMBER OF PAGES: xiii, 211

Abstract

Maintaining upright posture is seemingly an automatic task in younger adults, but it may require additional resources in late adulthood due to decreases in sensorimotor and cognitive functions. The thesis used a dual-task paradigm to investigate age-related changes in relation to the secondary task and context-dependent factors attributes to postural control. The postural task involved visuomotor tracking. Successfully performing the visuomotor task necessitated proper sensory feedback, motor response, and sensorimotor integration. Moreover, we used silent counting as a cognitive task to investigate attentional demands on postural control and age-related difference in cognitive processing.

We first investigated the relative contributions of visual feedback delay and cognitive task load on postural dynamics as well as age-related difference in this effect. Our results supported distinct timescale mechanisms for postural control. Moment-to-moment center of pressure fluctuations are dependent on cognitive performance during delayed visual feedback postural control. Also, we demonstrated the increased role of vision with age in postural control. Next, we investigated whether postural control improved when performing a cognitive task with an internal focus of attention. We found that devoting less attention internally by performing a cognitive dual-task enhanced postural control in young adults. Yet, the age-related declines diminish the attentional allocation ability. Lastly, we investigated how older and younger adults differ in employing sensorimotor strategies in a dual-task situation. Our results suggested that age-related changes in postural control may degrade the flexible coordination of the sensory feedback and motor execution. Furthermore, diminished cognitive and attentional capacities may alter postural performance in dual-task conditions.

This thesis adds to the current understanding of the role of sensorimotor processing, attentional influence and age in the control of posture. Our data provide convergent evidence that deterioration of peripheral sensorimotor systems and reduced flexibility in central information processing are responsible for the age-related differences in postural control.

Author Contributions

This thesis consists of six chapters, each of which constitutes original research conducted by the author, except for contributions made by the thesis co-supervisors, Drs. Timothy D. Lee and James Lyons, and by the co-authors of journal manuscripts arising from the research presented here. As primary author, I was involved in all aspects of the presented work, from experimental conception and design to data collection, analysis and subsequent writing of each manuscript.

For Chapters 2 and 3, I was supervised by former advisor Dr. Ramesh Balasubramaniam who was involved with conception, design, interpretation of results as well as editing and approval of the manuscript. Tyler Cluff assisted with data processing and involved in interpreting the results and writing the manuscript presented in Chapter 2 and 3. Jason Boulet helped with experimental setup and prepared the manuscript presented in Chapter 2.

The work presented in this thesis has been published (Chapters 2) or re-submitted (Chapter 3) for publication in peer-reviewed international journals. The publications associated with each chapter are listed below.

Chapter 2:

Yeh, T-T., Boulet, J.W., Cluff, T. & Balasubramaniam, R. (2010). Contributions of delayed visual feedback and cognitive task load to postural dynamics. *Neuroscience Letters* 483: 173-177.

Reproduced with permission from Elsevier:

http://www.elsevier.com/wps/find/authorsview.authors/rights

Chapter 3:

Yeh, T-T., Cluff, T., & Balasubramaniam, R. (revised and resubmitted) Increased reliance on visual feedback for balance control in older adults. (*PLoS ONE*, manuscript #: PONE-D-13-26121).

Acknowledgments

The path to a Ph.D. is never easy, but I have had the fortune to be surrounded by incredibly people that made this journey of growth and learning enjoyable.

I would like to acknowledge and sincerely thank my thesis co-supervisors, Drs. Tim Lee and Jim Lyons, for your guidance, support and feedback. You have provided insightful knowledge from different perspectives. Not only are you experts and true professional in your field, but you are great mentors and role models. I would also like to thank Dr. Ramesh Balasubramaniam, my previous advisor, for letting me become part of Sensorimotor Neuroscience lab, where I first began to learn how to do research and write papers, and where I met important fellows and friends.

I would like to thank my advisory committee member, Dr. Michael Cinelli for your helpful advice, comments and suggestions. I would also like to thank Drs. Jae Patterson and Laurie Wishart for their contribution as members of my comprehensive committee. Finally, special thanks to my external examiner, Dr. Allan Adkin, for the detailed and constructive examination of my thesis.

I am thankful to all members of the Sensorimotor Neuroscience and Motor Behavior Laboratories at McMaster University, both past and present, for their humor, tolerance and valuable assistance. In particular, I would like to acknowledge Dr. Tyler Cluff, Dr. Brian Richardson, Dr. Amanda Therrien and Jason Boulet for their help along the way with the invaluable suggestions and technical supports of my research program.

My sincere thanks and appreciation is also extended to all the senior participants from the Physical Activity Excellence Centre from McMaster University and the community. Without their cooperation and patience, this dissertation would not have been possible. I also extend my thanks to the administrators of the McMaster University, Department of Kinesiology.

My family in Taiwan, Mom and Dad, you have always supported me, even let me go 12000 km away from home to pursue my dream. Your unconditional love and encouragement have made all of this possible and I am forever grateful for it. People say that being away from home is hard, but you made it much easier for me. Darren, thank you for your continuous support, understanding and for believing in me.

List of Figures

List of Abbreviations

ANOVA	Analysis of variance
AP	Anteroposterior
CNS	Central nervous system
COG	Cognitive dual-task
COM	Center of mass
COP	Centre of pressure
DVF	Delayed visual feedback
EO	Eyes open
EXT-C	External focus with cognitive dual-task
EXT-NC	External focus without cognitive dual-task
F	Fisher ratio
*f*c	Cutoff frequency
Fs	Sampling frequency
HIGH	High-pass frequency
INT-C	Internal focus with cognitive dual-task
INT-NC	Internal focus without cognitive dual-task
LOW	Low-pass frequency

ML	Mediolateral
mm	Millimeters
ms	Milliseconds
NCOG	No cognitive dual-task
NVF	No visual feedback
SD	Standard deviation
Tukey’s HSD	Tukey’s honestly significant difference test
UNFILTERED	Untreated time series
VF	Visual feedback

Table of Contents

Chapter 1- General Introduction

1.1– MOTIVATION

When crossing a busy intersection, people’s attention can be drawn to the traffic light, the oncoming cars, pedestrians and sometimes the conversation with a companion. Maintaining the ability to cross a busy street safely and efficiently is essential to independent older adults, especially those who live in urban settings. In this complex situation, people need the ability to flexibly allocate attention between maintaining posture and performing secondary tasks at the same time (e.g., talking, scanning the busy street for threats or tracking visual targets). Thus, the coordination among vision, balance and secondary task seems to comprise a common element in our daily life activities.

Postural control was once assumed to consist of a set of reflexes that triggered equilibrium responses based on visual, vestibular or proprioceptive cues (Horak & Macpherson, 1996). Likewise, it was considered to be automatic, without needing any attentional resources. However, recent research has provided evidence against these assumptions (Kerr, Condon, & Mcdonald, 1985; Teasdale, Bard, Larue, & Fleury, 1993). The ability to stand, to walk and to perform daily activities in a safe manner depends on a complex interaction of the individual, task and environment (Shumway-Cook & Woollacott, 2001). In addition, the ability to control the body’s position in space emerges from a complex interaction of musculoskeletal and higher level neural systems, collectively referred to as the postural control system (Horak & Macpherson, 1996). An understanding of the components of the postural control system and age-related changes within the system is necessary. This thesis used a dual-task paradigm to investigate age-related changes in relation to the context-dependent attributes of human postural control.

1.2- CONTROL OF HUMAN POSTURE

Postural control is defined as the ability to maintain equilibrium in a gravitational field by keeping or returning the center of gravity within its base of support (Horak, 1987). Postural control requires both perception (the integration of sensory information to assess the position and motion of the body in space) and action (the ability to generate forces for controlling the body). Consequently, postural control requires a complex interaction of the sensorimotor system and higher-level integrative processes.

Mechanisms that contribute to postural control are served by distinct neurophysiological pathways and dynamical control structures that incorporate both open and closed-loop processes (Ahmed & Wolpert, 2009; Collins & De Luca, 1994). Collins and De Luca (1993) found that center of pressure (COP) trajectories could be modeled as fractional Brownian motion and two control systems—a short-term, and a long-term mechanism that operate during quiet standing. From the physiological point of view, the short-term or fast stochastic component (i.e., drift process) means that the posture system allows the COP to drift for some time and displacement – in more simply, it allows a certain amount of “slackness” in controlling posture without any feedback. On the other hand, when the COP drifts to a critical point (close to boundary of the base of support) the long-term or slow feedback control component (i.e., correct process) becomes involved. That is, by using a closed-loop feedback mechanism, the postural control system shifts the COP back to a relative equilibrium position after some time of drifting. Within this conceptual model, the central nervous system (CNS) still continually receives afferent information from peripheral sensory organs; however, such information is not used to modulate the efferent signals sent out to postural muscles unless a certain threshold value is exceeded.

Controlling posture requires the generation and coordination of forces that produce movements effective in controlling the body in space. For instance, increased ankle muscle stiffness can minimize the effect of gravitational forces, which tend to move the body off center (Winter, Patla, & Prince, 1998). On the other hand, peripheral information from visual, proprioceptive and vestibular systems is available to detect the body’s position and movement in space with respect to gravity and the environment. The goal of these three sensory systems is to detect and transmit sensory inputs from the environment to the CNS for subsequent processing. This higher-level integrative process ensures that the most appropriate sensory reference is selected for the task and the environment. It is suggested that the relative weight given to each sensory feedback system may vary as a function of the goal of the movement task, environment context or age (Shumway-Cook, & Woollacott, 2001).

Sensory information provided by the visual, vestibular and somatosensory system is partly redundant, thus we can maintain equilibrium with eyes closed. The multi-source sensory feedback might compensate for deficiencies and to resolve ambiguities that arise from a single sensory modality (Horak, Shupert, & Mirka, 1989). An important role of the CNS is to integrate sensory information from different resources, and select appropriate sensory references for postural control (Horak et al., 1989). For example, visual information becomes unavailable when a person walks into a movie theater (i.e., a dark room). Consequently, the CNS would re-select and re-weight sensory inputs from an unavailable or inaccurate sensory input (e.g., vision) to more reliable resources (e.g., somatosensory and vestibular feedback) in order to maintain upright stance.

The ability to re-weight sensory information for postural orientation has been quantitatively examined using a movable platform combined with a movable visual surround (Black, Shupert, Horak & Nashner, 1988). In these experiments, the platform and/or the visual surround could be rotated in proportion to the participant’s sway, which they termed “sway-referenced”. This sway-referenced feedback from somatosensory or vision provides misleading sensory feedback to the participant while standing. There were in total six experimental conditions; each condition examined the ability to rapidly and accurately select a reliable source of sensory information for postural control. Overall, their results demonstrated that healthy young participants are able to quickly and efficiently select reliable sensory resources to control posture even in highly challenging sensory contexts (e.g., the condition provided accurate vestibular feedback, but inaccurate visual and somatosensory information). However, a group of healthy older adults without any pathology appeared to have more postural sway with inaccurate visual or somatosensory information than the young participants (Black et al., 1988).

There is some evidence, however, that older individuals can learn to control posture in misleading sensory environment (Woollacott, Shumway-Cook, & Nashner, 1986). As a result, Black et al. (1988) suggested that older people have the ability to accurately select and re-weight sensory input, but the central selection or re-weighting process may be slowed, and not as efficient as young adults.

The older adults are subject to many pathological conditions which can result in loss of peripheral sensory function. For example, peripheral neuropathy can reduce or eliminate sensory feedback from the feet, it is possible that the somatosensation might be “down-weighted” or suppressed by the CNS, and the more accurate sensory input (e.g., the visual feedback) will be “up-weighted” (Horak, Nashner, & Diener, 1990). Thus, the ability to select and weight alternative orientation references adaptively may be one of the most critical factors in postural control in older people.

Aging and postural control

Upright balance control is of particular interest in the study of aging because lack of control in balance directly increases the possibility of falls. The high incident of falls in older adults is a serious public health problem. Falls occur in 30-60% of older adults each year (Rubenstein, 2006), and this is often resulting in dramatic consequences (e.g., hip fractures, hospitalization, and death). Post-fall syndrome also leads to a combination of anxiety, fear of falling, impaired functioning and mobility, which may lead to discontinue engaging in physical activity (Murphy & Isaac, 1982). This post-fall syndrome can ultimately result in a vicious cycle in their activities of daily living. For example, fear of falling occurs often for those who have fallen recently, and it causes the individual low perceived self-efficacy in balance control

(Carpenter, Frank, Silcher, & Peysar, 2001). Fear of falling and decreased balance confidence may restrict the person from engaging in physical activities. This restriction may further decrease muscle strength and joint flexibility, which in turn increases postural instability. Consequently, developing a thorough understanding of knowledge in controlling balance for older adults is an urgent area in a growing aging society.

It is widely recognized that falling is a common problem in the growing population of older people. Studies have shown that many falls in older adults occur while simultaneously standing or walking and performing a secondary task (such as engaging in conversation or carrying an object) (Shumway-Cook, Brauer, & Woollacott, 2000; Teasdale et al.,1993). Postural control is considered a complex motor skill derived from the interaction of multiple sensorimotor processes.

Horak (2006) proposed a six-resources framework for postural stability and suggested that older people tend to increase the risk of falling because of specific, unique constraints on their postural control system. A summary of six resources required for postural stability is shown in Figure 1.1. This framework suggests that a disorder in any one of the resources, or a combination of these resources, would lead to postural instability and increase the risk of falling. For instance, in the biomechanical constraints domain, the amount of force that a muscle produces declines with age, especially in the lower extremities (Carmeli, Reznick, Coleman, & Carmeli, 2000). This age-related change may affect the functional capacity to recover balance from an external perturbation, and may increase the risk of falling. In addition, Horak's framework states that the increased risk of falling associated with aging is not due to 'aging of the balance system' but an increased likelihood of impairment or pathology in these resources.

Among the six resources for controlling posture, this thesis mainly focuses on the influence of attention (cognitive processing), sensory, and motor strategies on postural control.

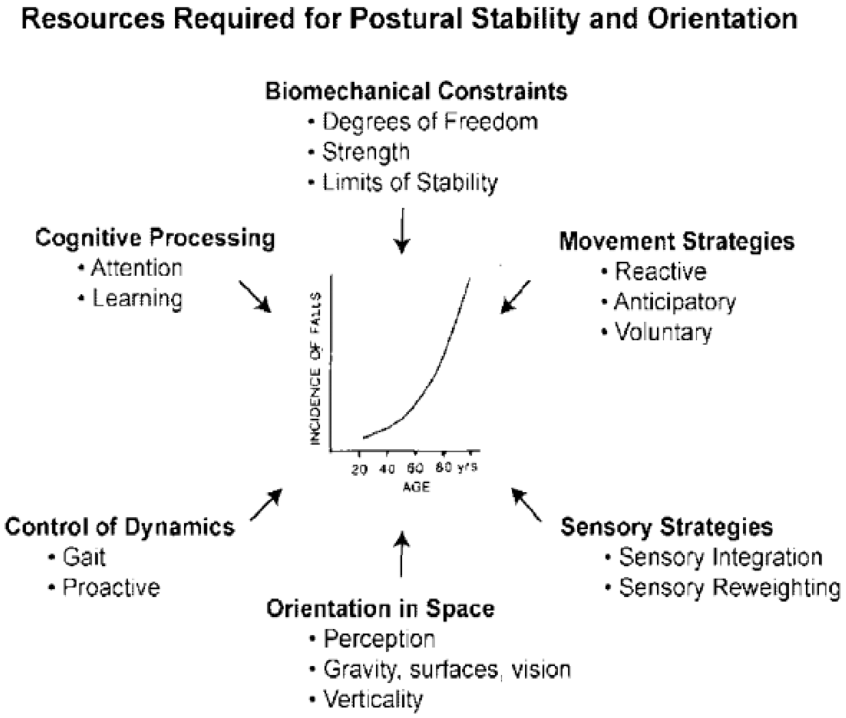

Figure 1.1 Schematic representation of the six resources of postural control on the incidence of falls in the elderly. The central plot shows the incidence of falls as a function of age in the general population (adapted from Horak, 2006).

1.3- ATTENTIONAL DEMAND ON POSTURAL CONTROL

In daily lives, people often perform concurrent physical or cognitive secondary tasks while standing, for example, talking on the phone or reading a text message. Scientists have known for many years that we have attentional limits that influence performance when we do more than one task at the same time (Kahneman, 1973; Palmer, 1990). The literature on posture-cognition interactions is vast. As documented by reviewed works on posture-cognition (Woollacott & Shumway-Cook, 2002) and gait-cognition (Yogev-Seligmann, Hausdorff, & Giladi, 2008), posture control is not as autonomous as previous assumed, but is ‘cognitively penetrable’ (Teasdale et al., 1993).

The contribution of attention to the regulation of balance is typically studied using a “dual-task paradigm” (Kerr et al., 1985). Specifically, the postural control is considered the primary task, and an additional physical or a cognitive task is considered the secondary task. The extent to which the performance on either task declines, relative to their performance when performed individually, is used to make inferences about the extent to which the two tasks share attentional resources (Kerr et al., 1985).

It is now well established that postural control requires cognitive or attentional resources, and these requirements vary depending on the postural task, age of the individual and their balance abilities (Woollacott & Shumway-Cook, 2002). Minimal attentional resources are needed in young adults compared to older adults in an undisturbed stance, but postural control becomes more cognitive-demanding under challenging postural tasks. Specifically, some studies manipulated challenges to postural control by varying the stance, for instance, by asking participants to maintain shoulder width or tandem stance while conducting a secondary task (Dault, Frank, & Allard, 2001; Lajoie, Teasdale, & Bard, 1993). Other studies had participants performing the secondary dual-task under balance disturbances by means of sudden movement of a platform on which they stood (Brauer, Woollacott, & Shumway-Cook, 2001; McIlroy et al., 1999). Other studies manipulated the visual input (Donker, Roerdink, Greven, & Beek, 2007; Jamet, Deviterne, Gauchard, Vancon, & Perrin, 2004), or some combination of these factors (Hunter & Hoffman, 2001; Teasdale et al., 1993). In summary, maintaining upright stance under conditions that challenge postural system is often found to degrade secondary cognitive task performance, suggesting an increased attentional demand for postural control.

If increasing the challenge of postural control degrades cognitive performance, then does postural control deteriorate as the challenge of the secondary task increases? Performing a secondary cognitive task while standing is found to increase sway amplitude or sway variability and therefore decrease postural stability (Andersson, Persson, Melin, & Larsen, 1998; Marsh, & Geel, 2000; Pellecchia, 2003). This effect is stronger in older adults compared to young adults (Brauer et al., 2001; Marsh & Geel, 2000; Redfern, Jennings, Martin, & Furman, 2001; Shumway-Cook, Woollacott, Kerns, & Baldwin, 1997) and in patients with balance disorders (Redfern, Talkowski, Jennings, & Furman, 2004).

An interesting finding is that a number of studies have reported *increased* postural stability in healthy young adults under cognitive dual-task situations (Andersson, Hagman, Talianzadeh, Svedberg, & Larsen, 2002; Dault et al., 2001; Dault, Yardley, & Frank, 2003; Riley, Baker, Schmit, & Weaver, 2005; Riley, Baker, & Schmit, 2003). The inconsistency of results from those dual-task studies might reflect differences in the secondary task used in these studies. For example, a verbal response task (Kerr et al., 1985; Lajoie et al., 1993), mental arithmetic (Andersson et al., 2002; Brown, Shumway-Cook, & Woollacott, 1999; Weeks, Forget, Mouchnino, Gravel, &

Bourbonnais, 2003), working memory task (or n-back tasks) (Doumas, Rapp, & Krampe, 2009; Doumas, Smolders, & Krampe, 2008), and visuo-spatial task (Cheng, Pratt, & Maki, 2013; Dault & Frank, 2004; Seidler et al., 2010) have been used in these studies.

One of the reasons why the nature of the secondary task could impact on postural control may be due to the motor requirements of the task, such as those that require an articulation (Dault et al., 2003; Yardley, Gardner, Leadbetter, & Lavie, 1999). Cognitive tasks that involve articulation cause interference between postural control and the cognitive task. Yardly (1999) used three secondary tasks: silent counting (attention demanding), number repetition (articulation demanding) and counting aloud (both attention and articulation demanding) while participants stood on a static or unstable surface. Their results showed that postural control decreased in the two tasks requiring articulation compared with silent counting. This finding suggested that decreased in postural control when performing a spoken mental arithmetic task is partly due to perturbing effects of articulation, rather than competing demands for attention. Thus, in order to accurately examine the effect of attentional demand on postural control, it is important to eliminate the effect of articulation in dual-task situations.

On the other hand, a number of studies have used mental arithmetic task as a secondary task while standing, and their results showed that silent counting lead to a decrease of postural sway (Andersson et al., 2002; Weeks et al., 2003). Andersson et al. (2002) suggested that postural enhancement was mediated by arousal. Specifically, the authors suggested that silent counting may have increased arousal level in comparison with the baseline task of standing without performing any task. They hypothesized that arousal and stress caused by a mental task ‘sharpen’ balance control. With the similar finding, however, Weeks et al. (2003) proposed a muscle “co-contraction strategy” during secondary task performance. Specifically, the authors suggested that when cognitive vigilance is necessary, the co-contraction strategy can be invoked to suppress postural sway.

Although the relationship between cognition and balance control has received much attention recently, there is no consensus about the relationship between aging, postural control and dual-tasking. A number of dual-task models have been proposed to explain dual-task interference effect.

1.4 - MODELS OF DUAL-TASKING

1.4.1 Central Resource Capacity Model

An assumption regarding the dual-task methodology is that there is a limited central processing capacity (Kahneman, 1973). This central resource capacity model postulates that performing a task requires a given portion of capacity within the CNS. Therefore, if two tasks are performed together and both share the processing capacity, the performance in one or both tasks can be disturbed if the total limits of the processing capacity are exceeded. Kahneman (1973) also noted that attentional interference is possible when two tasks are performed together, which is known as structural interference. Structural interference may occur when the cognitive task and postural control involve the same physical or neural mechanisms (e.g., the simultaneous use of receptors or processing systems). A decrease in the quality of performance may occur when different tasks, which use the same structures, are performed simultaneously as some competition between the postural task and the secondary task. To exclude the possibility of structural interference, it is better using secondary tasks that do not interfere with the visual or somatosensory system for postural control.

Supporting this model is the observation of decreased postural control by additional cognitive demands or decreased cognitive performance under more challenge postural conditions (Andersson et al., 1998; Marsh & Geel, 2000; Pellecchia, 2003). With normal aging, the available attentional resources diminished, which cause a negative effect on dual-task performance in older adults (Mitra, 2003; Pellecchia, 2003). Specifically, more attentional resources are needed for older adults to maintain the secondary performance; the cognitive activity may compete for more attentional resources so that postural performance is compromised.

This central resource capacity model, though, failed to explain studies which showed no change (Shumway-Cook et al., 1997) or even an enhancement in postural control under the dual-task paradigm (Andersson et al., 2002; Dault et al., 2001; Dault et al., 2003; Riley et al., 2005; Riley et al., 2003). Therefore, the inconsistency in current literature on postural control and dual-task effects suggest that the relationship between the two factors required further scrutiny.

1.4.2 Inverted U-shape Relationship Model

A more complex interaction between postural control and cognitive demand has emerged from the dual-task literature, which suggested an inverted U-shape relationship. Huxhold et al. (2006) used different cognitive dual-tasks, differing with regard to their cognitive demands, to investigate the effect of task difficulty on postural control in healthy young and older adults. Their results showed that when performing an easy cognitive task, postural stability was enhanced in both young and older participants compared to single baseline condition. However, when performing more demanding cognitive tasks, older participants decreased postural control by exhibiting greater COP displacements, whereas young adults did not show the postural instability. The authors argued that the relationship between cognitive demand and postural control might reflect the level of arousal associated with the secondary cognitive demand, similar to the inverted U-shape relationship in Yerkes-Dodson law (Yerkes & Dodson, 1908).

The Yerkes-Dodson law is an empirical relationship between arousal and performance. Arousal is the general state of excitability of a person, reflected in the activation levels of the person’s emotional, mental and physiological systems. According to the Yerkes-Dodson law (1908), the relationship between arousal level and performance can be a linear or non-linear (i.e., a U-shaped) function, depending on task difficulties. In brief, Yerkes and Dodson (1908) found that when a mouse did a simple discrimination task, their performance improved linearly with increases in arousal. However, with difficult tasks, the performance of the mice improved moderately with increases in arousal, but at the highest levels of arousal their performance was impaired. This law suggested that the nature of the relationship is highly task-dependent. With simple tasks, the relationship between arousal and performance is a linear function, whereas with difficult tasks, the relationship becomes an inverted U-shaped function. Thus, under conditions of high arousal, people show a high level of performance in simple tasks, but performance degraded in difficult tasks.

Under a dual-task paradigm, this concept explains that postural performance can be either improved or degraded depending on whether the cognitive demand of the secondary task is simple or difficult. Specifically, simple cognitive task increases the arousal level which promotes optimal postural performance in a linear function. However, when the cognitive task is difficult, the beyond-optimal arousal level may cause deterioration in postural performance (inverted U). Consequently, an inverted U-shape relationship has been suggested to explain the improved or diminished balance control in dual-task situations. In Huxhold et al. (2006), older adults' postural performance was in line with the inverted U-shape relationship that postural control was enhanced under a less-demanding cognitive task, but postural control diminished under a more cognitive-demanding task. However, young adults did not show a decrease in postural control with increasing cognitive demands. The authors suggested that the possible reason for the age-related different was that the level of cognitive demands was not difficult enough for young adults to show a detrimental effect. It may be that the cognitive tasks for young adults were considered relatively simple, which demonstrated the linear relationship between arousal and performance. A subsequent study has reported similar findings, showing an age-related difference between cognitive demand and postural control (Simoneau, Billot, Martin, Perennou, & Van Hoecke, 2008). Lacour et al. (2008) suggested that aging may change the function of the inverted U-shaped relationship. Specifically, the beneficial range of the cognitive task was reduced with aging, while the detrimental range was increased due to reduced attentional capacities in older adults.

Maki and McIlroy (1996) used different secondary tasks and measured arousal level as quantified by skin conductance while young participants were quiet standing. The secondary tasks included: 1) no task, 2) listen to “white noise“, 3) listen to an audio recording about a book content, and 4) silent counting. They hypothesized that “listening to white noise” and “silent counting” tasks should increase arousal level, whereas “listening to the audio recording” task would divert attention without affecting physiological arousal. Their results did not fully support their hypotheses. Specifically, “listening to white noise” task failed to show evidence of higher skin conductance relative to no task or “listening to the audio recording” task. Nonetheless, no correlation has been found between postural performance and level of arousal induced by the cognitive tasks (Maki & McIlroy, 1996). Therefore, an arousal-based explanation for the posture-cognition relationship was not supported in their study.

1.4.3 Postural Facilitation Viewpoint

A stable posture is necessary to execute precise motor skills as well as being important for mobility of humans. If standing upright requires greater energy expenditure than sitting or lying, then why bother to do so in our daily lives? From the primate evolutionary point of view, one clear benefit of standing up is to perform tasks such as carrying food, tools, or even fighting (Carrier, 2011). A number of studies have suggested that upright standing facilitates the performance of *suprapostural tasks* (Balasubramaniam, Riley, & Turvey, 2000; Riley, Stoffregen, Grocki, & Turvey, 1999b; Stoffregen, Pagulayan, Bardy, & Hattinger, 2000). Suprapostural task is defined as the task or behavioral goal that represents a *superior order* to the control of posture (Stoffregen, Smart, Bardy, & Pagulayan, 1999). According to Stoffregen et al. (2007), there are two kinds of suprapostural tasks: perceptual and cognitive tasks. Perceptual tasks involve some type of contact with the environment. For example, reading is a perceptual task; it requires the reader to control gaze in order to see the text clearly (reading individual letters and shifting gaze between letters). The perceptual task is achieved and maintained through adjustments of perceptual or information-gathering systems (e.g., eye and head movements that are used to optimize vision). On the other hand, a memory rehearsal task (e.g., mentally rehearsing a series of numbers) would be an example of a cognitive task because perform such tasks does not depend on control of visual perceptual system. According to Stoffregen et al. (2007), cognitive tasks refer to the tasks do not involve perceptual contact with the environment.

Stoffregen et al. (1999) suggested that performance of a postural task together with a suprapostural task may increase or decrease postural stability depending on the requirement of the suprapostural task. If the task requires head stabilization, postural stability may be increased and vice versa. For example, if a person wants to read newspapers while standing on a moving bus, success in that action will depend on the stability of one’s posture. Thus, a stable postural system would facilitate the achievement of this suprapostural task – improved balance would be a byproduct of facilitating this suprapostural task (i.e., reading). On the other hand, in some cases, the suprapostural goal might require increased postural sway, for instance, figure skating. In such case, minimize postural sway could hinder the achievement of the suprapostural goal (i.e., moves in the field).

Stoffregen et al. (2007) conducted two experiments and showed that tasks that need oculomotor demand facilitated postural control, but were not affected by non-perceptual cognitive demand. In the experiment 1, young subjects were standing and performed two tasks: a signal detection task (which required precise control of the oculomotor system) and a mental arithmetic task (which was not visually demanding). The results supported their hypotheses that body sway was reduced during performance of the visually-demanding signal detection task, but not during the mental arithmetic task where the control of oculomotor system was not needed. Yet, one can argue that the differences in body sway can be due to the fact that the two suprapostural tasks placed different types of demands on the central resources. It may be that one task drew more attentional resources from the central processing resources, resulting in fewer resources left for postural control, and increasing postural sway. To address this concern, in the experiment 2, they kept the mental arithmetic task but varied the level of mental load to manipulate the degree of difficulty. They hypothesized that there would be no significant differences in sway between the easy and hard mental arithmetic task conditions because both tasks were not visually demanding cognitive tasks (i.e., non-perceptual suprapostural tasks). Their results supported the hypothesis. Specifically, the results showed that counting was more accurate and faster during the easy task compared to the hard task. Postural sway, however, showed no difference between the easy and hard mental arithmetic conditions. Collectively, the two experiments suggested that variations in perceptual demand modulate postural sway; variations in non-perceptual cognitive demand had no effect on postural control. Therefore, the authors suggested that motor system adaptively modulates postural control to facilitate the suprapostural task that requires stabilization of perceptual performance.

Stoffregen et al. (1999) proposed a ‘facilitatory control’ view that the goal of the postural system is to act as a facilitator to achieve the suprapostural task goal which needs oculomotor demand. Increased postural stability serves as a means to achieve enhanced performance of the suprapostural tasks. In other words, postural stability is critical for the achievement of both goals, not just for one task or the other. For instance, when an archer aims at a target, the control of postural stability increases in order to facilitate precision in the aiming task.

1.4.4 Task Prioritization Model

Under some challenging balance conditions (e.g., standing at the edge of an elevated platform), older people prioritized postural control in sacrificing the secondary task performance in order to maintain equilibrium (Brown, Sleik, Polych, & Gage, 2002). This observed decreased postural sway cannot be explained by the postural facilitation viewpoint because, in Brown et al. (2002), the suprapostural task did not require gaze control or oculomotor demand.

Simultaneously performing two attentional demanding tasks not only causes a competition for attention resources, but also challenges the CNS to determine how to prioritize the two tasks. The task prioritization model suggests that a hierarchy exists in the allocation of attentional resources with posture being the first priority in situations where the risk of falling or the threat of injury is great (e.g., walking on an icy road or standing at the edge of a cliff) (Shumway-Cook et al., 1997). A good illustration is that older adults “stop talking while walking” (Lundin-Olsson, Nyberg, & Gustafson, 1997). Compared to young adults, older adults prioritize postural control in divided attention situations, especially in the case of frail older individuals with balance problem (Brown et al., 2002). This concept makes sense from an ecologic perspective because this “posture first” strategy minimizes loss of balance under increased postural threat. Indeed, several studies reported that older people tended to prioritize postural control over cognitive performance under dual-task situations (Berger & Bernard-Demanze, 2011; Brauer, Woollacott, & Shumway-Cook, 2002; Shumway-Cook et al., 2000). Prioritization of posture control in older adults can be seen as a compensatory strategy that they reallocate the attentional resources to the postural stability at the expense of the cognitive performance when dual-tasking.

Some findings in the literature, however, contradict this “posture first” prediction and showed that during the performance of a cognitive and postural task, decrements in performance were found in the postural stability measures rather than the cognitive measures (Shumway-Cook et al., 1997; Stoffregen et al., 1999). The authors explained that such discrepancies can be due to the fact that their postural task was not challenging enough to require a change in priorities (Shumway-Cook et al., 1997). Consequently, Shumway-Cook et al. (1997) further suggested that allocation of attention during the dual-task situation is complex, depending on many factors including the complexity of the postural and cognitive task, the instructions and the environmental context. In situations where postural control is relatively easy to maintain or is less likely to evoke the risk of falling, performance on a secondary task could then take priority.

In supporting this view, a number of studies have reported reduced sway in healthy young adults for a concurrent cognitive task without sacrificing the cognitive performance (Dault et al., 2001; Weeks et al., 2003). One could, therefore, propose a “cognitive first” strategy for the young adults (Barra, Bray, Sahni, Golding, & Gresty, 2006; Berger, & Bernard-Demanze, 2011), that is the mirror image of the “posture first” strategy in older adults. A recent study by Yogev-Seligmann et al. (2012) proposed a new comprehensive framework which suggests that task prioritization involves the weighting of the motor and cognitive state during the dual-task situation, the postural reserve, compensatory capabilities, and individual properties. The postural reserve reflects the individual’s capability to respond effectively to a postural threat. One can use the postural reserve to cope with the threat and avoid loss of balance in response to a postural destabilization. For example, proper muscle strength, joint flexibility, and sensory motor integration are critical factors to maintain upright standing. Healthy young adults have more postural reserve than older adults. Therefore, they can cope with challenging postural threats and demands. On the other hand, the individual properties include the expertise or skilled performance of the person. Other characteristics of the individual properties, such as personality state, may also affect dual-task performance and the prioritization strategy. For instance, people tend to allocate more attention resources toward the postural control over cognitive performance when standing with one foot or standing on a foam surface. Although some discrepancies contradict the task prioritization model, this model takes into account the adaptive responses to age-related declines which lead to compensatory responses, or strategies like task prioritization.

Taken together, these models/theories listed above have been interpreted to support the current findings; however, there is no consensus on the model/theory that best explains the relationship between aging, postural control and dual-tasking. Given the seemingly paradoxical pattern of findings, the motivation of this thesis is to better understand how concurrent cognitive processing affects postural control in healthy young and older adults.

1.5 - SUMMARY

In the previous sections, we provided a general background of postural control, postural performance under a dual-task situation and summarized the main relevant models capable of explaining the postural control changes in young and older adults. While an extensive literature has focused on the effect of a secondary task on postural control, few studies have considered how factors like visual feedback, sensorimotor integration combine with a suprapostural task influence postural control. Moreover, there is no agreement on the dual-task model that best describes the relationship between aging, postural control and dual-tasking. Also, while recent research has studied age-related changes in the subcomponents of postural control in isolation, the age-related changes combining sensorimotor and cognitive processing remain unclear. Figure 1.1 illustrates Horak's model (2006) which provided a concept that postural instability in the elderly is an emergent property of the complex interrelationships among these fundamental subcomponent processes. Our hypothesis is that the deterioration of peripheral sensorimotor systems as well as reduced flexibility in central information processing likely serve as co-mechanisms for the age-related difference in postural control. This thesis is designed to test the hypothesis. The three main research questions are:

1) Do vision and cognitive dual-task differentially influence slow and fast postural dynamics?
2) Are postural control mechanisms modulated by context and task demand?
3) How does age impact sensorimotor system and cognitive processing in postural control?

This thesis aims to address these research questions. The first question is motivated by the fact that postural control is served by two characteristic time scales (Boulet, Balasubramaniam, Daffertshofer, & Longtin, 2010; van den Heuvel, Balasubramaniam, Daffertshofer, Longtin, & Beek, 2009; Zatsiorsky & Duarte, 2000). The effect of vision on the two time scales of postural fluctuations, especially during the performance of secondary cognitive tasks, has only been studied to a limited extent (van den Heuvel et al., 2009). The second question examines the effect of task demands and instructions under dual-task situations on posture control. Our objective was to elaborate the existing literature and investigated the attentional focus

(McNevin & Wulf, 2002; Wulf & Prinz, 2001) on secondary task performance on postural control. In addition, the purpose was to understand how the control of standing balance was influenced by goal-directed behavior. The last question examines the age-related difference in question 1 and 2. Collectively, the goal of the thesis is to further examine those dual-task models and make an advance in knowledge in understanding the interactions of age, postural control and secondary task performance.

1.6 - THESIS OVERVIEW

The four studies presented in this thesis used a dual-task paradigm to investigate age-related changes in relation to the secondary task and context-dependent factors attributes to postural control. A key manipulation of the thesis was the addition of a suprapostural task to the postural task.

The postural task involved visuomotor tracking, which required participants to position a feedback cursor (representing their COP) in a fixed target. The nature of the postural task required participants to process the visual feedback and integrate visual cues to produce appropriate motor action to move the COP cursor on the target. Successfully performing the visuomotor task necessitated proper sensory feedback, motor response and sensorimotor integration. By using the visuomotor tracking postural task, this thesis examined how postural control mechanisms are modulated by task demands as well as age-related changes in sensorimotor strategies.

In order to investigate the attentional demands on postural control and age-related difference in cognitive processing, we used a cognitive task as a suprapostural task in young and older adults. A decrease in the quality of performance occurs when different tasks use the same structures are performed simultaneously. Therefore, it is important to choose one secondary task that excludes the possibility of structural interference (Kahneman, 1973). Specifically, the task must not interfere with the visual or somatosensory feedback for postural control. As a result, we implemented a silent arithmetic secondary cognitive task, after Weeks et al. (2003). This mental arithmetic task required subjects to perform serial arithmetic operations (addition, subtraction) while maintaining upright stance. The arithmetic operations were performed silently, with the final response verbalized after trial completion.

According to Stoffregen’s postural facilitation viewpoint (2007), only tasks that need oculomotor demand can facilitate postural control, but are not affected by non-perceptual cognitive demand. Our suprapostural task (i.e., silent counting) would be considered a non-perceptual task based on Stoffregen’s classification. Therefore, our data would support the postural facilitation viewpoint if postural performance is unaffected by the suprapostural task. However, the facilitation viewpoint might be questionable if the cognitive task influences postural performance.

On the other hand, our data would support the task prioritization model if healthy young subjects prioritize the cognitive task as long as the postural demanding is relatively low. However, with sensorimotor declines or when the postural task becomes complex, older people would adapt the “posture first” principle which they prioritize postural control in sacrificing the secondary task performance in order to maintain equilibrium.

1.7 - OULINE OF EXPERIMENTS AND HYPOTHESES

In Chapter 2, we **investigate the relative contributions of visual feedback delay and cognitive task load on postural dynamics.** Our study was motivated by research which demonstrated that delayed visual feedback has a generally destabilizing influence on postural control (Boulet et al., 2010; van den Heuvel et al., 2009). However, it remains unclear how delayed visual feedback interacts with a cognitive task in the context of postural control. Besides, the effect of delayed visual feedback on the low and high time scales of postural fluctuations, especially during the performance of secondary cognitive tasks has only been studied to a limited extent (van den Heuvel et al., 2009). Delayed visual feedback is thought to destabilize postural control and the magnitude of sway variability has been found to be proportionate to visual delay (Boulet et al., 2010; van den Heuvel et al., 2009). These findings lead to the compelling hypothesis that the magnitude of sway variability increases proportionately as visual delays increase. Previous studies have shown that vision is used to control low frequency of postural sway (Chagdes et al., 2009; Oppenheim, Kohen-Raz, Alex, Kohen-Raz, & Azarya, 1999); however, whether the cognitive dual-task differs in the low and high time scales of postural fluctuations remained to be elucidated. We hypothesized that delayed visual feedback and the secondary cognitive task affect the two time scales of postural fluctuations differently. The hypotheses were investigated in Chapters 2 as well as Chapter 3.

Chapter 3 extends the finding from Chapter 2 and **examines age-related changes in postural control during delayed visual feedback and cognitive load**. Age-related decline in postural control mechanisms and sensory information processing adversely affect balance control in older adults (Teasdale, Stelmach, Breunig, & Meeuwsen, 1991). The fact that older adults emphasize visual feedback to correct postural errors (Sundermier, Woollacott, Jensen, & Moore, 1996; Wade, Lindquist, Taylor, & Treat-Jacobson, 1995) leads to the hypothesis that visual feedback delays compromise posture to a greater extent in older adults than in young individuals.

Chapter 4 **investigates whether postural control improved when performing a concurrent cognitive task with an internal focus of attention, as well as the impact of age-related differences in this effect.** Our experiment was inspired by attentional focus research which demonstrated that an external focus of attention is beneficial for motor performance and learning, whereas an internal focus of attention degrades motor performance and inhibit motor learning (Wulf & Prinz, 2001; Wulf, McNevin, & Shea, 2001). Based on the results from Chapter 2 and 3, a cognitive suprapostural task reduced postural sway variability in the young adults. However, it is unclear if a cognitive task would benefit postural control when young participants focus attention on the movement itself (i.e., the internal focus of attention). The work by Wulf (2013) has suggested that attentional focus effects have been found for people of various age groups. The hypothesis was that attentional focus would have the same influence in both young and older adults in terms of postural control.

In Chapter 5, we **investigate how older and younger adults differ in employing sensorimotor strategies in a dual-task situation.** This experiment was motivated by research which demonstrated that optimal sensorimotor integration is needed to maintain the precision of a visuomotor postural task (Balasubramaniam et al., 2000; Riley, Balasubramaniam & Turvey, 1999a). Furthermore, cognitive resources have been suggested to be involved in maintaining balance, especially in the older adults (Marsh & Geel, 2000). Chapter 4 showed that the control of standing balance was influenced by goal-directed behavior and this direction-specific minimization of sway variability affects only in the direction that met the task goal. The experimental manipulations in Chapter 5 provided specific task goals when we manipulated different head orientations. The primary hypothesis was that postural instability would be greater in older adults to those observed in the young persons. A secondary hypothesis was that the assembly of postural organization in mediolateral (ML) and anteroposterior (AP) sway variability would respond differently to precision demands under different head orientations in both age groups.

In summary, the collective findings of the studies included in this thesis added to current understanding of the role of sensorimotor processing, attentional influence and age in the control of posture. Together, our results suggested that deterioration of peripheral sensorimotor systems as well as reduced flexibility in central information processing serve as co-mechanisms for the age-related difference in postural control. These studies combine to provide an aging-related component to the dual-task model. Specifically, the postural facilitation viewpoint was not supported by the results of this thesis. Rather, our results supported the hypothesis that young adults prioritize cognitive performance over postural control. While dual-tasking, posture control is more likely relegated to low-level subsystems that are governed by reflexive and compensatory mechanisms. However, attentional allocation ability degraded with aging. Given that age-related declines exist in many areas such as cognitive and sensorimotor functioning, the relation between postural control and attentional focus in older people is complex. Our results demonstrated that healthy older adults have less capability in the allocation of attention between two tasks compared to the young adults.

In addition, Chapter 2 supported distinct timescale mechanisms for postural control. Moment-to-moment COP fluctuations are dependent on cognitive performance during delayed visual feedback postural control in young adults. Chapter 3 demonstrated the increased role of vision with age in postural control. Moreover, the finding also showed the age-related difference under dual-task performance. Chapter 4 revealed that devoting less attention internally by performing a cognitive dual-task enhanced postural control in young adults. Yet, the age-related declines diminish the attentional allocation ability. Lastly, Chapter 5 provided evidence of deterioration of peripheral sensorimotor systems and reduced flexibility in central information processing are responsible for the age-related differences. The discussion of how these studies contribute to the literature, some concluding comments and future research directions are outlined in the general discussion section in Chapter 6.

1.8-REFERENCES

Ahmed, A. A., & Wolpert, D. M. (2009). Transfer of dynamic learning across postures. *Journal of Neurophysiology*, *102,* 2816–2824.

Andersson, G., Persson, K., Melin, L., & Larsen, H. C. (1998). Actual and perceived postural sway during balance specific and non-specific proprioceptive stimulation. *Acta Oto-laryngologica*, *118*, 461–465.

Andersson, G., Hagman, J., Talianzadeh, R., Svedberg, A., & Larsen, H. C. (2002). Effect of cognitive load on postural control. *Brain Research Bulletin*, *58,* 135–139.

Balasubramaniam, R., Riley, M. A, & Turvey, M. T. (2000). Specificity of postural sway to the demands of a precision task. *Gait and Posture*, *11*, 12–24.

Barra, J., Bray, A., Sahni, V., Golding, J. F., & Gresty, M. A. (2006). Increasing cognitive load with increasing balance challenge: recipe for catastrophe. *Experimental Brain Research*, *174,* 734–745.

Berger, L., & Bernard-Demanze, L. (2011). Age-related effects of a memorizing spatial task in the adults and elderly postural control. *Gait and Posture*, *33,* 300–302.

Black, F. O., Shupert, C. L., Horak, F. B., & Nashner, L. M. (1988) Abnormal postural control associated with peripheral vestibular disorders. In: Pompeiano, O.; Allum, J. H. J., eds. Progress in brain research, vol. 76. Amsterdam: Elsevier Science Publishers, B. V., 263-275.

Boulet, J., Balasubramaniam, R., Daffertshofer, A., & Longtin, A. (2010). Stochastic two-delay differential model of delayed visual feedback effects on postural dynamics. *Philosophical Transactions. Series A, 368*, 423–438.

Brauer, S. G., Woollacott, M., & Shumway-Cook, A. (2002). The influence of a concurrent cognitive task on the compensatory stepping response to a perturbation in balance-impaired and healthy elders. *Gait and Posture*, *15*, 83–93.

Brauer, S. G., Woollacott, M., & Shumway-Cook, A. (2001). The interacting effects of cognitive demand and recovery of postural stability in balance-impaired elderly persons. *The Journals of Gerontology*, *56A*, M489–M496.

Brown, L. A., Shumway-Cook, A., & Woollacott, M. (1999). Attentional demands and postural recovery: the effects of aging. *The Journals of Gerontology, 54A*, M165–M171.

Brown, L. A., Sleik, R., Polych M. A., & Gage, W. (2002). Is the prioritization of postural control altered in conditions of postural threat in younger and older adults? *The Journals of Gerontology*, *57A*, M785–M7992.

Carmeli, E., Reznick, A. Z., Coleman, R., & Carmeli, V. (2000). Muscle strength and mass of lower extremities in relation to functional abilities in elderly adults. *Gerontology*, *46*, 249–257.

Carpenter, M., Frank, J., Silcher, C., & Peysar, G. (2001). The influence of postural threat on the control of upright stance. *Experimental Brain Research*, *138,* 210-218.

Carrier, D. R. (2011). The advantage of standing up to fight and the evolution of habitual bipedalism in hominins. *PLoS ONE, 6,* e19630.

Chagdes, J. R., Rietdyk, S., Haddad, J. M., Zelaznik, H. N., Raman, A., Rhea, C. K., & Silver, T. A. (2009). Multiple timescales in postural dynamics associated with vision and a secondary task are revealed by wavelet analysis. *Experimental Brain Research, 197,* 297–310.

Cheng, K. C., Pratt, J., & Maki, B. E. (2013). Effects of spatial-memory decay and dual-task interference on perturbation-evoked reach-to-grasp reactions in the absence of online visual feedback. *Human Movement Science, 32,* 328–342.

Collins, J. J., & De Luca, C. J. (1994). Random walking during quiet standing. *Physical Review Letters, 73,* 764–767.

Collins, J. J., & De Luca, C. J. (1993). Open-loop and closed-loop control of posture: a random-walk analysis of center-of-pressure trajectories. *Experimental Brain Research, 95,* 308–318.

Dault, M. C., Frank, J. S., & Allard, F. (2001). Influence of a visuo-spatial, verbal and central executive working memory task on postural control. *Gait and Posture, 14,* 110–116.

Dault, M. C, & Frank, J. S. (2004). Does practice modify the relationship between postural control and the execution of a secondary task in young and older individuals? *Gerontology*, *50*, 157–164.

Dault, M. C., Yardley, L., & Frank, J. S. (2003). Does articulation contribute to modifications of postural control during dual-task paradigms? *Cognitive Brain Research*, *16*, 434–440.

Donker, S. F., Roerdink, M., Greven, A. J., & Beek, P. J. (2007). Regularity of center-of-pressure trajectories depends on the amount of attention invested in postural control. *Experimental Brain Research*, *181*, 1–11.

Doumas, M., Rapp, M. A., & Krampe, R. T. (2009). Working memory and postural control: adult age differences in potential for improvement, task priority, and dual tasking. *The Journals of Gerontology*, *64B*, 193–201.

Doumas, M., Smolders, C., & Krampe, R. T. (2008). Task prioritization in aging: effects of sensory information on concurrent posture and memory performance. *Experimental Brain Research*, *187*, 275–281.

Horak, F. B. (1987). Clinical measurement of postural control in adults. *Physical Therapy*, 1881–1885.

Horak, F. B., Nashner, L. M., & Diener, H. C. (1990). Postural strategies associated with somatosensory and vestibular loss. *Experimental Brain Research,82,* 167-177.

Horak, F. B. (2006). Postural orientation and equilibrium: what do we need to know about neural control of balance to prevent falls? *Age and Ageing*, *35,* ii7–ii11.

Horak, F. B., & Macpherson J.M. (1996) Postural orientation and equilibrium. In: Shepard, J. & Rowell, L. (eds) Handbook of Physiology. Oxford University Press, New York, 255-292

Horak, F. B., Shupert, C. L., & Mirka, A. (1989). Components of postural dyscontrol in the elderly: a review. *Neurobiology of Aging*, *10,* 727–38.

Hunter, M. C., & Hoffman, M. A. (2001). Postural control: visual and cognitive manipulations. *Gait and Posture*, *13*, 41–48.

Huxhold, O., Li, S.-C., Schmiedek, F., & Lindenberger, U. (2006). Dual-tasking postural control: aging and the effects of cognitive demand in conjunction with focus of attention. *Brain Research Bulletin*, *69,* 294–305.

Jamet, M., Deviterne, D., Gauchard, G. C., Vancon, G. & Perrin, P. P. (2004). Higher visual dependency increases balance control perturbation during cognitive task fulfilment in elderly people. *Neuroscience Letters*, *359*, 61–64.

Kahneman, D. (1973) Attention and effort, Englewood Cliffs, NJ: Prentice Hall

Kerr, B., Condon, S. M., & McDonald, L. A. (1985). Cognitive spatial processing and the regulation of posture. *Journal of Experimental Psychology:Human Perception and Performance*, *11,* 617–622.

Lacour, M., Bernard-Demanze, L., & Dumitrescu, M. (2008). Posture control, aging, and attention resources: models and posture-analysis methods. *Clinical Neurophysiology*, *38*, 411–421.

Lajoie, Y., Teasdale, N., & Bard, C. (1993). Attentional demands for static and dynamic equilibrium. *Experimental Brain Research*, 97, 139–144.

Lundin-Olsson, L., Nyberg, L., & Gustafson, Y. (1997). " Stops walking when talking" as a predictor of falls in elderly people. *Lancet*, *349*, 617.

Maki, B. E., & McIlroy, W. E. (1996). Influence of arousal and attention on the control of postural sway. *Journal of Vestibular Research:Equilibrium & Orientation*, *6*, 53–59.

Marsh, A. P., & Geel, S. E. (2000). The effect of age on the attentional demands of postural control. *Gait and Posture*, *12*, 105–113.

McIlroy, W. E., Norrie, R. G., Brooke, J. D., Bishop, D. C., Nelson, A. J., & Maki, B. E. (1999). Temporal properties of attention sharing consequent to disturbed balance. *Neuroreport*, *10*, 2895–2899.

McNevin, N. H., & Wulf, G. (2002). Attentional focus on supra-postural tasks affects postural control. *Human Movement Science*, *21*, 187–202.

Mitra, S. (2003). Postural costs of suprapostural task load. *Human Movement Science*, *22*, 253–270.

Murphy, J., & Isaacs, B. (1982). The post-fall syndrome. A study of 36 elderly patients.

Gerontology, 28, 265-270.

Oppenheim, U., Kohen-Raz, R., Alex, D., Kohen-Raz, A, & Azarya, M. (1999). Postural characteristics of diabetic neuropathy. *Diabetes Care, 22*, 328–332.

Palmer, J. (1990). Attentional limits on the perception and memory of visual information. *Journal of Experimental Psychology. Human Perception and Performance, 16,* 332-350.

Pellecchia, G. L. (2003). Postural sway increases with attentional demands of concurrent cognitive task. *Gait and Posture, 18,* 29–34.

Redfern, M. S., Jennings, J. R., Martin, C., & Furman, J. M. (2001). Attention influences sensory integration for postural control in older adults. *Gait and Posture, 14*, 211–216.

Redfern, M. S., Talkowski, M. E., Jennings, J. R., & Furman, J. M. (2004). Cognitive influences in postural control of patients with unilateral vestibular loss. *Gait and Posture*, *19*, 105–114.

Riley, M. A., Baker, A. A., Schmit, J. M., & Weaver, E. (2005). Effects of visual and auditory short-term memory tasks on the spatiotemporal dynamics and variability of postural sway. *Journal of Motor Behavior, 37,* 311–324.

Riley, M. A., Balasubramaniam, R., & Turvey, M. T. (1999a). Recurrence quantification analysis of postural fluctuations. *Gait and Posture, 9*, 65–78.

Riley, M. A., Stoffregen, T., Grocki, M., & Turvey, M. T. (1999b). Postural stabilization for the control of touching. *Human Movement Science*, *18*, 795–817.

Riley, M. A., Baker A. A., & Schmit, J. M. (2003). Inverse relation between postural variability and difficulty of a concurrent short-term memory task. *Brain Research Bulletin*, *62*, 191–195.

Rubenstein L. Z. (2006). Falls in older people: epidemiology, riskfactors and strategies for prevention. *Age and Ageing*, *35*, Suppl 2:ii37–ii41.

Seidler, R. D., Bernard, J. A., Burutolu, T. B., Fling, B. W., Gordon, M. T., Gwin, J. T., Kwak, Y., & Lipps, D. B. (2010). Motor control and aging: links to age-related brain structural, functional, and biochemical effects. *Neuroscience and Biobehavioral Reviews*, *34*, 721–733.

Shumway-Cook, A., Brauer, S., & Woollacott, M. (2000). Predicting the probability for falls in community-dwelling older adults using the Timed Up & Go Test. *Physical Therapy*, *80*, 896–903.

Shumway-Cook, A., & Woollacott, M. (2001). Motor control: theory and practical applications, second edition. Philadelphia: Lippincott Williams and Wilkins.

Shumway-Cook, A., Woollacott, M., Kerns, K. A., & Baldwin, M. (1997). The effects of two types of cognitive tasks on postural stability in older adults with and without a history of falls. *The Journals of Gerontology*, *52A*, M232–M240.

Simoneau, E. M., Billot, M., Martin, A., Perennou, D., & Van Hoecke, J. (2008). Difficult memory task during postural tasks of various difficulties in young and older people: a pilot study. *Clinical Neurophysiology*, *119*, 1158–65.

Stoffregen, T. A, Hove, P., Bardy, B. G., Riley, M., & Bonnet, C. T. (2007). Postural stabilization of perceptual but not cognitive performance. *Journal of Motor Behavior*, *39*, 126–38.

Stoffregen, T. A., Smart, L. J., Bardy, B. G., & Pagulayan, R. J. (1999). Postural stabilization of looking. *Journal of Experimental Psychology: Human Perception and Performance*, *25*, 1641–1658.

Stoffregen, T.A., Pagulayan, R., Bardy, B. G., & Hettinger, L. J. (2000). Modulating postural control to facilitate visual performance. *Human Movement Science, 19*, 203–220.

Sundermier, L., Woollacott, M. H., Jensen, J. L., & Moore, S. (1996). Postural sensitivity to visual flow in aging adults with and without balance problems. *The Journals of Gerontology, 51A*, M45–M52.

Teasdale, N., Bard, C., Larue, J., & Fleury, M. (1993). On the cognitive penetrability of posture control. *Experimental Aging Research*, *19*, 1–13.

Teasdale, N., Stelmach, G. E., Breunig, A., & Meeuwsen, H. J. (1991). Age differences in visual sensory integration. *Experimental Brain Research, 85,* 691–696.

van den Heuvel, M. R. C., Balasubramaniam, R., Daffertshofer, A., Longtin, A., & Beek, P. J. (2009). Delayed visual feedback reveals distinct time scales in balance control. *Neuroscience Letters*, *452*, 37–41.

Wade, M G, Lindquist, R, Taylor J R, & Treat-Jacobson, D. (1995). Optical flow spatial orientation and the control of posture in the elderly. *The Journals of Gerontology*, *50B*, P51–P58.

Weeks, D. L., Forget, R., Mouchnino, L., Gravel, D., & Bourbonnais, D. (2003). Interaction between attention demanding motor and cognitive tasks and static postural stability. *Gerontology*, *49*, 225–232.

Winter, D., Patla, A., & Prince, F. (1998). Stiffness control of balance in quiet standing. *Journal of Neurophysiology*, *80*, 1211–1221.

Woollacott, M. H., & Shumway-Cook, A. (2002). Attention and the control of posture and gait: a review of an emerging area of research. *Gait and Posture*, *16*, 1–14.

Woollacott, M. H., Shumway-Cook, A., & Nashner, L. M. (1986). Aging and posture control: changes in sensory organization and muscular coordination. *International Journal of Aging & Human Development*, *23*, 97–114.

Wulf, G, & Prinz, W. (2001). Directing attention to movement effects enhances learning: a review. *Psychonomic Bulletin & Review*, *8*, 648–660.

Wulf, G. (2013). Attentional focus and motor learning: a review of 15 years. *International Review of Sport and Exercise Psychology*, *6*, 77–104.

Wulf, G., McNevin, N., & Shea, C. H. (2001). The automaticity of complex motor skill learning as a function of attentional focus. *The Quarterly Journal of Experimental Psychology, 54A*, 1143–1154.

Yardley, L., Gardner, M., Leadbetter, A, & Lavie, N. (1999). Effect of articulatory and mental tasks on postural control. *Neuroreport*, *10*, 215–219.

Yerkes, R., & Dodson, J. (1908). The relation of strength of stimulus to rapidity of habit-formation. *Journal of Comparative Neurology and Psychology, 18,* 459–482.

Yogev-Seligmann, G., Hausdorff, J. M., & Giladi, N. (2012). Do we always prioritize balance when walking? Towards an integrated model of task prioritization. *Movement Disorders, 27,* 765–770.

Yogev-Seligmann, G., Hausdorff, J. M., & Giladi, N. (2008). The role of executive function and attention in gait. *Movement Disorders, 23*, 329–342.

Zatsiorsky, V. M., & Duarte, M. (2000). Rambling and trembling in quiet standing. *Motor Control, 4*, 185–200.

Chapter 2-Contributions of Delayed Visual Feedback and Cognitive Task Load to Postural Dynamics

2.1-ABSTRACT

In this experiment, we examine the impact of a visual feedback delay and the presence of a secondary cognitive task on postural control. Fourteen healthy young participants performed a balance task in eyes-open (EO) and delayed visual feedback (DVF) conditions. DVF was presented at delays ranging from 0 to 1200ms in 300ms increments. Cognitive load was implemented by a silent arithmetic task. High and low-pass filtering (fc=0.3Hz) distinguished LOW and HIGH frequency components, which were used to compute the variability of anteroposterior (AP) center of pressure (COP) trajectories on fast (>0.3Hz) and slow (<0.3Hz) timescales. Results show that imposed visual delay increased sway variability at both LOW and HIGH components. Cognitive task performance, however, influenced only the HIGH components. This findings support distinct timescale mechanisms for postural control. Vision influences low and high frequency components of postural sway. High frequency components are dependent on cognitive performance during delayed visual feedback postural control.

2.2- INTRODUCTION

Standing balance requires that the vertical projection of the body’s centre of mass (COM) remain within the bounds of the physical support. Postural control is a complex process involving mechanisms that support the maintenance of upright stance in response to self and environmental perturbation (Balasubramaniam & Wing, 2002). Mechanisms that contribute to postural control are served by distinct neurophysiological pathways and dynamical control structures that incorporate both closed and open-loop processes (Ahmed & Wolpert, 2009; Collins & De Luca, 1994). The control of posture is a complicated physical task with multiple physical degrees of freedom in the joint-muscle space that must be assembled appropriately to stabilize the postural system.

Postural control works through the assembly of synergies featuring the interplay of visco-elastic and reflexive muscle dynamics with adaptive mechanisms that reflect both anticipatory and compensatory components. The integrity of these control mechanisms is dependent on the salience of multimodal sensory feedback, which stems from visual, vestibular, and somatosensory (proprioceptive) sources. A large number of studies distinguish between mechanisms that support eyes-open and eyes-closed postural control, or selectively manipulate the integrity of visual feedback by sensory perturbations, using moving room displays, for example (Lestienne, Soechting, & Berthoz, 1977). Several of these studies have also examined the dependence of posture on the spatial salience of or lack of visual feedback. More recently researchers have investigated the extent to which postural control is influenced by the temporal integrity of visual feedback (Boulet, Balasubramaniam, Daffertshofer, & Longtin, 2010; van den Heuvel, Balasubramaniam, Daffertshofer, Longtin, & Beek, 2009).

Delayed visual feedback (DVF) is a technique that can be implemented to determine whether postural control is influenced by the temporal contiguity of visual feedback (Boulet et al., 2010; Rougier, 2004; van den Heuvel et al., 2009). Though small temporal delays for visual feedback reduce sway variability (Rougier, 2004), subsequent research has demonstrated that DVF has a generally destabilizing influence on posture. Said differently, the magnitude of sway variability appears to be proportionate to visual delay (Boulet et al., 2010; van den Heuvel et al., 2009).

The complexity of control is further exacerbated by the fact that individuals often engage in secondary task performance while standing—rarely is posture controlled solely to maintain standing balance. Therefore it is important for research to take into consideration the interaction between secondary task performance (physical or cognitive) and the neurophysiological and dynamical mechanisms for postural control.

To address the cognitive penetrability of standing balance, postural and cognitive tasks are typically combined in the dual-task experimental paradigm (Lajoie, Teasdale, & Bard, 1993). These studies have revealed that there is a great deal of interaction between high-level cognitive processes and postural control, a result that might seem surprising if postural control is viewed as spinal or sub-cortical in nature and cognition is considered purely cortical (see Balasubramaniam & Wing 2002 for review). However, a large body of research over the last two decades has shown that neither of these two views is tenable nor accurate. The cerebellum has been implicated in sensory processing and cognition and there is growing evidence of cortical involvement in postural reflexes (Balasubramaniam & Wing, 2002).

Though several studies have considered reciprocal postural-cognitive influences in dual-task performance, consensus regarding the interaction between posture and cognition has yet to be established. While some studies report an increase in postural sway when performing a cognitive task, others report the converse (Huxhold, Li, Schmiedek, & Lindenberger, 2006; Riley, Baker, & Schmit, 2003). The inconsistency of results might reflect methodological differences in postural assessment, task load and the timescales studied in the analysis method. Dual-task studies typically manipulate the difficulty of the postural component by varying stance (Dault, Frank,

& Allard, 2001; Hunter & Hoffman, 2001; Kerr, Condon, & McDonald, 1985), somatosensory (Brauer, Woollacott, & Shumway-Cook, 2001; McIlroy et al., 1999) or visual input (Donker, Roerdink, Greven, & Beek, 2007; Hunter & Hoffman, 2001; Jamet, Deviterne, Gauchard, Vancon, & Perrin, 2004), or any combination of these factors (Hunter & Hoffman, 2001; Teasdale, Bard, Larue, & Fleury, 1993), which might also precipitate the inconsistency of the findings.

The dynamical structure of postural fluctuations has attracted considerable interest in recent years. A variety of analysis techniques (van den Heuvel et al., 2009; Zatsiorsky & Duarte, 2000) have revealed that postural sway has two characteristic timescales. A fast (or high frequency) timescale capturing rapid processes that reflect open-loop control or exploratory activity is complemented by a slower (low frequency) timescale that reflects corrective or feedback based control processes. The effect of DVF on the two timescales of postural fluctuations, especially during the performance of secondary cognitive tasks has only been studied to a limited extent (van den Heuvel et al., 2009).

In this experiment we sought to examine the relative contributions of visual feedback delay and cognitive task load on postural dynamics. Specifically, we manipulated the temporal salience of visual feedback by imposed feedback delay. We graded the integrity of the visual feedback in a visual tracking task by varying the delay of the stimulus from 0 to 1200ms in 300ms increments (cf. Boulet et al., 2010; van den Heuvel et al., 2009). The purpose of this experiment was to determine the manner in which DVF interacted with cognitive load to influence postural control. Secondly, we ask if DVF and the secondary cognitive task differentially influence the two timescales (slow and fast) commonly observed in postural control. Cognitive load, in this context, was implemented by a simple, serial arithmetic task (Weeks, Forget, Mouchnino, Gravel, & Bourbonnais, 2003). On the basis of those manipulations, we sought to distinguish timescale-dependent postural control mechanisms and the influence of visual and cognitive task components for standing balance. Our purpose is consistent with the view that postural sway can be divided into two characteristic timescales. Therefore, the questions we address in this experiment are (1) whether cognitive load and delayed visual feedback interact to influence postural control and (2) if distinct timescale mechanisms for postural control are influenced by visual and cognitive task performance.

2.3- METHODS

Fourteen healthy young participants (6 males and 8 females; mean age=24.6, SD=4.3) participated in this study. Participants reported no visual, orthopedic or neurological disorders. Participants provided written informed consent. The experimental protocol was approved by the Ethics Review Board at McMaster University prior to the experiment. COP time series were collected by a force platform (OR6-2000, AMTI, Newton, MA, USA) sampled at 1000Hz. Delayed visual feedback of the COP position was implemented by custom MATLAB^{TM} code (7.9.0, The Mathworks, Natick, MA, USA).

Participants were asked to stand on the force platform with arms placed at their sides and maintain a comfortable posture. A 19inch LCD monitor located at eye level, 70cm in front of the platform provided visual feedback of the COP location. A red dot (13mm) at the center of the monitor corresponded to the visual target. A smaller white dot (10mm) represented (real-time or delayed) COP position from both AP and ML planes. Participants were instructed to shift their center of mass to center the white dot (COP feedback) within the red dot (fixed target). The gain factor-relating COP to the visual feedback of the COP was set at 5. Previous work (Rougier, 2004; Rougier, 2008) did not report differences in performance for gain factors ranging from 2 to 20. The display apparatus had a lag time that ranged from 43 to 81.5ms due to machine processing delays and the operating system. Foot position for individual participants was determined prior to the experiment and corresponded to the position where the least amount of effort was spent to make COP position overlap onto the visual target. Foot positioning was kept constant for each participant for all trials.

In the dual-task conditions, participants performed a simple, serial arithmetic task. Prior to trial onset, participants received a two-digit number. Participants performed a series of six randomized arithmetic operations (addition or subtraction) at a rate of one computation per 5s interval. They computed the running sum of operations and verbalized their response following trial completion, thereby eliminating articulation effects for COP displacements (Yardley, Gardner, Leadbetter, & Lavie, 1999). The experiment consisted of 12 conditions: eyes-open (EO) and 5 delayed visual feedback (DVF) conditions: 0, 300, 600, 900 and 1200ms, with and without a concurrent mental arithmetic task (Control, COG). In the EO condition, only a stationary visual target (red dot) was shown, without COP position feedback. The 0ms condition refers to the participant receiving real-time feedback about their COP location. Five 31s trials were performed in each condition, resulting in a total of 60 trials per participant. Trial order was randomized within blocks (all conditions were randomly presented within each block) to minimize learning effects.

The first 1.2s of collected data accounted for the length of the maximum visual delay. Therefore, only the last 29.8s of each trial were used for anteroposterior (AP)

COP time series analysis. Time series were coarse-grained by a non-overlapping, 10 sample moving average, resulting in a time series of 2980 points and an effective sampling frequency of 100Hz. Next, the time series were mean-detrended. Subsequently, COP time series were filtered according to van den Heuvel (2009) which translated to time series consisting of low (LOW) and high-pass frequency (HIGH) components (Fig. 2.1). Filtering was performed using a dual-pass, second-order Butterworth filter with a cutoff frequency of 0.3Hz. Subsequent linear trends were removed from the LOW and HIGH time series using well established techniques used by van den Heuvel et al. (2009). The untreated time series are referred to as UNFILTERED for the remainder of the manuscript. Standard deviations were computed from each time series (UNFILTERED, LOW and HIGH).

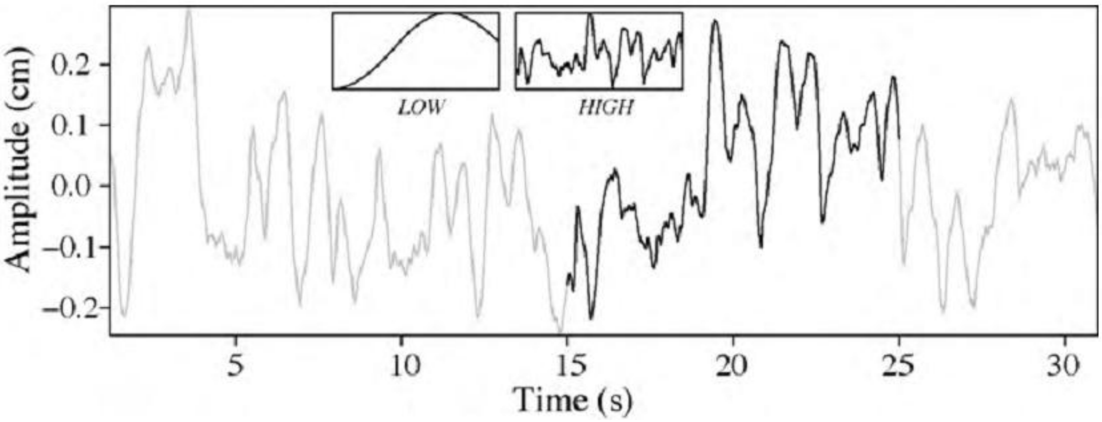

Figure 2.1. A sample time series plot of the anteroposterior (AP) COP of a participant performing the 300ms DVF condition with a cognitive task shown from 1.2 to 31s.

For the purpose of demonstration, LOW and HIGH frequency components of the COP are shown for the highlighted time interval (15–25 s). Filtering was performed using a dual-pass, second-order Butterworth filter with a cutoff frequency of 0.3Hz. Subsequent analysis was performed for entire original (UNFILTERED), low and high-pass filtered time series.

Mean differences in sway variability (standard deviation) were contrasted across DVF and dual-task cognitive conditions using a 2 (Control, COG) ×6 (DVF: EO, 0, 300, 600, 900, 1200ms) analysis of variance (ANOVA) with repeated measures. The Greenhouse–Geisser correction factor for statistical degrees of freedom was used to correct sphericity violations (Mauchly's Test, $p<0.05$). Post hoc analysis was performed with Bonferroni corrections for pair-wise means comparisons.

2.4- RESULTS

The main findings of the study are illustrated in Fig. 2.2. As shown in the left panel for UNFILTERED data, sway variability was dependent on imposed visual delay [F (2.43, 31.62) = 10.29, $p<0.01$] and cognitive task performance [F (1, 13) = 5.74, $p<0.01$]. There was no significant DVF×COG interaction [F (2.74, 35.67) = 0.23, $p>0.05$]. Pair-wise comparisons revealed that sway variability in the 0ms condition (M=1.93, SE=0.11mm) was reduced relative to the 600ms (M=2.29, SE=0.10mm) ($p<0.001$), 900ms (M=2.59, SE=0.15mm) (*p*<0.01), and 1200ms conditions (M=2.55, SE=1.6mm) (*p*<0.001). Moreover, the 300ms condition (M=2.01, SE=0.11mm) was reduced relative to the 600ms (*p*<0.01), 900ms (*p*<0.01) and 1200ms conditions (*p*<0.001). Moreover, the addition of the cognitive dual-task reduced sway variability relative to the control condition.

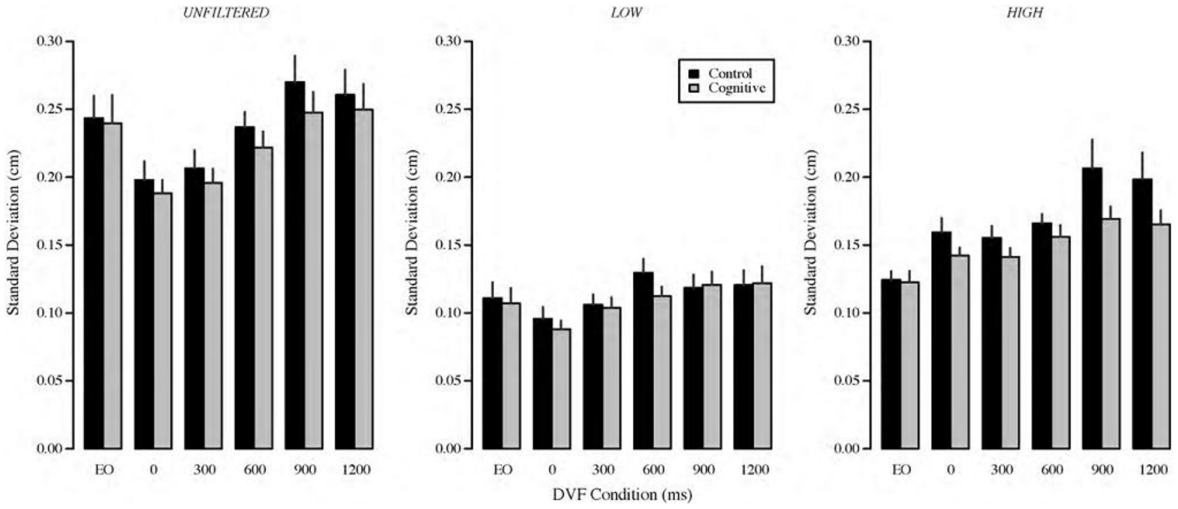

Figure 2.2. Standard deviations of the UNFILTERED, LOW and HIGH AP COP time series for eyes open (EO) and delayed visual feedback (DVF) conditions (0, 300, 600, 900, and 1200ms) in the presence and absence of the cognitive dual task. The control condition is shown in black while the cognitive dual-task condition is shown in grey. Error bars represent ±1 standard error.

For the LOW data, sway variability was dependent on the temporal salience of visual feedback [*F* (2.59, 33.62) = 4.58, *p*<0.05], but was not influenced by cognitive load [*F* (1, 13) = 1.69, $p>0.05$]. We also did not see a significant interaction between DVF and the cognitive task. Sway variability was reduced when COP position feedback was real-time or 0ms (M=0.92, SE=0.06mm) relative to 600ms (M=1.21±0.07mm) ($p<0.001$), 900ms (M=1.20, SE=0.09mm) ($p<0.05$), and the 1200ms delay conditions (M=1.21±0.10mm) ($p<0.05$). Sway variability was reduced for the 300ms (M=1.05, SE=0.07mm) relative to 600ms delay condition ($p<0.01$). These results are summarized in the middle panel of Fig. 2.2.

Sway variability of the high-pass filtered COP trajectories (HIGH) was again dependent on visual feedback [*F* (1.62, 21.05) = 10.75, $p<0.01$] and cognitive task component [*F* (1, 13) = 9.97, $p<0.01$], but the DVF×COG interaction, [*F* (1.83, 23.84) = 1.41, $p>0.05$] was not significant. A careful inspection of Fig. 2.2 (right panel) reveals that cognitive load reduced the variability of high-pass filtered AP COP time series. Although sway variability monotonically increased with longer time delays, post hoc analyses revealed a statistical difference only for the following. Sway variability was reduced in the EO (M=1.23, SE=0.07mm) relative to 0ms (M=1.51, SE=0.08mm) ($p<0.05$), 300ms (M=1.48, SE=0.07mm) ($p<0.01$), 600ms (M=1.61,SE=0.07mm) ($p<0.001$), 900ms (M=1.88±0.13mm) ($p<0.05$), and 1200ms (M=1.82, SE=0.12mm) ($p<0.05$) conditions. Also, sway variability was reduced in the

300ms relative to 600ms condition ($p<0.05$).

2.5-DISCUSSION

This study examined the extent to which sway variability was influenced by the interplay between delayed visual feedback and cognitive task performance in an upright postural task. We examined whether the magnitude of sway variability attributable to imposed visual delay and cognitive load combined interactively or independently influenced postural control. We implemented a two-timescale model for postural control, decomposing sway variability into distinct frequency components by low (LOW) and high-pass filtered (HIGH) COP time series. Our results show that sway variability computed from UNFILTERED, low and high-pass filtered COP time series increased as a function of the visual delay. In contrast, concurrent cognitive performance reduced the variability of both UNFILTERED and high-pass filtered AP COP time series. The results showed that cognitive load make distinct contributions to postural stability.

Previous studies that examined the influence of conjoint cognitive performance on sway variability have generated inconsistent and often-times paradoxical results. Perturbed (Pellecchia, 2003), reduced (Riley et al., 2003) and unaffected (Dault et al., 2001) sway variability have been reported for dual-task posture-cognition studies. In addition to these inconsistent findings and lack of consensus on the role of cognition in posture control, a clear determination of mechanisms by which cognition influences sway variability does not appear to exist (Balasubramaniam & Wing, 2002; Rougier, 2008). In the present study, we applied a systematic analysis that parsed sway variability into LOW and HIGH frequency components. Our results demonstrate that reduced sway variability in the dual-task cognitive condition is attributable to reduced amplitude in the fast component that defines moment-to-moment COP fluctuations.

Imposed visual feedback delay resulted in increased sway variability in UNFILTERED, low and high-pass filtered COP time series. However, when a task with low to moderate cognitive load was added, we found the control mechanisms switch to a more efficient, automatic process, thereby stabilizing and reducing postural fluctuations in the high-pass component. Consequently, we concluded that serial arithmetic tasks under the presence of DVF affected the faster time-scale component of postural sway. One might argue that these results are consistent with the autonomous viewpoint for postural control (Kerr et al., 1985). According to this viewpoint, imposed cognitive demand diverts attentional resources to secondary task performance (Kerr et al., 1985; McIlroy et al., 1999; Vuillerme, Nougier, & Teasdale, 2000). When performing cognitive tasks one could make the case that posture control is more likely relegated to low-level subsystems that are governed by reflexive and compensatory mechanisms (Torres-Oviedo, Macpherson, & Ting, 2006).

Sway in the AP axis is largely governed by rotations about the ankle joint involving plantarflexion and dorsiflexion. Several studies have proposed the underlying low-level mechanism for reduced sway variability in dual-task cognitive performance is related to ankle joint stiffness (Dault et al., 2001), which is reflected by increased frequency, reduced amplitude COP excursions. This proposition is consistent with our data and may reflect increased tonic drive to musculature spanning the ankle joint. Another plausible mechanism involves damping about the ankle joint, which is mediated by increased stretch reflex gain. Postural control characterized by increased autonomy of control proffers from increased stringency reflex activation, a process that is governed by lower level control systems. The involvement of these lower level control mechanisms need to be tested in future studies using electrophysiological and biomechanical analyses of the ankle joint.

In the present study, we limited our analyses to the AP axis. In future work, it would be interesting to apply this method to radial sway and fluctuations specific to the mediolateral (ML) axis (Maki & McIlroy, 2005). The influence of cognitive tasks on ML fluctuations and the underlying lower-limb dynamics (hip loading/unloading and ankle stiffness/damping) especially in older adults need to be explored in a future study using spectral techniques. Important questions regarding the independence of the control processes governing AP and ML sway could also be tested using this paradigm.

There are some important caveats to note about the filtering method that we used to separate the fast and slow timescales in postural control. Following previous work from our laboratory by van den Heuvel et al. (2009), we chose a frequency-based method to identify control mechanisms that underlie stance regulation. It would be interesting to see the present results corroborated by employing other methods used to infer dual time-scale postural mechanisms such as the rambling/trembling decomposition (Zatsiorsky & Duarte, 2000), statistical mechanics based approaches and autocorrelation functions (Boulet et al., 2010; Collins & De Luca, 1994) and dynamical systems analysis using higher dimensional embedding (Balasubramaniam & Wing, 2002; Donker et al., 2007). Furthermore, the term “distinct” timescales should be exercised with caution when referring to the outcome of frequency-based analyses. The frequency spectrum in postural sway does not typically show distinct peaks that correspond to low and high frequency contributions. For example, in a recent wavelet-based analysis, Chagdes and co-workers (2009) illustrated the scale-invariant properties of postural sway. Following this work, it appears that nearly all timescales seem to contribute actively to standing balance.

Upright balance control in the wake of DVF and attentional dual tasks is of particular interest in the study of aging. It has been suggested that there is an increased likelihood of destabilization during the performance of cognitive dual tasks in the elderly (Lacour, Bernard-Demanze, & Dumitrescu, 2008; Maylor & Wing, 1996; Rankin, Woollacott, Shumway-Cook, & Brown, 2000; Shumway-Cook, Woollacott, Kerns, & Baldwin, 1997). This has been attributed to reduce lower limb muscle strength, diminished information processing capacity, and most importantly, the age-related decline in multisensory integration (Woollacott & Shumway-Cook, 2002). The present study is of particular relevance in older adults, who also suffer from greater delays in the processing of sensory information. We are currently pursuing the issue of how DVF and cognitive load influence postural control in older adults.

2.6-REFERENCES

Ahmed, A. A., & Wolpert, D. M. (2009). Transfer of dynamic learning across postures. *Journal of Neurophysiology*, *102,* 2816–2824.

Balasubramaniam, R., & Wing, A. M. (2002). The dynamics of standing balance. *Trends in Cognitive Sciences*, *6,* 531–536.

Boulet, J., Balasubramaniam, R., Daffertshofer, A., & Longtin, A. (2010). Stochastic two-delay differential model of delayed visual feedback effects on postural dynamics. *Philosophical Transactions. Series A, 368*, 423–438.

Brauer, S. G., Woollacott, M., & Shumway-Cook, A. (2001). The interacting effects of cognitive demand and recovery of postural stability in balance-impaired elderly persons. *The Journals of Gerontology, 56A*, M489–M496.

Chagdes, J. R., Rietdyk, S., Haddad, J. M., Zelaznik, H. N., Raman, A., Rhea, C. K., & Silver, T. A. (2009). Multiple timescales in postural dynamics associated with vision and a secondary task are revealed by wavelet analysis. *Experimental Brain Research*, *197*, 297–310.

Collins, J. J., & De Luca, C. J. (1994). Random walking during quiet standing. *Physical Review Letters*, *73,* 764–767.

Dault, M. C., Frank, J. S., & Allard, F. (2001). Influence of a visuo-spatial, verbal and central executive working memory task on postural control. *Gait and Posture*, *14*, 110–116.

Donker, S. F., Roerdink, M., Greven, A. J., & Beek, P. J. (2007). Regularity of center-of-pressure trajectories depends on the amount of attention invested in postural control. *Experimental Brain Research, 181,* 1–11.

Hunter, M. C., & Hoffman, M. A. (2001). Postural control: visual and cognitive manipulations. *Gait and Posture, 13,* 41–48.

Huxhold, O., Li, S.-C., Schmiedek, F., & Lindenberger, U. (2006). Dual-tasking postural control: aging and the effects of cognitive demand in conjunction with focus of attention. *Brain Research Bulletin, 69,* 294–305.

Jamet, M., Deviterne, D., Gauchard, G. C., Vancon, G. & Perrin, P. P. (2004). Higher visual dependency increases balance control perturbation during cognitive task fulfilment in elderly people. *Neuroscience Letters, 359,* 61–64.

Kerr, B., Condon, S. M., & McDonald, L. A. (1985). Cognitive spatial processing and the regulation of posture. *Journal of Experimental Psychology:Human Perception and Performance*, *11*, 617–622.

Lacour, M., Bernard-Demanze, L., & Dumitrescu, M. (2008). Posture control, aging, and attention resources: models and posture-analysis methods. *Clinical Neurophysiology, 38,* 411–421.

Lajoie, Y., Teasdale, N., & Bard, C. (1993). Attentional demands for static and dynamic equilibrium. *Experimental Brain Research,* 97, 139–144.

Lestienne, F., Soechting, J., & Berthoz, A. (1977). Postural readjustments induced by linear motion of visual scenes. *Experimental Brain Research, 28,* 363–384.

Maki, B. E., & McIlroy, W. E. (2005). Change-in-support balance reactions in older persons : An emerging research area of clinical importance. *Neurologic Clinics, 23*, 751–783.

Maylor, E. A., & Wing, A. M. (1996). Age differences in postural stability are increased by additional cognitive demands. *The Journals of Gerontology, 51B*, 143–154.

McIlroy, W. E., Norrie, R. G., Brooke, J. D., Bishop, D. C., Nelson, A. J., & Maki, B. E. (1999). Temporal properties of attention sharing consequent to disturbed balance. *Neuroreport*, *10*, 2895–2899.

Pellecchia, G. L. (2003). Postural sway increases with attentional demands of concurrent cognitive task. *Gait and Posture*, *18*, 29–34.

Rankin, J. K., Woollacott, M. H., Shumway-Cook, A., & Brown, L. A. (2000). Cognitive influence on postural stability: a neuromuscular analysis in young and older adults. *The Journals of Gerontology*, *55A*, M112-M119.

Riley, M. A., Baker A. A., & Schmit, J. M. (2003). Inverse relation between postural variability and difficulty of a concurrent short-term memory task. *Brain Research Bulletin*, *62*, 191–195.

Rougier, P. (2004). Optimising the visual feedback technique for improving upright stance maintenance by delaying its display: behavioural effects on healthy adults. *Gait and Posture*, *19*, 154–163.

Rougier, P. (2008). What insights can be gained when analysing the resultant centre of pressure trajectory? *Neurophysiologie Clinique*, *38,* 363–373.

Shumway-Cook, A., Woollacott, M., Kerns, K. A., & Baldwin, M. (1997). The effects of two types of cognitive tasks on postural stability in older adults with and without a history of falls. *The Journals of Gerontology. Series A*, *52,* M232–M240.

Teasdale, N., Bard, C., Larue, J., & Fleury, M. (1993). On the cognitive penetrability of posture control. *Experimental Aging Research, 19,* 1–13.

Torres-Oviedo, G., Macpherson, J. M., & Ting, L. H. (2006). Muscle synergy organization is robust across a variety of postural perturbations. *Journal of Neurophysiology, 96,* 1530–1546.

van den Heuvel, M. R. C., Balasubramaniam, R., Daffertshofer, A., Longtin, A., & Beek, P. J. (2009). Delayed visual feedback reveals distinct time scales in balance control. *Neuroscience Letters*, *452,* 37–41.

Vuillerme, N., Nougier, V., & Teasdale, N. (2000). Effects of a reaction time task on postural control in humans. *Neuroscience Letters, 291*, 77–80.

Weeks, D. L., Forget, R., Mouchnino, L., Gravel, D., & Bourbonnais, D. (2003). Interaction between attention demanding motor and cognitive tasks and static postural stability. *Gerontology*, *49*, 225–232.

Woollacott, M. H., & Shumway-Cook, A. (2002). Attention and the control of posture and gait: a review of an emerging area of research. *Gait and Posture*, *16*, 1–14.

Yardley, L., Gardner, M., Leadbetter, A, & Lavie, N. (1999). Effect of articulatory and mental tasks on postural control. *Neuroreport*, *10*, 215–219.

Zatsiorsky, V. M., & Duarte, M. (2000). Rambling and trembling in quiet standing. *Motor Control*, *4*, 185–200.

Chapter 3-Increased Reliance on Visual Feedback for Balance Control in Older Adults

3.1 -ABSTRACT

Sensory information helps guide and correct balance. Less appreciated, however, is that delays in the transmission of sensory information can exceed several 10s of milliseconds. Investigating how these time-delayed sensory signals influence balance control is critical to understanding the postural system. Here, we investigate how delayed visual feedback and cognitive task performance influence postural control in healthy young and older adults. The task required that participants position a feedback cursor representing their center of pressure (COP) in a fixed target as accurately as possible in delayed visual feedback conditions. On selected trials, the participants also performed a silent arithmetic task. We separated COP time-series into distinct frequency components using low and high-pass filtering routines. We found that visual feedback delay affects both low and high frequency postural corrections but cognitive performance only influences the variability of rapid center of pressure displacements. We found substantial increases in postural variability in both young and older adults when we imposed visual feedback delays, with markedly larger increases in sway variability for the group of older adults. Our results demonstrate older adults prioritize vision to control posture and show that this visual reliance persists even when feedback about the task is delayed by several hundreds of milliseconds.

3.2- INTRODUCTION

Although we can stand on a crowded bus with little difficulty, standing balance involves complex interactions between our body and the environment. Feedback we receive from vision, proprioception and vestibular system provide ongoing information about the body's equilibrium and is critical in monitoring and controlling balance (Ting, 2007). Understanding the role of sensory feedback in balance control is central to unraveling the complexities of the postural control system.

While standing, vision, proprioception, and vestibular inputs provide information about the body's orientation within the environment (Peterka, 2002). The contribution of these sensory modalities to the internal representation of the body's orientation and equilibrium varies depending on how the CNS assigns weight to each sensory modality (Stevenson, Fernandes, Vilares, Wei, & Körding, 2009). In older adults, a number of studies have shown that the sensory receptors that monitor body orientation become less sensitive (see Goble, Coxon, Wenderoth, Van Impe, & Swinnen, 2009; Gu, Schultz, Shepard, & Alexander, 1996 for review). This reduced sensitivity has been linked to falling (Horak, 2006) and over-reliance on visual feedback to guide postural corrections (Simoneau et al., 1999; Sundermier, Woollacott, Jensen, & Moore, 1996; Wade, Lindquist, Taylor, & Treat-Jacobson, 1995), which may disrupt postural control when visual input is altered and/or unreliable (Jeka, Allison, & Kiemel, 2010; Jeka et al., 2006; O'Connor, Loughlin, Redfern, & Sparto, 2008). In addition to reductions in sensory reliability, delays in the transmission of feedback from the lower limb can increase with aging and exceed several tens of milliseconds (Purves, Augustine, & Fitzpatrick, 2001). This increase in feedback delay may be problematic because the neural circuitry engaged in postural control must rely on information from the past to correct balance errors (Lockhart & Ting, 2007; Milton, 2011). Despite evidence that sensory delays increase during the normal aging process (Blaszczyk, Hansen, & Lowe, 1993; Woollacott, Shumway-Cook, & Nashner, 1986), it is unclear how these additional feedback delays affect balance control.

One way to investigate how feedback delays influence postural control is to impose artificial delays on visual information about the task (Rougier, 2004; van den Heuvel, Balasubramaniam, Daffertshofer, Longtin, & Beek, 2009). We have recently used this technique to show that visual feedback delays destabilize postural control in young adults (Yeh, Boulet, Cluff, & Balasubramaniam, 2010). Others have constructed a model of the time-delayed postural control system (Boulet, Balasubramaniam, Daffertshofer, & Longtin, 2010). The increase in sway variability observed in visual delay conditions is consistent with model simulations and previous work suggesting that postural corrections likely arise from the feedback loop (Boulet et al., 2010; Jeka et al., 2006). What is still unknown however is how delayed visual feedback influences postural control in older adults. The notion that older adults emphasize visual feedback to correct postural errors (Sundermier et al., 1996; Wade et al., 1995) leads to the prediction that visual feedback delays will compromise posture to a greater extent in older adults than young individuals.

The ability to maintain balance under dual-task conditions also depends on the successful interaction between neural mechanisms engaged for postural control and secondary (or suprapostural) task performance. Numerous studies on postural control have used dual-task paradigms to investigate how cognitive (Maki, Zecevic, Bateni, Kirshenbaum, & McIlroy, 2001; Shumway-Cook, Woollacott, Kerns, & Baldwin, 1997; Stoffregen, Smart, Bardy, & Pagulayan, 1999) and motor tasks (Cluff, Boulet, & Balasubramaniam, 2011; Cluff, Gharib, & Balasubramaniam, 2010; Weeks, Forget, Mouchnino, Gravel, & Bourbonnais, 2003) influence balance control in young and older adults. The emerging consensus is that older adults compromised balance control under secondary task performance (Lacour, Bernard-Demanze, & Dumitrescu, 2008; McDowd, 1997). The apparent link between balance control, sensory feedback, and cognitive ability suggests that postural equilibrium will be disrupted to a greater extent by visual feedback delays and cognitive performance in older adults.

Here, we use a dual-task paradigm to investigate how visual feedback delays and cognitive performance influence postural control in healthy young and older adults. Visual information was manipulated by imposing artificial time delays on feedback about the position of the center of pressure (COP). The postural task required that participants position a cursor representing their COP in a fixed target as accurately as possible in an eyes-open condition (no visual feedback about the centre of pressure location) and conditions where visual feedback about the COP was delayed by as much as 900ms. The key feature of the visuomotor tracking task is the explicit goal to stay within the postural target by minimizing COP deviations. This feature enables us to directly test how visual feedback delays affect balance control because sway compromises postural task performance. In some conditions subjects performed a simultaneous silent arithmetic task to explore the interplay between cognitive performance and postural control.

Based on previous work (Chagdes et al., 2009; Yeh et al., 2010), we hypothesized that visual feedback delays would affect the slow and fast component of postural sway in both healthy young and older adults. We predicted that the variability of low and high frequency COP displacements would increase in the presence of artificial visual feedback delays, and this increase would be greater in older adults than the group of young participants Secondly, we hypothesized that dual-task cognitive performance would only modify the faster component of postural sway (>0.3 Hz) in young and older adults. Based on our previous work (Yeh et al., 2010), we predicted that cognitive dual-tasking would decrease the variability of high frequency COP displacements in young adults. Given the age-related decline in available attentional resources (Horak, 2006), we predicted that sway variability would increase when older adults performed a cognitive task under delayed visual feedback postural conditions.

3.3- METHODS

3.3.1-Participants

Healthy young (n = 14, age = 23.5 ± 3.2) and older adults (n = 14, age = 72.4 ± 4.7) participated in the study. The older participants were recruited from a local physical activity program where they exercise at least two days per week. The participants did not report any balance deficits, visual impairments, orthopedic or neurological disorders. The McMaster University Research Ethics Board approved the experimental procedures and the participants provided written informed consent prior to the experiment. The participants could withdraw from the study at any time without penalty.

3.3.2-Appratus

Center of pressure (COP) data were recorded from a force platform (OR6-2000, AMTI, Newton, MA, USA) positioned 1 meter in front of a 19inch flat-panel LCD monitor located at eye level (Viewsonic, 60Hz refresh rate, 5ms delay; Fig. 3.1A). COP data from the anteroposterior (AP) and mediolateral (ML) axes were sampled at 100Hz (National Instruments DAQ PCI-6200) with MATLAB™ code developed in our laboratory (7.9.0, The Mathworks, Natick, MA, USA) and stored offline for further analysis. COP data were collected under five visual conditions where participants either performed a non-verbal arithmetic task or not (i.e., cognitive task). Delayed visual feedback of the AP and ML COP position was displayed during the task using custom MATLAB™ code (see Boulet et al., 2010 for further details). The system gain was set such that a 1cm AP or ML COP displacement produced 1cm of motion on the visual feedback display. The participants stood comfortably in a shoulder-wide stance with their arms placed at their sides. We marked each participant’s preferred foot placement on the platform to ensure it was consistent during the experiment.

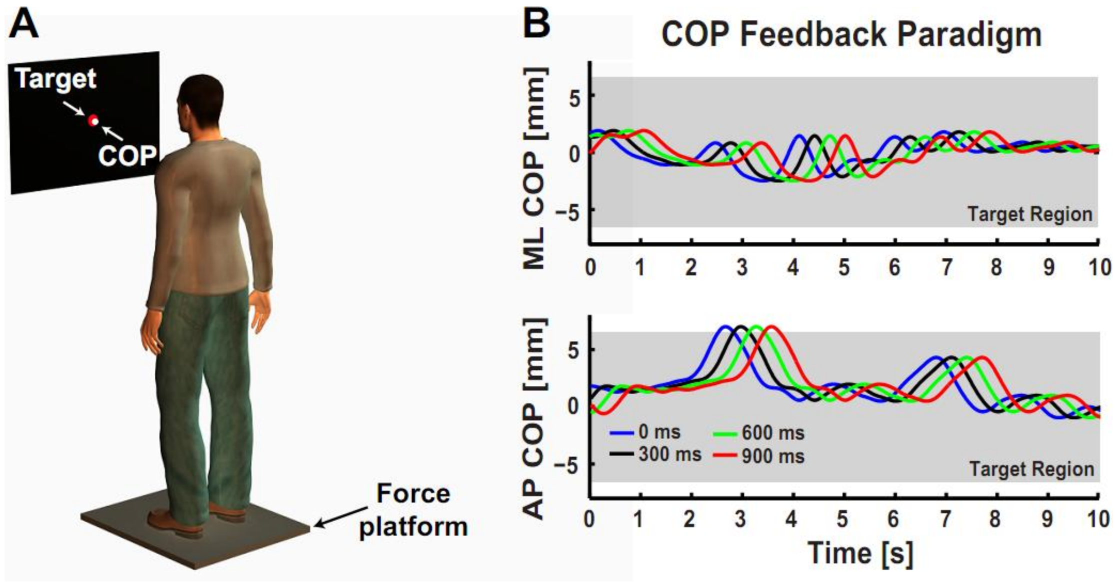

Figure 3.1. Experimental apparatus and delayed visual feedback paradigm. **A.** Schematic of the experimental setup showing the participant standing on the force platform in a comfortable shoulder-width posture with their arms placed at their sides. Participants were instructed to position their COP on the fixed target as accurately as possible throughout the trial. **B.** Representative data taken from a single trial performed by a young subject to illustrate how the feedback delay influenced the COP position shown on the visual display. Ten seconds of COP data are plotted to show the effect of the visual feedback delay. The blue traces are the true mediolateral (ML COP, top panel) and anteroposterior (AP COP, bottom panel) COP position displayed in the 0 ms visual feedback delay condition. The black (300 ms delay), green (600 ms delay) and red (900 ms delay) traces correspond to what was shown on the visual display in the delayed visual feedback conditions. Shaded grey region corresponds to the boundaries of the fixed COP target.

3.3.3-Task and procedure

At the start of each trial the visual display consisted of a fixed postural target (13mm diameter red circle). We set the location of this fixed target for each subject based on a 5-s window of quiet standing at the start of each trial. We also used the COP data collected during this initial time period as a buffer allowing us to display the COP position at the start of each delayed visual feedback trial. We instructed the participants to position the feedback cursor (10mm diameter white circle) representing the time-varying position of their COP as accurately as possible within the postural target for a period of 31s. The COP-target position was fixed in one location for the duration of each trial. At the end of each trial, we removed feedback about the stationary target and COP position from the visual display and the participant took a short break before beginning the next trial. Foot positioning was kept constant in each participants for all trials. Before data collection, participants performed several practice trials to become familiar with the task. During these practice trials, the experimenter made sure that participants understood that the goal of the postural task was to make their COP feedback cursor in the stationary target during the trial.

The experiment consisted of five feedback conditions: eyes open (EO), and visual feedback about the COP position delayed by 0 ms (instantaneous feedback), 300, 600, and 900ms. The total display and machine processing delay were approximately 50ms (determined using high-speed video analysis). In the eyes open condition, the visual display consisted of a stationary target with no visual feedback about the center of pressure position. The subjects were instructed to focus on the center of the stationary target and stand as still as possible for trials in the eyes-open condition. Fig. 3.1B shows representative data from a single trial performed by a young subject in the 0ms delay condition. In order to illustrate how the delayed visual feedback paradigm influenced the feedback display we have plotted anteroposterior (AP) COP position data time shifted by 0ms (blue trace, instantaneous COP feedback), 300ms (black trace), 600ms (green trace) and 900ms (red trace). Increasing the visual feedback delay causes a discrepancy between the true and displayed position of the COP, thereby allowing us to contrast the effect of visual feedback delays on posture control in young and older adults.

In the cognitive dual-task condition the participants performed a silent arithmetic task used in previous studies (Mak, Yeh, Boulet, Cluff, & Balasubramaniam, 2011; Week et al., 2003; Yeh et al., 2010; Cluff et al. 2011). Prior to each trial, the participant was asked to remember a two-digit number. During the trial, the participant performed a series of seven operations where they added or subtracted a single digit number from the running total at a rate of one calculation every 5s. An example series is: 53 (before trial) ＋ 2 (start of trial)－8 (5s)－2 (10s)＋7 (15s)－1 (20s)－9 (25s) ＋3 (30s) = 45 (30＋s). The participants were asked to silently calculate the running total and then verbalize their response when the trial was completed and visual feedback cursors disappeared from the display. Overall, the participants performed 3 trials in each condition (30 trials in total). We randomized the order of the ten conditions (5 visual conditions × 2 cognitive conditions) within each block of trials (10 trials/ block) and the participants were given the opportunity to rest when needed. The total time taken to complete the experiment was ~1hr.

3.3.4-Data analysis

We discarded the first 900ms of each time series because it was considered the maximum length of the visual delay (+machine processing and display updating delays). The remaining 30.1s of each trial were used in the subsequent analysis. We examined performance in the postural task by calculating the time the COP was outside of the fixed target on each individual trial by comparing the radial COP position to the radius of the fixed target. The total time spent outside of the target was determined for each trial on a subject-by-subject basis and then averaged across trials in each condition. We performed the COP decomposition analysis by filtering ML and AP COP signals using a bidirectional, second-order Butterworth filter with a cutoff frequency of 0.3Hz (van den Heuvel et al., 2009). The 0.3Hz cutoff frequency was selected based on the work of van den Heuvel et al. (2009) and the finding that visual feedback influences primarily the slow component of the COP signal (Rougier, 2007; Rougier, 2004). We used high and low-pass Butterworth filtering routines to decompose COP data and compute the variability of low (< 0.3Hz) and high frequency (> 0.3Hz) COP trajectories. Standard deviations were calculated from individual time series for each subject and then averaged to contrast COP variability between visual feedback and cognitive dual-task conditions. We also compared error rates in the cognitive task between the group of young and older adults.

3.3.5-Statistical analysis

Differences in time spent in the postural target (performance measure), low and high-pass ML and AP COP sway variability (standard deviation) were contrasted using a 2 AGE (Young vs. Old) × 2 COG (No Cognitive task vs. Cognitive task) × 5 feedback conditions (EO (no COP feedback), 0ms (no COP feedback delay), 300, 600, 900ms) mixed factor analysis of variance (ANOVA) with repeated measures on the cognitive task and visual feedback conditions. We used the Huyhn-Feldt correction factor when our data violated the sphericity assumption of the ANOVA test (Mauchley's test, $p<0.05$). Significant interaction effects were further analyzed using *post hoc* paired sample *t*-tests between tasks for each group separately or independent samples *t*-tests between the two age groups. Bonferroni adjustments were applied to correct for multiple comparisons with the threshold significance level set at $p<0.05$ for each contrast. In addition, we conducted an independent sample *t*-test on error rates to compare cognitive performance between the two age groups.

3.4- RESULTS

Performance in the postural task

Figure 3.2A-B shows unfiltered COP data from a representative young and older adult. For this example, we have plotted COP data from a single trial in the 0 (blue trace) and 900 ms delay (black trace) conditions when the posture task was performed with (right column) and without (left column) the cognitive task (i.e., arithmetic task). Our measure of task performance was the time spent outside of the postural target. This performance measure was influenced by a main effect of visual feedback delay [(F (2.3, 69.4) = 9.82, $p<0.001$; Huynh-Feldt correction] and a significant visual feedback delay × age interaction [F (4, 104) = 2.9, $p<0.05$]. *Post hoc* analysis revealed that increased feedback delays reduced the time that older adults spent in the postural target [F (2.52, 32.75) = 6.97, $p<0.01$; 900 < 600, 300, 0 ms, and EO, all p's<0.05]. We found similar performance decrements for the group of young adults [F (4, 52) =

3.37, $p<0.05$; 600 ms< EO, $p<0.05$]. The interaction effect of COG × AGE [F (1, 26) = 5.46, $p<0.05$] was also significant, and *post hoc* analysis revealed a significant increase in the time that young adults spent in the postural target during the cognitive task [F (1, 13) = 6.88, $p<0.05$], but did not alter performance in the group of older adults [F (1, 13) = 0.661, p =0.47].

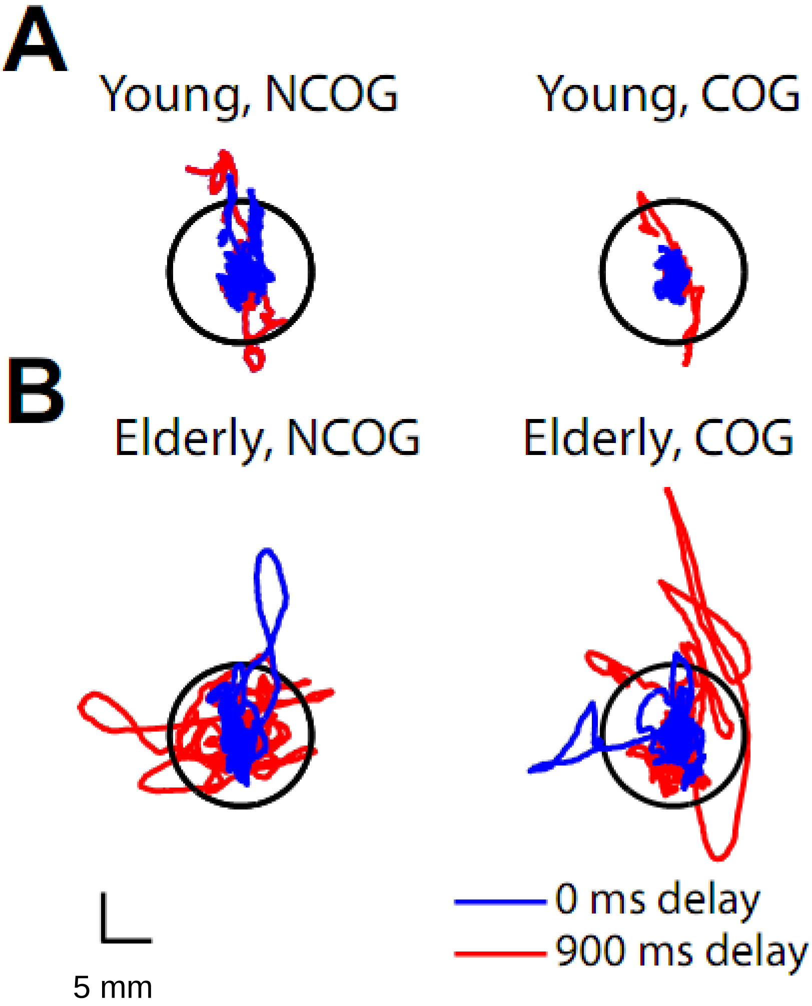

Figure 3.2. Comparison of COP displacements exhibited during simultaneous

cognitive task performance and delayed visual feedback in young and older adults. **A.** COP data from a single trial performed by a representative young subject. Black circle corresponds to the COP target. Blue and red traces correspond to data from the 0 ms and 900 ms visual feedback delay conditions, respectively. Representative COP data from the 0 ms and 900 ms delay conditions are shown with (right column) and without (left column) simultaneous cognitive performance. **B.** Same format as in A, but COP data are from a single trial performed by a representative older adult.

Low frequency COP displacements

We found that low frequency ML COP displacements were influenced by the main effects of visual feedback delay [*F* (4, 104) = 2.89, $p<0.05$] and AGE [*F* (1, 26) = 11.54, $p<0.01$]. Pair-wise comparison revealed that sway variability in the 300 ms condition (*M* = 1.53, SE = 0.14 mm) was reduced relative to the 900 ms condition (*M* = 1.84, SE = 0.14 mm) ($p<0.01$). In addition, sway variability for the young adults (*M* = 1.21, SE = 0.16 mm) was reduced compared to older adults (*M* = 2.00, SE = 0.16 mm). The interaction of visual feedback × AGE was also significant [*F* (4, 104) = 2.96, $p<0.05$, Figure 3.4A], and *post hoc* analysis showed that older adults had greater sway variability across all visual feedback conditions compared to young adults (0 ms: *t* (26) = 2.53, 300 ms: *t* (26) = 3.51, 600 ms: *t* (26) = 2.43, and 900 ms: *t* (26) = 3.75, all *p'*s<0.01), but not in the EO condition ($p>0.01$). The cognitive task did not significantly change the variability of low-frequency ML COP displacements [*F* (1, 26) = 0.37, *p*=0.55].

Similar to the results in the ML sway axis, we found significant main effects of visual feedback delay [*F* (2.32, 60.38) = 5.42, *p*<0.01; Huynh-Feldt correction] and AGE [*F* (1, 26) = 23.90, *p*<0.001] in the AP axis. Pair-wise comparisons demonstrated that sway variability in the 0 ms (*M* = 1.66, SE = 0.08 mm) and 300 ms conditions (*M* = 1.66, SE = 0.10 mm) was reduced compared to the 900 ms visual delay condition (*M* = 2.14, SE = 0.16 mm) (both *p*<0.01). Moreover, sway variability for the young adults (*M* = 1.36, SE = 0.12 mm) was reduced compared to the older adults (*M* = 2.21, SE = 0.12 mm). However, the visual feedback × AGE interaction was not significant [*F* (2.32, 60.38) = 1.64, *p* = 0.20; Huynh-Feldt correction, Figure 3.4C], and the cognitive task did not significantly alter the variability of low-frequency AP COP displacements [*F* (1, 26) = 0.76, *p*=0.39]. Collectively, these results illustrate that visual feedback delays affected low frequency postural displacements in both age groups, but most importantly, that visual feedback delays increased sway variability to a greater extent in older adults. Figure 3.3 showed representative low and high-pass filtered COP data from the AP axis for a single trial performed by a young and older subject.

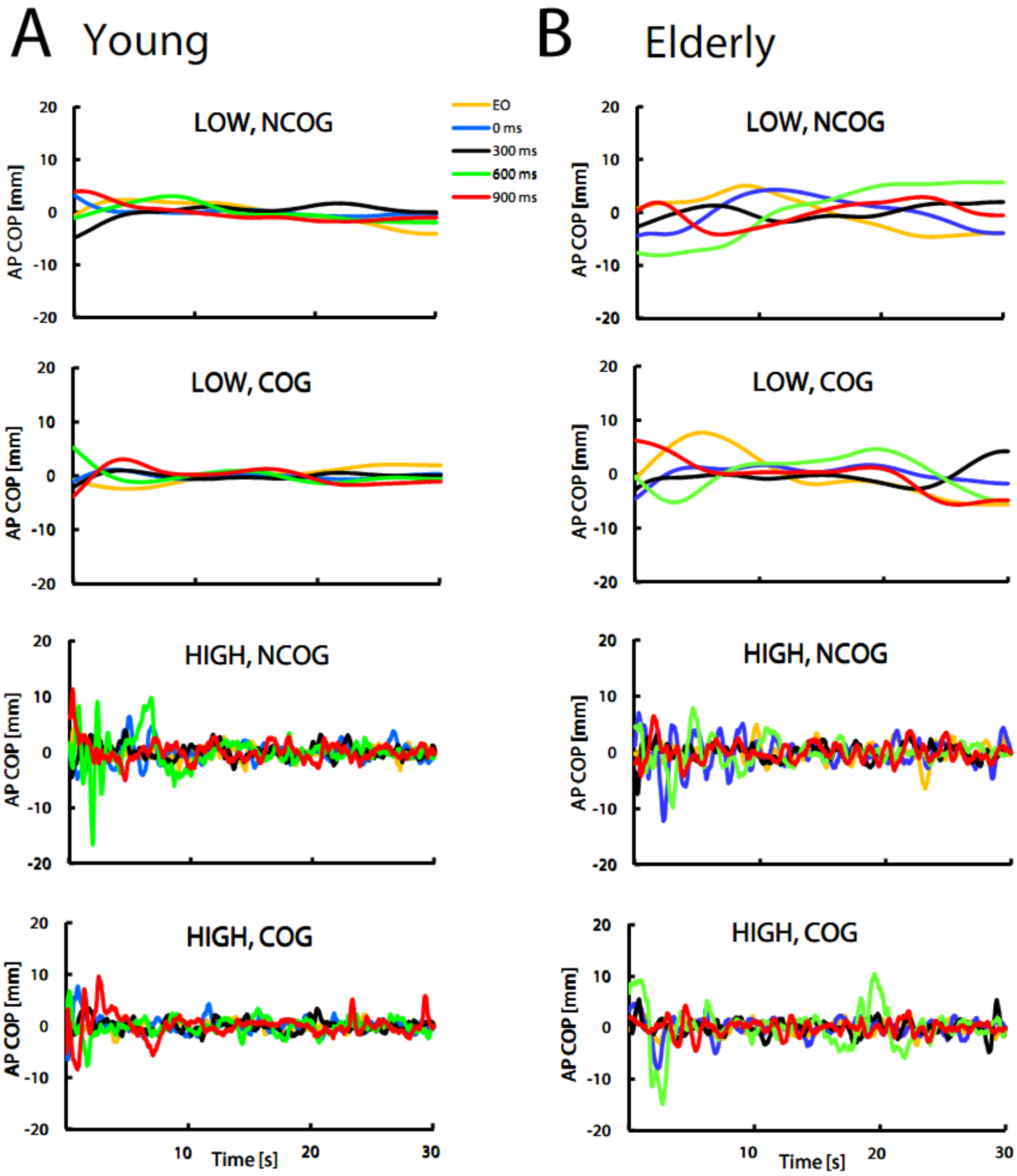

Figure 3.3. High and low-pass filtered anteroposterior (AP) COP displacements in delayed visual feedback and cognitive dual-task conditions. **A.** Representative low (LOW) and high-pass filtered (HIGH) AP COP time series from a single trial performed by a representative young participant in the visual feedback conditions with

(COG) or without (NCOG) performing the simultaneous mental arithmetic task (Yellow: EO; Blue: 0 ms delay; Black: 300 ms delay; Green: 600 ms delay; Red: 900 ms delay). **B.** Same format as in **A** but from a single trial performed by a representative older participant.

High frequency COP displacements

Figure 3.4B shows the variability of high frequency ML COP data. The ANOVA showed main effects of visual feedback delay [*F* (3.13, 81.28) = 17.20, *p*<0.001; Huynh-Feldt correction] and AGE [*F* (1, 26) = 14.35, *p*<0.01]. Pair-wise comparisons revealed that sway variability in the EO condition (*M* = 1.22, SE = 0.09 mm) was reduced relative to the 0 ms (*M* = 1.82, SE = 0.12 mm), 300 ms (*M* = 2.04, SE = 0.17 mm), 600 ms (*M* = 2.00, SE = 0.13 mm) and 900 ms visual delay conditions (*M* = 2.33, SE = 0.18 mm) (all *p*'s<0.01), and in the 0 ms relative to 900 ms condition (*p*<0.01). Sway variability for the young adults (*M* = 1.46, SE = 0.16 mm) was reduced compared to the older adults (*M* = 2.30, SE = 0.16 mm). We observed a significant visual feedback × AGE interaction [*F* (3.13, 81.28) = 2.84, *p*<0.05; Huynh-Feldt correction], with *post hoc* analysis revealing that compared to the young, older adults had greater high-frequency ML sway variability across all visual feedback conditions (EO: *t* (26) = 2.12, and for the visual conditions: 0, 300, 600, 900 ms, all *t* values were greater than 2.12, all *p*'s<0.01). The visual feedback × COG interaction was also significant [F (2.94, 76.44) = 3.06, $p<0.05$; Huynh-Feldt correction]. For the young group, high-frequency sway variability in the EO [t (13) = 2.66, $p<0.01$] and 600 ms conditions [t (13) = 3.05, $p<0.01$] were reduced with the cognitive task. In comparison, the cognitive task did not significantly alter the variability of high-frequency ML COP displacements in older adults (all p's>0.01). We also found a trend that the young adults decreased high-frequency ML COP displacement under cognitive dual-task, whereas older adults showed the opposite. The interaction between cognitive task and AGE was marginally significant [F (1, 26) = 4.19, $p=0.051$].

Figure 3.4D demonstrates that the variability of high-pass filtered AP COP trajectories was affected by the main effects of visual feedback delay [F (2.62, 67.99) = 18.99, $p<0.001$; Huynh-Feldt correction] and AGE [F (1, 26) = 19.85, $p<0.001$]. Pair-wise comparisons revealed that sway variability in the EO condition (M = 1.97, SE = 0.13 mm) was reduced relative to the 0 ms (M = 2.61, SE = 0.15 mm), 300 ms (M = 2.68, SE = 0.14 mm), 600 ms (M = 2.75, SE = 0.17 mm) and 900 ms (M = 3.24, SE = 0.24 mm) visual delay conditions (all p's<0.01). Reduced sway variability was also noted in the 0 ms relative to 900 ms condition ($p<0.01$), as well as for the young adults (M = 2.02, SE = 0.20 mm) compared to older adults (M = 3.28, SE = 0.20 mm). Finally, we found a significant three-way COG × AGE × visual feedback delay interaction [*F* (3.69, 95.93) = 2.61, $p<0.05$; Huynh-Feldt correction]. To examine this interaction, *post hoc* tests were applied separately for the young and older group. For the young subjects, the cognitive task decreased high-frequency AP COP in the 0 ms condition only [*t* (13) = 2.42, $p<0.01$] (Figure 3.4D). In the older group, the cognitive task was not affected in any of the conditions (all *p's*>0.05). These results suggest that although young subjects exhibited a reduction in sway variability during dual-task postural control, postural control in older adults did not benefit from the cognitive task, and moreover, older adults made more errors in the cognitive task [*t* (26) = 3.36, $p<0.05$, Figure 3.5].

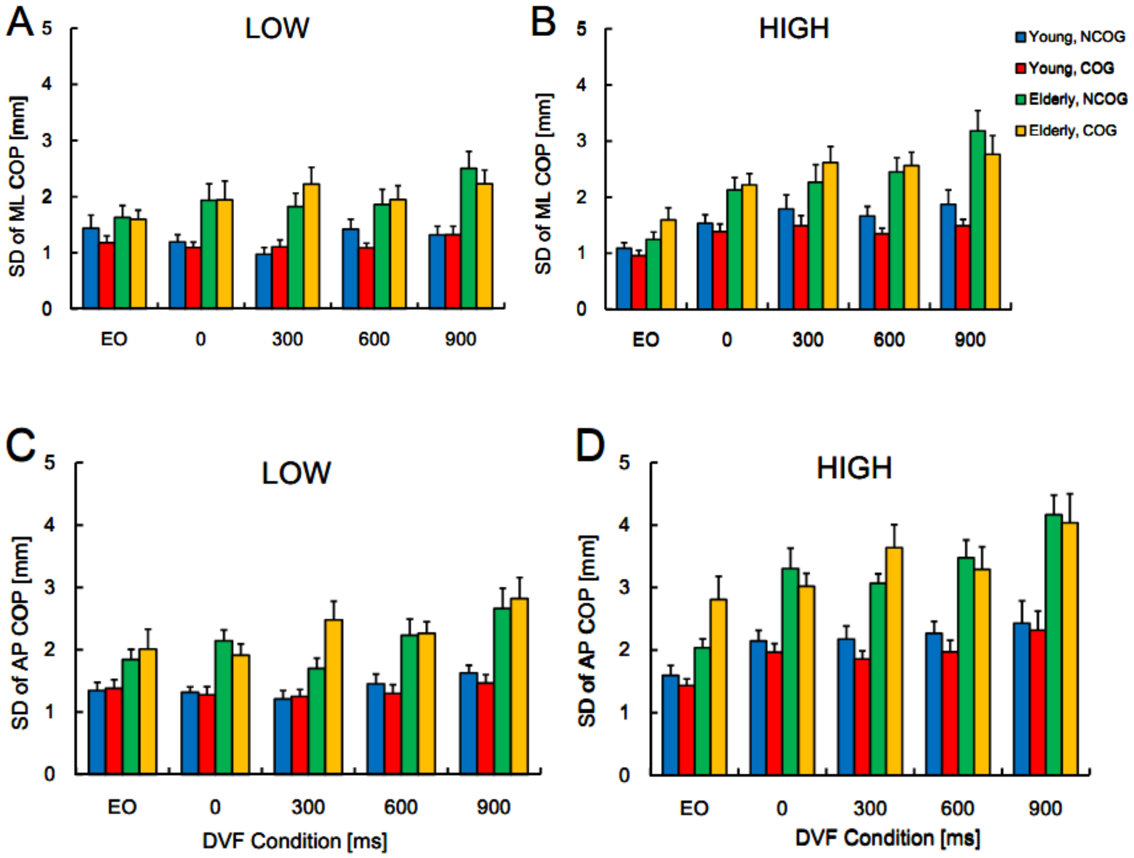

Figure 3.4. Summary plot of standard deviation of the LOW (left panel) and HIGH (right panel) ML (**A, B**) and AP (**C, D**) COP time series in the presence (COG) and absence (NCOG) of the cognitive dual-task in eyes open (EO) and DVF conditions (0, 300, 600, 900 ms) in young and older participants. *Error bars* represent ±1 SEM.

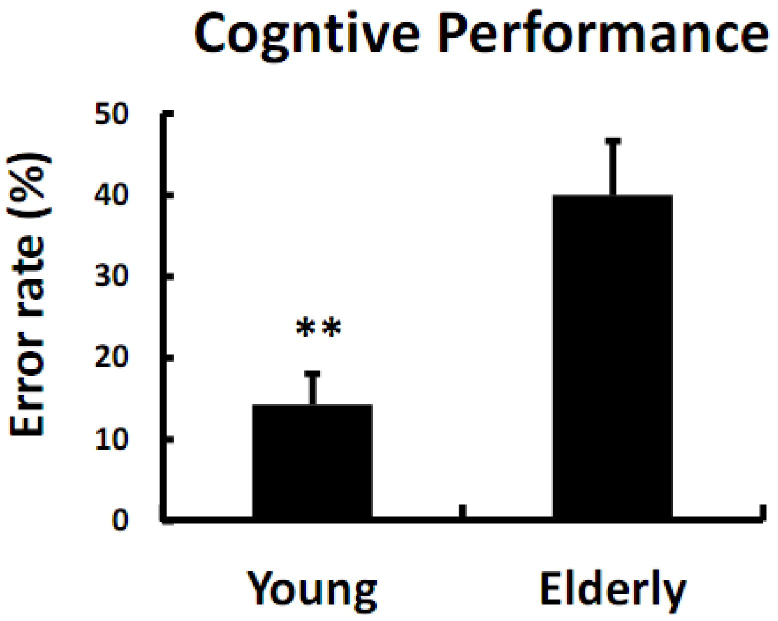

Figure 3.5. Cognitive dual-task performance in young and older adults. Cognitive performance was determined by error rate (numbers of errors/total number of questions*100%). *Error bars* represent ±1 SEM. ** $p < 0.01$.

3.5-DISCUSSION

Although it is well established that sensory feedback is important to postural control, less appreciated is that feedback delays can destabilize standing balance (Lockhart & Ting, 2007). In the present study we artificially delayed visual feedback about COP movements and found that this manipulation increased sway variability and compromised performance in a goal-directed posture task. Note that increased variability reflects a decrement in balance control since the goal of our postural task was to hold the COP feedback cursor within a stationary target for the duration of the trial. The key finding of the present study is that compared to young adults, postural variability caused by delayed visual feedback was substantially larger for older adults in the ML axis across all visual feedback delays. This result provides direct evidence that older people rely on visual information to control their posture.

Another notable finding was that delayed visual feedback increased the variability of low and high-frequency postural deviations in both age groups. Furthermore, we found that simultaneous cognitive task performance had different effects on center of pressure variability between age groups: the cognitive task improved postural performance (decrease COP sway variability) in the group of young participants but had no affect on task performance for the older adults. Taken together, the present work supports and extends the idea that older adults may rely more on visual information to guide and correct posture – even when visual information about the task is delayed by as much as 900ms. Moreover, the finding that older subjects show a trend to increase COP variability under dual-task conditions may suggest that they have difficulty shifting attention from postural control to secondary task performance.

3.5.1 Increased Reliance on Visual Feedback for Postural Control in Older Adults

During our goal-directed posture task, we found that in both age groups visual feedback delays resulted in an almost 25% (young adults: 22%, older adults: 28%) increase in sway variability compared to veridical visual feedback about the COP position. We found that these changes were linked to increased variability in both the slow and fast component of postural sway. Our interpretation of this novel finding is that delayed visual feedback may disrupt the relationship between the predicted consequences of postural corrections and feedback displayed during the task. Indeed, a number of modeling studies have suggested that sway variance during unperturbed standing arises from estimation errors about the body's orientation, with increases in visual information about standing balance reducing variance in the slow component of postural sway (Kiemel, Oie, & Jeka, 2002; van der Kooij & de Vlugt, 2007). These estimation processes are thought to use knowledge about the body's dynamics and descending motor commands to predict the state of the body, and combine these predictions with sensory feedback to form accurate body state estimates.

There is modeling evidence suggesting that the CNS relies on an internal model of the body's dynamics to enable rapid postural control in the presence of self-generated errors and external perturbations (Morasso, Baratto, Capra, & Spada, 1999; Ting, 2007). Our finding that altered visual feedback disrupts postural control may be consistent with this idea. We suggest that delayed visual feedback may create uncertainty about the task because it creates conflict between feedback and predictions about the state of the body. Similar results have been noted in tendon vibration studies where postural destabilization is large when subjects are initially exposed to tendon vibration, but decreases as subjects learn to ignore proprioceptive feedback because it does not provide accurate information about the task (Allison, Kiemel, & Jeka, 2006; Doumas & Krampe, 2010; Teasdale & Simoneau, 2001). Although the mechanism is still unclear, an interesting avenue for future research will be to determine whether adaptation to visual feedback delays can reduce postural instability. This line of interrogation may provide important insight on the role of visual feedback for balance control in older adults.

Another striking result was that visual feedback delays destabilized posture to a greater extent in older than younger subjects. One possible explanation for this finding is that age-related changes in peripheral sensory function cause older adults to rely more on visual information during postural control. Indeed, it has been suggested that normal aging delays sensory reweighting processes, and causes postural instability when visual feedback is altered during postural control (Eikema, Hatzitaki, Konstantakos, & Papaxanthis, 2013). Moreover, a number of studies have shown that older adults have persistent increases in postural sway when they are exposed to visual motion stimuli, suggesting that older adults are unable to suppress unreliable visual cues (Jeka et al., 2010; O’Connor et al., 2008). It would be interesting to examine whether our results extend to other sensory modalities such as time delays imposed on light-touch feedback during postural control (Jeka & Lackner, 1994; Jeka, 1997).

3.5.2 Interaction between Delayed Visual Feedback and Cognitive Performance Stabilizes Posture in Young but Not Older Adults

We found that fast postural deviations were reduced when young adults performed the secondary cognitive task. This finding replicates our previous work that moment-to-moment COP fluctuations are dependent on cognitive task during delayed visual feedback postural control (Yeh et al., 2010).Our results are in agreement with previous work showing a generalized reduction in postural sway variability when young, trained subjects engaged in a cognitive task while balancing a stick on their fingertip (Cluff et al., 2010). It has been shown that postural control enhancement in young adults when attention is diverted from postural control is evidenced by smaller COP excursions, accompanied by increased higher-frequency components (McNevin & Wulf, 2002). We propose that young adults may use tighter control of postural strategy (i.e., increased ankle joint stiffness) to produce higher frequency of corrective adjustments when attention is directed to the cognitive task. Stins et al. (2010)

suggested that ankle joint stiffness can be facilitated by an increased co-activation of the lower leg muscles or a tighter neuromuscular control or a combination of both factors.

Ankle joint stiffness can be invoked in which joints are “stiffened” by the surrounding musculature to restrain postural sway when cognitive attention was required (Dault, Frank, & Allard, 2001; Ehrenfried, Guerraz, Thilo, Yardley, & Gresty, 2003; Weeks et al., 2003) . This muscle co-contraction strategy can reduce cognitive load on postural control since the independent commands produced for controlling each joint would be reduced. Therefore, the co-contraction strategy requires less attentional capacity for postural control. Although we did not measure muscle activities to assess this hypothesis, our results demonstrated that reduced sway variability in the dual-task conditions is attributable to reduced amplitude in the high-frequency component of COP time series. Winter et al. (1998) demonstrated that ankle joint stiffness is reflected by increased frequency, reduced amplitude of COP excursions. Therefore, it is possible that postural sway variability decreased due to an increased activity of ankle musculature in dual-task situations. This plausible mechanism needs to be corroborated in future studies using electromyography or biomechanical analyses of the ankle joint.

On the other hand, seemingly automatic motor tasks like standing balance may require additional cognitive resources in late adulthood due to generalized decreases in sensorimotor (Wade & Jones, 1997) and cognitive-attention functions (Lacour et al., 2008; McDowd, 1997), thereby contributing to increases in postural sway when older adults maintain standing balance while they are engaged in other tasks.

In conclusion, this study revealed that visual feedback delays can reduce postural control in a goal-directed posture control task. The extent of postural instability caused by these feedback delays depended on age, with older adults exhibiting greater sway variability in delayed visual feedback conditions and difficulty performing the postural task. Further investigation of the mechanisms underlying postural control in the presence of visual feedback delays, including adaptation and sensory reweighting mechanisms, may help unravel the complexities of postural control in young and older adults. Rehabilitation strategies for older adults with balance problems should take into account the phenomenon of over reliance on visual feedback.

3.6-REFERENCES

Allison, L. K., Kiemel, T., & Jeka, J. J. (2006). Multisensory reweighting of vision and touch is intact in healthy and fall-prone older adults. *Experimental Brain Research.*, *175*, 342–352.

Blaszczyk, J. W., Hansen, P. D., & Lowe, D. L. (1993). Postural sway and perception of the upright stance stability borders. *Perception*, *22*, 1333–1341.

Boulet, J., Balasubramaniam, R., Daffertshofer, A., & Longtin, A. (2010). Stochastic two-delay differential model of delayed visual feedback effects on postural dynamics. *Philosophical Transactions. Series A*, *368*, 423–438.

Chagdes, J. R., Rietdyk, S., Haddad, J. M., Zelaznik, H. N., Raman, A., Rhea, C. K., & Silver, T. A. (2009). Multiple timescales in postural dynamics associated with vision and a secondary task are revealed by wavelet analysis. *Experimental Brain Research*, *197*, 297–310.

Cluff, T., Boulet, J., & Balasubramaniam, R. (2011). Learning a stick-balancing task involves task-specific coupling between posture and hand displacements. *Experimental Brain Research.*, *213*, 15–25.

Cluff, T., Gharib, T., & Balasubramaniam, R. (2010). Attentional influences on the performance of secondary physical tasks during posture control. *Experimental Brain Research*, *203*, 647–58.

Dault, M. C., Frank, J. S., & Allard, F. (2001). Influence of a visuo-spatial, verbal and central executive working memory task on postural control. *Gait and Posture, 14*, 110–116.

Doumas, M., & Krampe, R. T. (2010). Adaptation and reintegration of proprioceptive information in young and older adults' postural control. *Journal of Neurophysiology, 104*, 1969–1977.

Eikema, D. J. A., Hatzitaki, V., Konstantakos, V., & Papaxanthis, C. (2013). Elderly adults delay proprioceptive reweighting during the anticipation of collision avoidance when standing. *Neuroscience, 234*, 22–30.

Ehrenfried, T., Guerraz, M., Thilo, K. V, Yardley, L., & Gresty, M. A. (2003). Posture and mental task performance when viewing a moving visual field. *Cognitive Brain Research*, *17*, 140–53.

Goble, D. J., Coxon, J. P., Wenderoth, N., Van Impe, A., & Swinnen, S. P. (2009). Proprioceptive sensibility in the elderly: degeneration, functional consequences and plastic-adaptive processes. *Neuroscience and Biobehavioral Reviews, 33*, 271–278.

Gu, M. J., Schultz, A. B., Shepard, N. T., & Alexander, N. B. (1996). Postural control in young and elderly adults when stance is perturbed: dynamics. *Journal of Biomechanics*, *29*, 319–329.

Horak, F. B. (2006). Postural orientation and equilibrium: what do we need to know about neural control of balance to prevent falls? *Age and Ageing, 35,* ii7–ii11.

Jeka, J. J. (1997). Light touch contact as a balance aid. *Physical Therapy*, *77*, 476–487.

Jeka, J. J., & Lackner, J. R. (1994). Fingertip contact influences human postural control. *Experimental Brain Research*, *100*, 495–502.

Jeka, J.J., Allison, L. K., Saffer, M., Zhang, Y., Carver, S., & Kiemel, T. (2006). Sensory reweighting with translational visual stimuli in young and elderly adults: the role of state-dependent noise. *Experimental Brain Research*, *174*, 517–527.

Jeka, J. J., Allison, L. K., & Kiemel, T. (2010). The dynamics of visual reweighting in healthy and fall-prone older adults. *Journal of Motor Behavior*, *42*, 197–208.

Kiemel, T., Oie, K. S., & Jeka, J. J. (2002). Multisensory fusion and the stochastic structure of postural sway. *Biological Cybernetics*, *87*, 262–277.

Lacour, M., Bernard-Demanze, L., & Dumitrescu, M. (2008). Posture control, aging, and attention resources: models and posture-analysis methods. *Clinical Neurophysiology*, *38*, 411–421.

Lockhart, D. B., & Ting, L. H. (2007). Optimal sensorimotor transformations for balance. *Nature Neuroscience*, *10*, 1329–1336.

Mak, L., Yeh, T. T., Boulet, J., Cluff, T., & Balasubramaniam, R. (2011). Interaction between delayed visual feedback and secondary cognitive tasks on postural control in older adults. *Science & Motricité*, *88*, 81–88.

Maki, B. E., Zecevic, A., Bateni, H., Kirshenbaum, N., & McIlroy, W. E. (2001). Cognitive demands of executing postural reactions: does aging impede attention switching? *Neuroreport, 12,* 3583–3587.

McDowd, J. M. (1997). Inhibition in attention and aging. *The Journals of Gerontology, 52B,* 265–273.

McNevin, N. H., & Wulf, G. (2002). Attentional focus on supra-postural tasks affects postural control. *Human Movement Science, 21*, 187–202.

Milton, J. G. (2011). The delayed and noisy nervous system: implications for neural control. *Journal of Neural Engineering, 8,* 065005.

Morasso, P. G., Baratto, L., Capra, R., & Spada, G. (1999). Internal models in the control of posture. *Neural Networks, 12,* 1173–1180.

O'Connor, K. W., Loughlin, P. J., Redfern, M. S., & Sparto, P. J. (2008). Postural adaptations to repeated optic flow stimulation in older adults. *Gait and Posture, 28*, 385–391.

Peterka, R. J. (2002). Sensorimotor integration in human postural control. *Journal of Neurophysiology, 88,* 1097–1118.

Purves, D., Augustine, G. J., & Fitzpatrick, D. (2001) Neuroscience. 2nd edition. Sunderland (MA): Sinauer Associates.

Rougier, P. R. (2004). Optimising the visual feedback technique for improving upright stance maintenance by delaying its display: behavioural effects on healthy adults. *Gait and Posture*, *19*, 154–163.

Rougier, P. R. (2007). How visual feedback of decomposed movements of the center of pressure trajectories affects undisturbed postural control of healthy individuals. *IEEE Transactions on Bio-medical Engineering*, *54*, 813–820.

Shumway-Cook, A., Woollacott, M., Kerns, K. A., & Baldwin, M. (1997). The effects of two types of cognitive tasks on postural stability in older adults with and without a history of falls. *The Journals of Gerontology*, *52A*, M232–M240.

Simoneau, M., Teasdale, N., Bourdin, C., Bard, C., Fleury, M., & Nougier, V. (1999). Aging and postural control: postural perturbations caused by changing the visual anchor. *Journal of the American Geriatrics Society*, *47*, 235–240.

Stevenson, I. H., Fernandes, H. L., Vilares, I., Wei, K., & Körding, K. P. (2009). Bayesian integration and non-linear feedback control in a full-body motor task. *PLoS Computational Biology, 5*, e1000629.

Stins, J. F., Roerdink, M., & Beek, P. J. (2010). To freeze or not to freeze? Affective and cognitive perturbations have markedly different effects on postural control. *Human Movement Science, 30*, 190–202.

Stoffregen, T. A., Smart, L. J., Bardy, B. G., & Pagulayan, R. J. (1999). Postural stabilization of looking. *Journal of Experimental Psychology: Human Perception and Performance*, *25*, 1641–1658.

Sundermier, L., Woollacott, M. H., Jensen, J. L., & Moore, S. (1996). Postural sensitivity to visual flow in aging adults with and without balance problems. *The Journals of Gerontology, 51A*, M45–M52.

Teasdale, N., & Simoneau, M. (2001). Attentional demands for postural control: the effects of aging and sensory reintegration. *Gait and Posture*, *14,* 203–210.

Ting, L. H. (2007). Dimensional reduction in sensorimotor systems: a framework for understanding muscle coordination of posture. *Progress in Brain Research*, *165,* 299–321.

van den Heuvel, M. R. C., Balasubramaniam, R., Daffertshofer, A., Longtin, A., & Beek, P. J. (2009). Delayed visual feedback reveals distinct time scales in balance control. *Neuroscience Letters*, *452,* 37–41.

van der Kooij, H., & de Vlugt, E. (2007). Postural responses evoked by platform pertubations are dominated by continuous feedback. *Journal of Neurophysiology*, *2*, 730–743.

Wade, M. G., & Jones, G. (1997). The role of vision and spatial orientation in the maintenance of posture. *Physical Therapy, 77*, 619–628.

Wade, M. G., Lindquist, R., Taylor, J. R., & Treat-Jacobson, D. (1995). Optical flow spatial orientation and the control of posture in the elderly. *The Journals of Gerontology, 50B*, P51–58.

Weeks, D. L., Forget, R., Mouchnino, L., Gravel, D., & Bourbonnais, D. (2003). Interaction between attention demanding motor and cognitive tasks and static postural stability. *Gerontology*, *49*, 225–232.

Winter, D., Patla, A., & Prince, F. (1998). Stiffness control of balance in quiet standing. *Journal of Neurophysiology*, *80*, 1211–1221.

Woollacott, M. H., Shumway-Cook, A., & Nashner, L. M. (1986). Aging and posture control: changes in sensory organization and muscular coordination. *International Journal of Aging & Human Development*, *23*, 97–114.

Yeh, T. T., Boulet, J., Cluff, T., & Balasubramaniam, R. (2010). Contributions of delayed visual feedback and cognitive task load to postural dynamics. *Neuroscience Letters*, *481*, 173–177.

Chapter 4- Decreasing Internal Focus of Attention by Executing a Secondary Task Improves Postural Control in Healthy Younger Adults, but Not Older Adults

4.1 -ABSTRACT

We investigated the effects of shifting attentional focus from a postural control task to a concurrent, attentionally-demanding task (silent counting) in younger and older adults. Participants of both age groups performed a balancing task with instructions to focus their attention either internally or externally. The task was to stand on a force platform and move a centre of pressure feedback cursor along the mediolateral direction in a specific target location. Participants were asked to focus internally on keeping their weight evenly distributed between both legs or to focus externally on keeping the feedback cursor within the target. On some trials, participants performed a concurrent silent arithmetic task together with the postural task. Results revealed that younger adults, but not older adults, had less sway variability when they focused externally, or performed silent counting. This finding suggests that for younger adults, devoting less attention internally by performing a cognitive dual-task could enhance postural control. Older adults, however, did not exhibit the same improvement. Age-related declines in older adults may contribute to attention allocation deficits. While there is consistent evidence showing the benefits of an external focus compared to an internal focus, the relationship between focus of attention and its effect on postural control in older individuals requires further exploration.

4.2- INTRODUCTION

The ability to control and maintain an upright posture is fundamental to almost all activities in our daily lives, for example, standing in a moving bus or putting on the green in golf. This seemingly automatic task, however, does draw on attentional resources (Kerr, Condon, & McDonald, 1985; Lajoie, Teasdale, & Bard, 1993).

A frequent topic of studies carried out in the last decade has been the influence of focus of attention on postural control (Huxhold, Li, Schmiedek, & Lindenberger, 2006; McNevin & Wulf, 2002; McNevin, Weir, & Quinn, 2013; Nafati & Vuillerme, 2011; Vuillerme & Nafati, 2007; Wulf, Mercer, McNevin, & Guadagnoli, 2004). Wulf et al. (2001) described an external focus of attention as focusing on the effects of one’s movements (i.e., the outcomes of an action) and an internal focus of attention as focusing on the movements themselves (i.e., the limb segment). A consistent finding is that an external focus facilitates motor performance and learning, whereas an internal focus degrades motor performance and inhibits motor learning (see Wulf, 2013, for review). One hypothesis to explain the advantage of an external focus over an internal focus of attention is the “constrained action hypothesis” (Wulf & Prinz, 2001; Wulf, McNevin, & Shea, 2001). The hypothesis proposes that adopting an external focus promotes the utilization of a more automatic or self-organizing control process, whereas an internal focus is more likely to consciously intervene and disrupt the relatively automatically control process.

A separate stream of research across a variety of contexts has shown that an attentionally-demanding secondary task facilitates postural control in young adults (e.g., Andersson, Hagman, Talianzadeh, Svedberg, & Larsen, 2002; Dault, Yardley, & Frank, 2003; Riley, Baker, Schmit, & Weaver, 2005; Riley, Baker, & Baker, 2003; Yeh, Boulet, Cluff, & Balasubramaniam, 2010). These studies used a dual-task paradigm to investigate the interaction between a balancing task and a secondary task. For instance, we used silent counting as a secondary cognitive task while participants stood and were provided with either on-line visual feedback or with delayed visual feedback (Yeh et al., 2010). The results showed that young people benefitted from the secondary task — the participants' postural control improved while dual-tasking. One possible explanation for the results was that the attentional focus released from controlling posture toward a concurrent cognitive task allows postural control to work in a more automatic and efficient manner. In addition, postural control is more likely to be relegated to low-level subsystems that are governed by reflexive and compensatory mechanisms when simultaneously performing a cognitive task (Torres-Oviedo, Macpherson, & Ting, 2006). Existing research from McNevin and

Wulf have shown that an internal focus of attention is thought to compromise postural performance by constraining biomechanical degrees of freedom that contribute to movement execution (McNevin, Shea, & Wulf, 2003; McNevin & Wulf, 2002). According to Wulf and Prinz (2001), an internal focus induces a conscious type of control, causing individuals to constrain their motor system by interfering with automatic control processes. In this paper, we investigated whether performance of postural tasks while applying an internal focus of attention could improve with a cognitive secondary task.

Nafati and Vuillerme (2011) examined how devoting less attentional focus invested internally could affect postural performance. In their study, younger adults were asked to stand upright on a force platform in two experimental conditions. In the control condition, the participants stood quietly without any specific instruction concerning their focus of attention. In the experimental condition, the participants performed a short-term digit-span memory task. The digit-span task was designed to draw their attention away from postural control. Their results suggested that shifting attention away from postural control by executing a concurrent attention-demanding task could improve postural performance and efficiency. However, in their study, there was no guidance for participants on how to invest their focus of attention. For example, in the control condition, the study does not force, guide, or suggest to participants specially *how* to focus internally. Even though the instruction of “stand as immobile as possible” might direct participants’ attention internally towards the actual execution of relatively automatized postural control process, these instructions are ambiguous, and indeed, could be interpreted by some as an external focus of attention (e.g., by staring at a distant object).

In this present study, we extended the Nafati and Vuillerme (2011) study by providing specific, explicit instructions to participants to focus their attention externally or internally and by combining these manipulations with a secondary-task method. For an internal focus of attention, we told our participants to “keep your weight evenly on both legs”. In the external focus, we told them to “keep a feedback cursor in a target”. We chose the silent-counting task as our cognitive secondary task in order to draw participants’ attention away from postural control (e.g., Mak, Yeh, Boulet, Cluff, & Balasubramaniam, 2011; Yeh et al., 2010). Silent counting also reduces the potential impact on postural control that could be induced by the motions activated to produce overt counting (Yardley, Gardner, Leadbetter, & Lavie, 1999). We measured postural sway variability during quiet standing to assess the separate and combined effects of attentional focus instructions and the secondary tasks.

The second purpose of this study was to extend the previous research by including older adults. Most studies have examined attentional focus effects in healthy young adults (McNevin & Wulf, 2002; Nafati & Vuillerme, 2011; Wulf et al., 2004). To our knowledge, only a few studies have examined the attentional focus effects on healthy older adults (Chiviacowsky, Wulf, & Wally, 2010; McNevin et al., 2013). The Chiviacowsky et al. (2010) study used a group of older adults and separated them into an internal and an external focus group. They examined whether instructions that induced an external versus internal attentional focus would differentially affect the learning of a balance task. The results demonstrated that the learning benefit of an external attentional focus is generalizable to older adults. However, it is not clear whether the two groups of older people differed in terms of balance ability at baseline. Therefore it remains questionable whether the learning benefit was solely from the external focus manipulation. McNevin et al. (2013) tested the hypothesis that external focus instructions promote superior tracking and reduced postural sway for both older and young adults. Their finding provided limited support in older adults on external focus advantage on postural control. Thus, both studies offered limited evidence for a beneficial effect of an external focus on postural control in healthy older adults.

The question of whether or not older people would show the same postural control benefit as younger adults from an external focus attention is not a trivial issue. It is conceivable that the age-related declines in various levels of brain mechanisms (Labyt et al., 2003), as well as cognitive (Li & Lindenberger, 2002) and sensorimotor processing (Li, Aggen, Nesselroade, & Baltes, 2001; Lindenberger, Marsiske, & Baltes, 2000; Maki, Zecevic, Bateni, Kirshenbaum, & McIlroy, 2001), impair the successful employment of attentional resources for effective postural control. It has been hypothesized that age-related declines would lead to a higher need for cognitive involvement in sensorimotor processing among older adults compared to younger ones (Huxhold et al., 2006).

In this study, we sought to determine whether postural control with an internal focus of attention could be improved while performing a concurrent cognitive dual-task in both younger and older adults. We have two main hypotheses. First, based on the task prioritization model (Yogev-Seligmann, Hausdorff, & Giladi, 2012), we hypothesized that when the postural challenge is relatively low in younger groups, performance on a secondary task could then take priority. Therefore, shifting attentional focus from a postural control task to a concurrent, attentionally-demanding task (silent counting) would facilitate postural control. That is, postural sway variability was expected to decrease when participants performing the silent counting task compared to no counting. This hypothesis was based on the findings of Nafati and Vuillerme (2011). Secondly, we hypothesized that a cognitive dual-task would influence postural control in younger and older adults differently. Specifically, given the evidence of age-related declines in sensorimotor and cognitive-attention functions, we hypothesized that older adults would improve less than the younger ones in postural control while performing a cognitive dual-task in both focus of attention conditions.

4.3- METHODS

Twelve healthy younger (mean age=23.7, SD=5.1, 7 female) and twelve healthy older adults (mean age=74.8, SD=5.6, 5 female) participated in this study. Participants had normal or corrected vision, with no neurological or musculoskeletal disorder. The older participants were recruited from a local physical activity program in which they did at least two days of exercise per week. The participants did not report any balance deficits. The protocol was approved by the McMaster University Research Ethics board and the participants gave written informed consent prior to the study. Participants were compensated for their time.

Participants stood with feet apart at shoulder width on a force platform under four experimental conditions: (1) external focus without cognitive dual-task

(EXT-NC), (2) external focus with cognitive dual-task (EXT-C), (3) internal focus without cognitive dual-task (INT-NC) and (4) internal focus with cognitive dual-task (INT-C). During the external focus condition, participants were shown a fixed target (a 12mm ×12mm black square) on the monitor. The participants were instructed to shift their center of mass on the force plate to centre a feedback cursor (a 12mm by 12mm red cross) that represented their mediolateral (ML) center of pressure (COP) within the fixed target. The fixed target position was determined by calculating the mean position from the first 5s of COP data from both the ML and anteroposterior (AP) directions. As a result, in the first 5s of the trial, there was no target on the screen; only the feedback cursor (the red cross) was shown. Each trial lasted 25s. In the first 15s, the red cross was displayed for 5s, followed by a fixed black square (target) on the screen. After 15s, both the feedback cursor and fixed target were disappeared (no visual feedback), and participants were told to imagine both images were still there and asked to keep performing the task until the end of the trial (another 10s). We implemented the visual feedback of the COP position using custom-written LabView software (LabView 8.5, National Instruments).

For the internal focus of attention condition, participants were told to focus on keeping their weight evenly distributed on both legs throughout the trial. In the external focus condition, participants were told to focus on keeping the cross within the square throughout the trial. The feedback display was the same for both attentional focus conditions. The only difference between the two conditions was the instruction. In particular, participants focused either on their body movement (internal focus) or the red cross with the black square on the screen (external focus). It is important to note that attentional focus refers to the participant's concentration, not visual focus, and that visual information was kept constant across both internal and external focus conditions. The focus of attention instruction was given prior to the start of a trial. Accordingly, participants adopted only one of the instructions throughout the trial.

In the dual-task condition, participant performed a silent, serial arithmetic task used in previous studies (Mak et al., 2011; Weeks, Forget, Mouchnino, Gravel, & Bourbonnais, 2003; Yeh et al., 2010). Prior to a trial onset, the participant was told a two-digit number by the experimenter. The participant then performed a series of six arithmetic operations (single-digit addition or subtraction) at a rate of one computation per 5s interval. An example series for the cognitive dual-task condition follows: "53" (two-digit number given before start of trial) "＋2" (trial onset) "－8" (5s into trial) "－2" (10s) "＋7" (15s) "－1" (20s) "－9" (25s)="42" (answer). The choice of single-digit numbers (1-9) and arithmetic operation (addition or subtraction) were randomly determined with the provision that the running computation always resulted in a two-digit number. Participants silently computed the running total and verbalized their responses following trial completions, thereby eliminating articulation effects for COP displacements (Yardley et al., 1999). A baseline cognitive task performance was measured with participants standing freely on the floor with no balance task.

The presentation of the two attentional-focus blocks was counterbalanced across participants. In each block, the trial order followed the sequence "ABBA-BAAB-ABBA", in which A was postural task only, without a secondary task; B was postural task with dual-tasking. Practice trials were given to participants before data collection in order to familiarize them with the task. Each participant received a total of six trials for each condition, so 24 total trials were collected in a single session (~50 minutes). Participants were provided rests between trials.

We recorded the position of the COP from ML and AP directions with a force platform sampled at 1000 Hz (AMTI OR6 2000, Newton, MA). The statistical stability of postural control was determined by the standard deviation (SD) of the COP. The first 5s of data was discarded and only the remaining 20s of data was analyzed. We then separated the remaining 20s into two portions: with visual feedback and no visual feedback as a manipulation check. This manipulation check was used to determine whether participants were actually focusing their attention on. In particular, SD COP was used to compare the visual feedback conditions to determine whether the participants were focusing internally or externally. The hypothesis was that when participants focused internally, there should be no difference between the feedback versus no feedback portions of a trial in both the ML and AP directions. On the other hand, when they focused externally, the data should show a difference between the feedback versus no feedback portions in ML direction only because the feedback was only provided along the ML direction. These effects should be observable in both age groups.

After the manipulation check, a two-way analysis of variance (ANOVA) with repeated measures on the 2 attentional focus (external vs. internal) and 2 cognitive influence (with cognitive dual-task vs. no cognitive task) on ML and AP COP in both age groups was conducted. In addition, cognitive task performance was compared to baseline, internal focus, and external focus conditions. Statistical differences was measured at the $p=0.05$ level of significance. Greenhouse-Geisser corrections were employed for sphericity violations (Mauchly's test, $p<0.05$).

4.4- RESULTS

Effects of Focus of Attention Instructions

ML direction. To verify that participants did, in fact, adhere to the instructions, the visual feedback portion was compared to the portion with no visual feedback. In younger adults, the internal focus of attention conditions showed no difference between the visual feedback and no feedback portions [F (1, 11) = 2.16, $p>0.05$]. When they focused externally however, sway variability was dependent on the visual feedback [F (1, 11) = 29.71, $p<0.01$]. Postural sway variability decreased when the feedback was removed (No feedback, M=0.91, SD=0.34; visual feedback, M=1.10, SD=0.41, Fig. 4.1A). These results confirmed our operational assumption regarding the effects of instructions given to the younger participants.

We did not observe the same pattern of results in older adults. There was a significant main effect of visual feedback [F (1, 11) = 7.57, $p<0.05$] under internal focus conditions, suggesting that older participants did not comply with the instruction. Specifically, during internal focus conditions, sway variability decreased when visual feedback was removed (M=1.46, SD=0.53) in comparison to the visual feedback (M=1.61, SD=0.53). A significant main effect of visual feedback was also found under external focus conditions [F (1, 11) = 12.10, $p<0.01$]. In particular, visual feedback increased sway variability (No feedback, M=1.45, SD=0.69; visual feedback, M=1.82, SD=0.91, Fig. 4.1B). These results indicated that older participants did not adhere to the instructional constraints. They may still rely on the visual feedback even when they were asked to focus internally.

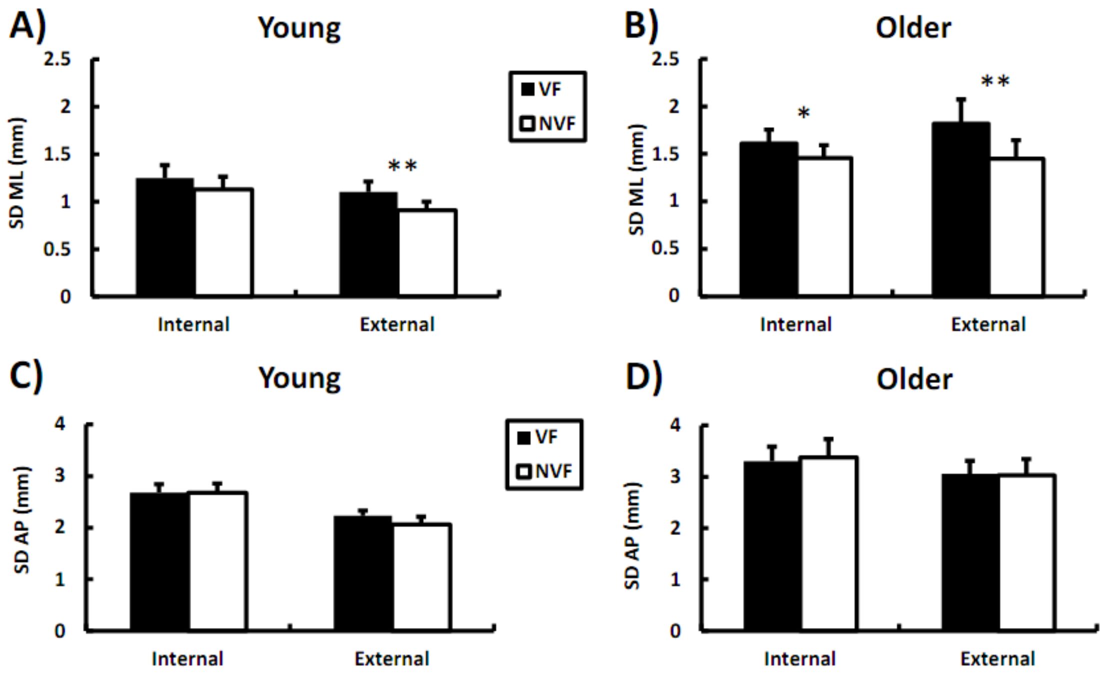

Figure 4.1. Mean standard deviations of the ML and AP COP time series for external and internal conditions in the presence (VF) and absence of visual feedback (NVF). Upper and lower panels represent ML and AP axes, respectively in young (A, C) and older participants (B, D). The visual feedback condition is shown in black while the no visual feedback condition is shown in white. Error bars represent ± 1 standard error. (* p<0.05;** p<0.01).

AP direction. Figures 4.1C and 4.1D show that there were no statistically difference between the visual feedback and no feedback portions during the internal and external focus of attention conditions in both age groups (all $p>0.05$). Since visual feedback was provided only along the ML direction, sway variability should not be affected in the AP direction.

Effects of Cognitive Dual-task in Younger Adults

By using the manipulation check, we confirmed that younger adults complied with the instruction sets, but not the older adults. Therefore, further analyses examining the effect of attentional focus and the cognitive dual-task were only conducted in younger participants. Postural sway variability in ML direction was reduced by the external focus of attention [F (1, 11) =5.96, $p<0.05$], and the cognitive dual-task [F (1, 11) =6.16, $p<0.05$] (see Fig. 4.2 A). No interaction between focus of attention and cognitive task was found ($p>0.05$). These results were replicated in the AP direction. Postural sway variability in AP direction decreased when participants focused externally [F (1, 11) =5.26, $p<0.05$] and under dual-tasking [F (1, 11) =9.41, $p<0.05$] (see Fig. 4.2B). No interaction was observed in the AP direction as well ($p>0.05$).

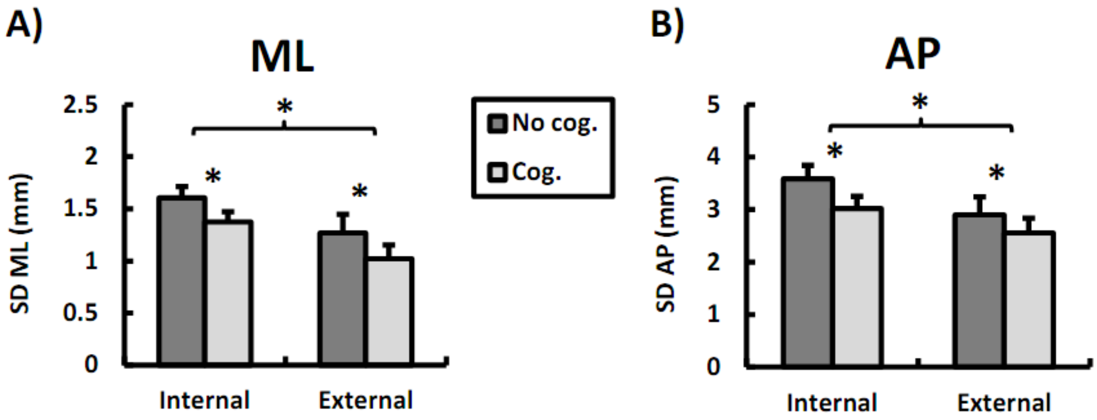

Figure 4.2. Mean standard deviations of the (A) ML and (B) AP COP time series for external and internal conditions in the presence and absence of the cognitive dual-task in young participants. The no cognitive task condition is shown in dark grey while the cognitive dual-task condition is shown in light grey. Error bars represent ± 1 standard error. (* $p<0.05$).

Cognitive Performance

To test the cognitive performance under baseline, internal and external focus of attention condition, repeated measures of ANOVA was conducted in younger adults. The results showed that there was no difference across these three conditions (mean error rate: 22%) ($p>0.05$).

4.5-DISCUSSION

The purpose of this study was to determine whether directing focus of attention internally on postural control could be enhanced through performing a concurrent cognitive task (e.g., silent counting) in younger and older adults. We sought to determine whether a task-irrelevant cognitive dual-task would increase postural control by devoting less attention internally. In the external focus conditions, participants were instructed to focus on keeping a horizontal feedback cursor within a specific target. In contrast, under the internal focus attentions, participants were asked to focus on keeping their weight evenly distributed between both legs. In addition, we used a silent serial arithmetic task as a secondary task to draw participants' attention away from the postural task. We assessed the effects of attentional focus and concurrent cognitive dual-task on postural control in both age groups.

The first novel contribution of this study was to use a manipulation check to ascertain that participants were adhering to the specific instructional constraints under each condition. Our manipulation check showed that only younger adults followed our experimental instructions. The older participants did not adhere to the instructions and did not focus internally as instructed. They seemed to rely on the visual cue to control posture even when they were asked to focus on their body movements. It was unclear whether the older participants were unwilling to or unable to follow the instructions.

Although the attentional focus literature has consistently demonstrated that an external focus can enhance motor performance and learning relative to an internal focus, one major concern remains. One of the key challenges in attentional focus research relates to the ‘purity’ of instructions under different conditions (Davids, 2007). Even though experimental instructions may have required participants to focus on different informational sources, one cannot be sure whether participants adhered to the specific instructions based solely on behavioral outcome measures. The manipulation check allowed us to examine quantitative data to evaluate what the participants might have been focusing their attention on (Kee, Chatzisarantis, Kong, Chow, & Chen, 2012; Peh, Chow, & Davids, 2011). Unfortunately, the majority of attentional focus research does not use manipulation check or any specific experimental design to ensure that participants actually adopt the attentional focus. To the best of our knowledge, a few studies have used subjective ratings to determine where participants placed their attentional focus (Nafati & Vuillerme, 2011; Vuillerme & Nafati, 2007). For instance, in Vuillerme and Nafati’s study (2007), participants were asked to rate their degree of active involvement in body sway control after completing each trial. In their Control condition, participants stood upright without any specific instruction concerning their attentional focus. In the Attention condition, participants were instructed to deliberately focus attention on their body sways and to increase their active intervention into postural control. The ratings were made using a 7-point Likert scale anchored with 1 (completely uninvolved, not trying hard at all) and 7 (extremely involved, trying as hard as possible). Analysis of self-reported active engagement in body sway control showed increased values in the Attention condition compared to the Control condition (5.0±0.5 vs. 2.6±1.7). According to the self-reported ratings, the authors stated that participants were adhering to the specific instructional constraints of each condition.

Although a self-reported rating scale may have provided some quantitative data to assess what the participants might have been focusing attention on, this approach also has limitations. For instance, the nature of the scale is very subjective. Also, the scale lies in the assumption that the distance between each interval is the same in the eyes of participants (Knapp, 1990). In terms of advancing research methodology in the study of the effects of attentional focus on postural control, our experimental design introduced a novel approach to determine what participants were actually focusing on. To our knowledge, this is the first study using an objective approach as a manipulation check to assess the real effect of attentional influence on postural control.

The second contribution of this study was that we provided further evidence to support previous findings: devoting less attention internally by performing a cognitive dual-task enhanced postural control. However, our results were found only in younger adults, not older ones. In younger adults, analyses of the sway variability showed a decreased COP variability (increased postural control) along the ML and AP direction under the cognitive condition relative to no cognitive condition, as well as under external focus condition relative to internal focus (see Fig. 4.2A and 4.2B), and these effects were independent. An internal focus has been considered to compromise postural control by inducing a conscious type of control, causing an individual to constrain their motor system by interfering with the automatic control process. However, in the present study, an imposed cognitive dual-task may be acting as an external focus which promotes a more automatic mode of control in order to facilitate postural control. That is to say, when participants did the silent counting while focusing internally, some of the attention was allocated from the body movement to the counting task. By devoting less attention or little conscious control in the body movement, the postural system may utilize a more reflexive control process during the cognitive dual-tasking. Our study is directly related to the finding from Nafati and Vuillerme (2011) who suggested that decreasing internal focus of attention improved postural control during quiet standing. We extended their experiment by explicitly directing participants’ attention to two tasks simultaneously—focused internally or externally, and while performing a silent counting task. In order to achieve the dual-task goals, the participants should flexibly allocate attention between the two tasks. Our findings indicate that younger participants have the ability to allocate their attention back and forth between focus of attention externally/internally and the counting task. This result is consistent with previous studies which showed that younger adults are able to flexibly update information in the dual-task paradigm that required them to switch attentional focus according to specific instructions (Mayr, & Liebscher, 2001; Siu & Woollacott, 2007). One of the limitation of the cognitive measurement was that since quiet standing needs cognitive resources (Kerr et al., 1985), the baseline of cognitive performance should have been conducted while participants were sitting instead of freely standing.

Lastly, in this study, the finding that older people failed to adopt the internal focus of attention may suggest that age-related decline impaired attentional dynamics. Significant postural control changes in ML direction under internal focus when the visual feedback was removed, suggesting that older participants did not adhere to the internal focus of instructions (Fig. 4.1B). It is possible that older adults experience impaired ability to inhibit and redirect attention allocated to distraction tasks (Maki et al., 2001; McDowd, 1997; Siu, Lugade, & Chou, 2008; Siu, Chou, Mayr, van Donkelaar, & Woollacott, 2009). It is also possible that age-related changes in peripheral sensory function cause older people rely more on visual information during postural control (Eikema, Hatzitaki, Konstantakos, & Papaxanthis, 2013).

A recent review by Wulf (2013) suggested that the external focus advantages have been found for people of various age groups. Despite the fact that many studies have examined attentional focus effects in children (Chiviacowsky, Wulf, & Avila, 2013), younger adults (see a review by Wulf, 2013) and older adults (Chiviacowsky et al., 2010; McNevin et al., 2013), the statement that the external focus advantages could generalize to all ages need to be interpreted cautiously. First of all, in this study, although we could not draw conclusions about whether the internal focus of attention has a negative effect on postural control in older adults, our study demonstrates that these focus-related experiments are difficult to control. Many experimental designs may not have examined whether participants can properly comply with experimental instructions, putting their conclusions in question. Consequently, we believe that by employing instructional manipulations, a researcher can ensure proper adherence to experimental instructions and, therefore, ascertain more replicable results. Secondly, to date, only a few studies had examined attentional focus effects in healthy older adults (Chiviacowsky et al., 2010; McNevin et al., 2013). Nevertheless, those studies offered limited evidence of the beneficial effects of an external focus on postural control. For example, the Chiviacowsky et al. (2010) study used a group of older adults (age=60-85 years) and separated them into an internal and an external focus group. The baseline comparison between the two groups to determine whether the two groups of older adults differed significantly was not conducted, or at least not reported. We suggested that at least the demographic characteristics data (e.g., mean age, gender, Mini-Mental State Examination (MMSE) or physical activity levels) in the two groups could be provided.

In another study, McNevin et al. (2013) examined whether suprapostural goal and postural control could be enhanced through an external focus manipulation in older adults. Contrary to the hypothesis, their findings did not support the beneficial effects of an external focus. Thus, given the limited evidence in the current literature, the relationship between postural control and attentional focus effects in older people needs further investigation.

The intent of the original study was to examine the effects of attentional focus and concurrent cognitive dual-task on postural control in both age groups. However, because older adults did not follow the instruction, we could not draw definitive conclusions. Future study should have checks in place to ensure all participants can follow the experimental instructions. One approach will be explaining the instruction explicitly by emphasizing the control of body movements during practice trials. For example, in our task, we could say: focus on your hip, knee and feet to keep your weight evenly distributed on both legs. The experimenter should also ensure participants understand the experimental instruction before data collection. Then, using the manipulation check in terms of comparing the feedback and no feedback portions of a trial after a couple of practice trials in order to obtain the objective data. During data collection, the experimenter should remind participants every time before a trial starts. Lastly, providing subjective ratings after each trial to ask participants reporting what they are attending to and make sure they comply with the instruction. Altogether, these approaches could provide better insight on whether instructions are effectively presented and adhered by participants. Our study nevertheless provides groundwork that can guide future experiments employ specific experimental design and careful experimental procedures to investigate the interaction of focus of attention and cognitive dual-task on postural control in the older population.

In conclusion, younger adults seem to have a high degree of flexibility in attentional allocation without sacrificing performance in both tasks. The ability to shift attention away from body movement to a concurrent cognitive dual-task could facilitate postural control. However, the attentional allocation ability might degrade with aging. Given that age-related declines exist in many areas such as cognitive and sensorimotor functioning, the relation between postural control and attentional focus in older people is complex. Combined with the difficulty to control participants' focus, focus-related postural control research with older participants presents real changes methodologically. We propose to use manipulation checks in concert with participant self-ratings to ensure proper adherence to instructions.

While the attentional focus literature is growing at a rapid rate, some questions remain unanswered. More research is needed to understand how feature of attentional focus influences on postural control in older individuals, or people with balance impairments—for example, whether inability to allocate attention externally contributes to the risk of falling. Research along these lines will improve our understanding of attentional focus and postural control with aging, as well as developing a theoretical foundation to better guide rehabilitation practices.

4.6-REFERENCES

Andersson, G., Hagman, J., Talianzadeh, R., Svedberg, A., & Larsen, H. C. (2002). Effect of cognitive load on postural control. *Brain Research Bulletin*, *58*, 135–139.

Chiviacowsky, S, Wulf, G., & Avila, L. T. G. (2013). An external focus of attention enhances motor learning in children with intellectual disabilities. *Journal of Intellectual Disability Research*, *57*, 627–634.

Chiviacowsky, S., Wulf, G., & Wally, R. (2010). An external focus of attention enhances balance learning in older adults. *Gait and Posture*, *32*, 572–575.

Dault, M. C., Yardley, L., & Frank, J. S. (2003). Does articulation contribute to modifications of postural control during dual-task paradigms? *Cognitive Brain Research*, *16*, 434–440.

Davids, K. (2007). Increases in jump-and-reach height through an external focus of attention: a commentary. *International Journal of Sports Science and Coaching*, *2*, 285–288.

Eikema, D. J. A, Hatzitaki, V., Konstantakos, V., & Papaxanthis, C. (2013). Elderly adults delay proprioceptive reweighting during the anticipation of collision avoidance when standing. *Neuroscience*, *234*, 22–30.

Huxhold, O., Li, S.-C., Schmiedek, F., & Lindenberger, U. (2006). Dual-tasking postural control: aging and the effects of cognitive demand in conjunction with focus of attention. *Brain Research Bulletin*, *69*, 294–305.

Kee, Y. H., Chatzisarantis, N. N. L. D., Kong, P. W., Chow, J. Y., & Chen, L. H. (2012). Mindfulness, movement control, and attentional focus strategies: effects of mindfulness on a postural balance task. *Journal of Sport & Exercise Psychology, 34*, 561–579.

Kerr, B., Condon, S. M., & McDonald, L. A. (1985). Cognitive spatial processing and the regulation of posture. *Journal of Experimental Psychology:Human Perception and Performance*, *11*, 617–622.

Knapp, T. R. (1990). Treating ordinal scales as interval scales: an attempt to resolve the controversy. *Nursing Research*, *39*, 121–123.

Labyt, E., Szurhaj, W., Bourriez, J.-L., Cassim, F., Defebvre, L., Destée, A., Guieu, J.-D., Derambure, Ph. (2003). Changes in oscillatory cortical activity related to a visuomotor task in young and elderly healthy subjects. *Clinical Neurophysiology, 114*, 1153–1166.

Lajoie, Y., Teasdale, N., & Bard, C. (1993). Attentional demands for static and dynamic equilibrium. *Experimental Brain Research*, 97, 139–144.

Li, K. Z. H., & Lindenberger, U. (2002). Relations between aging sensory/sensorimotor and cognitive functions. *Neuroscience and Biobehavioral Reviews*, *26*, 777–783.

Li, S., Aggen, S., Nesselroade, J., & Baltes, P. (2001). Short-term fluctuations in elderly people’s sensorimotor functioning predict text and spatial memory performance: the MacArthur successful aging studies. *Gerontology, 47,* 100–116.

Lindenberger, U., Marsiske, M., & Baltes, P. B. (2000). Memorizing while walking: increase in dual-task costs from young adulthood to old age. *Psychology and Aging, 15*, 417-436.

Mak, L., Yeh, T. T., Boulet, J., Cluff, T., & Balasubramaniam, R. (2011). Interaction between delayed visual feedback and secondary cognitive tasks on postural control in older adults. *Science & Motricité*, *88*, 81–88.

Maki, B. E., Zecevic, A, Bateni, H., Kirshenbaum, N., & McIlroy, W. E. (2001). Cognitive demands of executing postural reactions: does aging impede attention switching? *Neuroreport*, *12,* 3583–3587.

Mayr, U., & Liebscher, T. (2001). Age differences in the selection of mental sets: the role of inhibition, stimulus ambiguity, and response-set overlap. *Psychology and Aging*, *13*, 47-69.

McDowd, J. M. (1997). Inhibition in attention and aging. *The Journals of Gerontology*, *52B*, P265–P273.

McNevin, N. H., Shea, C. H., & Wulf, G. (2003). Increasing the distance of an external focus of attention enhances learning. *Psychological Research, 67*, 22–29.

McNevin, N. H., & Wulf, G. (2002). Attentional focus on supra-postural tasks affects postural control. *Human Movement Science, 21*, 187–202.

McNevin, N.H., Weir, P., & Quinn, T. (2013). Effects of attentional focus and age on suprapostural task performance and postural control. *Research Quarterly for Exercise and Sport*, *84*, 96–103.

Nafati, G., & Vuillerme, N. (2011). Decreasing internal focus of attention improves postural control during quiet standing in young healthy adults. *Research Quarterly for Eexercise and Sport*, *82*, 634–643.

Peh, S. Y.-C., Chow, J. Y., & Davids, K. (2011). Focus of attention and its impact on movement behaviour. *Journal of Science and Medicine in Sport, 14*, 70–78.

Riley, M.A., Baker A. A., Schmit J. M., (2003). Inverse relation between postural variability and difficulty of a concurrent short-term memory task. *Brain Research Bulletin*, *62*, 191–195.

Riley, M. A., Baker, A. A., Schmit, J. M., & Weaver, E. (2005). Effects of visual and auditory short-term memory tasks on the spatiotemporal dynamics and variability of postural sway. *Journal of Motor Behavior, 37,* 311–324.

Siu, K.-C., Lugade, V., & Chou, L.-S. (2008). Dual-task interference during obstacle clearance in healthy and balance-impaired older adults. *Aging Clinical and Experimental Research,20,* 349-354 .

Siu, K.-C., Chou, L.-S., Mayr, U., van Donkelaar, P., & Woollacott, M. H. (2009). Attentional mechanisms contributing to balance constraints during gait: the effects of balance impairments. *Brain Research*, *1248*, 59–67.

Siu, K.-C., & Woollacott, M. H. (2007). Attentional demands of postural control: the ability to selectively allocate information-processing resources. *Gait and Posture, 25,* 121–126.

Torres-Oviedo, G., Macpherson, J. M., & Ting, L. H. (2006). Muscle synergy organization is robust across a variety of postural perturbations. *Journal of Neurophysiology, 96,* 1530–1546.

Vuillerme, N., & Nafati, G. (2007). How attentional focus on body sway affects postural control during quiet standing. *Psychological Research, 71*, 192–200.

Weeks, D. L., Forget, R., Mouchnino, L., Gravel, D., & Bourbonnais, D. (2003). Interaction between attention demanding motor and cognitive tasks and static postural stability. *Gerontology, 49*, 225–232.

Wulf, G, & Prinz, W. (2001). Directing attention to movement effects enhances learning: a review. *Psychonomic Bulletin & Review, 8*, 648–660.

Wulf, G. (2013). Attentional focus and motor learning: a review of 15 years. *International Review of Sport and Exercise Psychology, 6*, 77–104.

Wulf, G., Mcnevin, N., & Shea, C. H. (2001). The automaticity of complex motor skill learning as a function of attentional focus. *The Quarterly Journal of Experimental Psychology, 54A,* 1143–1154.

Wulf, G., Mercer, J., McNevin, N., & Guadagnoli, M. A. (2004). Reciprocal influences of attentional focus on postural and suprapostural task performance. *Journal of Motor Behavior*, *36,* 189–199.

Yardley, L., Gardner, M., Leadbetter, A, & Lavie, N. (1999). Effect of articulatory and mental tasks on postural control. *Neuroreport*, *10*, 215–219.

Yeh, T. T., Boulet, J., Cluff, T., & Balasubramaniam, R. (2010). Contributions of delayed visual feedback and cognitive task load to postural dynamics. *Neuroscience Letters*, *481*, 173–177.

Yogev-Seligmann, G., Hausdorff, J. M., & Giladi, N. (2012). Do we always prioritize balance when walking? Towards an integrated model of task prioritization. *Movement Disorders*, *27*, 765–770.

Chapter 5- Dual-Tasking Postural Control: Age-Related Changes in Visuomotor Control and Attentional Capacity

5.1 -ABSTRACT

Optimal sensorimotor integration is needed to maintain the precision of a visuomotor postural task. Furthermore, cognitive resources have been suggested to be involved in maintaining balance, especially in the older adults. This study investigated how older and younger adults differ in employing sensorimotor strategies in a dual-task situation. Twelve healthy elderly (age 65-84 years) and 12 young subjects (age 19-30 years) performed a visually-based, postural tracking task in four different body orientations, which necessitated slightly different task goals. On some trials, participants performed a concurrent silent arithmetic task with the visuomotor tracking task. The results demonstrated that sensorimotor control degraded with aging. Older adults demonstrated less precision in tracking which required detecting sensory information from vision and proprioception and executing movement response accurately. However, young adults had better postural control under dual-task situations compared to older group. Besides, young adults showed more flexible postural coordination between mediolateral and anteroposterior planes. We propose that deterioration of peripheral sensorimotor systems and reduced flexibility in central information processing are responsible for the age-related differences.

5.2- INTRODUCTION

When crossing the busy intersection, people’s attention can be drawn to the traffic light, the coming cars, pedestrians and sometimes the conversation with a companion. Maintaining the ability to cross the busy street safely and efficiently is fundamental to be independent in older adults especially who live in urban settings. In this complex situation, people need the ability to flexibly allocate attention between maintaining posture and the secondary task (ex., talking, scanning the busy street for threats or tracking visual targets) at the same time. Thus, the coordination among vision, posture and secondary task comprises a common element in our daily life activities.

Investigations of visuomotor control in balance have shown that aging deteriorates the ability to perform goal-directed movements (Dault, de Haart, Geurts, Arts, & Nienhuis, 2003; Freitas & Duarte, 2012; Hatzitaki & Konstadakos, 2007). The coordination between vision and posture has been examined by a visual tracking task that requires participants to maintain their real-time visual feedback of the center of pressure (COP) within a reference. Dault et al. (2003) found that young adults, but not older adults, decreased the COP variability with augmented visual feedback. Specifically, when young participants stood in front of a computer screen with the COP feedback, they became aware of their body in space, and they could associate the incoming visual feedback with proprioception from the ankle and pressure on the feet to maintain the task goal. Older adults, however, were not able to utilize the visual feedback to stabilize the COP position. It has been suggested that the inability of older adults to maintain the task goal can be related to the motor and sensory modifications with aging (Dault et al., 2003).

When looking straight ahead to the screen, the task goal is to control the real-time visual feedback of the COP from both mediolateral (ML) and anteroposterior (AP) directions and make the feedback cursor stay within a fixed target. What would happen in postural control while looking with head turned sideways but the feedback cursor and target stayed the same? The task would likely become more challenging because COP movement in the ML direction from the force platform would be converted into movement in the AP direction on the feedback cursor on the screen and vice versa. When the head is turned sideways, conflicts between visual feedback and proprioceptive cues challenge the postural control system, requiring adjustments in the CNS integration process to determine the correct orientation in space and the appropriate motor response in maintaining the precision goal (Redfern, Yardley, & Bronstein, 2001). Therefore, changing head orientations is a way to generate different postural precision demands. A question that remained to be addressed was how the posture system organizes ML and AP control for the postural precision task under different head orientations? In addition, are there age-related differences in sensorimotor strategies in controlling posture when head orientation is manipulated? The first aim of this study was to investigate the pattern of postural organization in ML and AP directions used by young and older individuals during visual tracking tasks.

One approach to study the effect of head orientations on postural control is to ask the participants to maintain head straight forward (0°) or head turned to the side (90°) (Balasubramaniam, Riley, & Turvey, 2000; Riley, Balasubramaniam, & Mitra, 1998; Stoffregen, Smart, Bardy, & Pagulayan, 1999). However, decline in functional movement is one of the most significant alterations that occur during the aging process (Bemben, 1999). Aging is a normal biological process associated with changes in the elasticity of connective tissues, and resulting in a significant decrease in flexibility (Campanelli, 1996). Therefore, pathological and degenerative changes in aging can decrease the cervical spine range of motion (Tousignant, Smeesters, Breton, Breton, & Corriveau, 2006). It has been suggested that the loss of normal cervical lordosis leads to limited neck movements especially neck rotation (Maigne, 2000). Nevertheless, turning the head to the side (90°) seems not to be a functional posture used in our daily lives. Bennett et al. (2002) examined the mean active range of motion of the cervical spine required to perform 13 daily functional tasks in healthy young adults. The functional tasks included tying shoes, backing up a car, washing hair in the shower, and crossing the street. Specifically, they found that rotation of the cervical spine, which is less than 90° (67.6° ± 11.8°) without trunk motion, was greatest in the task of backing up a car. In summary, because of the non-functional head position and the decreased head rotation during the aging process, our manipulation of head rotation in an aging population was to have participants turning their head from 0° to maximum 45° to the side.

The complexity of postural control is further exacerbated by the fact that people often engage in secondary task performance while standing. Consequently, it is important to take into consideration the interaction between the postural task and secondary task performance. In an earlier study, we used a dual-task paradigm to examine the extent to which postural control is influenced by visual and cognitive task performance in young and older adults (Yeh, Cluff, & Balasubramaniam, Chapter 3). During our delayed visual feedback task, we found that compared to young adults, older adults increased reliance on visual feedback for postural control even though the visual feedback was delayed by several hundreds of milliseconds (Yeh et al., Chapter

3). In addition, our results also revealed that performing a secondary task stabilized posture in young but not older adults. Seemingly automatic task like standing may require additional cognitive resources in late adulthood due to generalized decreases in sensorimotor (Wade & Jones, 1997) and cognitive-attention functions (Lacour, Bernard-Demanze, & Dumitrescu, 2008; McDowd, 1997), thereby contributing to increases in postural sway when older adults maintain standing balance while they are engaged in other tasks. The second aim of this study was to investigate whether the age-related difference in this postural precision task sensitive to the secondary task.

To address the two research questions, young and older adults were asked to perform a postural precision task which they moved a center of pressure feedback cursor along the mediolateral (ML) direction in a specific target location. In some trials, the participants performed a concurrent arithmetic task. The experimental setup necessitated slightly different task goals under different head orientations. We then compared changes in postural control in terms of standard deviation (SD) of COP and mean velocity of COP in both age groups. The primary hypothesis was that postural instability would be greater in older adults compared to young adults. There are a growing number of studies suggest that increased sway variability does not necessarily reflect compromised balance. Rather, sway variability may reflect the characteristics of exploratory behavior (Carpenter, Murnaghan, & Inglis, 2010; Murnaghan, Horslen, Inglis, & Carpenter, 2011; Riley, Mitra, Stoffregen, & Turvey, 1997). In the present study, however, increased sway variability reflected a decrement in balance control since our task goal was to maintain the COP feedback cursor within a fixed target.

A secondary hypothesis was that the assembly of postural organization in mediolateral (ML) and anteroposterior (AP) sway variability would respond negatively to the precision demands of the postural task when head orientation changes from 0° to 45°. Specifically, the SD in the ML and AP was expected to vary systematically with head orientation, with ML increasing and AP decreasing when head orientation changes from 0° to 45°. This was because in the 0° (or head forward) condition, the task goal was to minimize sway variability in the ML direction in order to make the horizontal COP feedback cursor in the target. In this condition, less control was required over the AP axis because sway in this direction was irrelevant to the task goal. When the body turned away from the 0°, increased control from the AP axis was necessary because the COP cursor incorporated feedback from both the ML and AP directions. In order to maintain the task goal, minimizing sway in both ML and AP axis were required.

Finally, based on previous works which demonstrated postural control in older adults appeared to be more attentional demanding compared to young adults (Brauer, Woollacott, & Shumway-Cook, 2001; Brown, Shumway-Cook, & Woollacott, 1999; Redfern, Jennings, Martin, & Furman, 2001; Shumway-Cook, Woollacott, Kerns, & Baldwin, 1997; Teasdale, Bard, Larue, & Fleury, 1993), we expected that a secondary cognitive dual-task would have a stabilizing effect on postural control in younger adults, but a destabilizing effect in older adults.

5.3- METHODS

5.3.1-Participants

We recruited two groups of participants for this study: a young group whose ages ranged from 19 to 30 years (mean age=22.8, SD=3.9; n=12, 7 female) and an older group whose age ranged from 65 to 84 years (mean age=72.3, SD=5.7; n=12, 5 female). The older participants were recruited from a local physical activity program where they exercise at least two days per week. The participants did not report any balance deficits, visual impairments, orthopedic or neurological disorders. The McMaster University Research Ethics Board approved the experimental procedures and the participants provided written informed consent prior to the experiment. Participants were compensated for their time.

5.3.2-Apparatus

Center of pressure (COP) data were recorded from a force platform (OR6-2000, AMTI, Newton, MA, USA) positioned 1 meter in front of a 19inch flat-panel LCD monitor located at eye level (Viewsonic, 60Hz refresh rate, 5ms delay). Force data were sampled at 1000Hz (National Instruments DAQ PCI-6200) with custom LabView code (LabView 8.5, National Instruments) and stored offline for further analysis. COP data from the ML and AP axes were collected under four body orientation conditions, either together with or without a non-verbal arithmetic task. Visual feedback of the COP position was displayed during the task on the LCD monitor.

5.3.3-Task and Procedure

Participants stood with their feet together and with their arms hanging loosely at their sides. We marked each participant's foot placement on the platform to ensure consistency throughout the experiment. At the start of each trial, the visual display consisted of a fixed postural target (a 12mm ×12mm black square). The participants were instructed to shift their center of mass on the force plate to center a feedback cursor (a 12mm by 12mm red cross) that represented their ML center of pressure (COP) within the fixed target. The fixed target position was determined by calculating the mean position from the first 5s of COP data. Each trial lasted 30s. At the end of each trial, the participant took a short break (~1 minute) before the next trial.

The experiment consisted of four different body orientation conditions: head and body oriented in 0° (body faced forward), or with their bodies turned 15°, 30° and 45° to the right. During the 0° condition, participant stood on the force platform and looked at the visual display (Fig. 5.1A). For the 15°, 30° and 45° conditions, the visual display stayed the same, and the force platform was rotated to varying degrees. Thus, when the participant assumed the preset foot positions on the platform, their bodies were rotated to a set degree relative to the LCD display (Fig. 5.1).

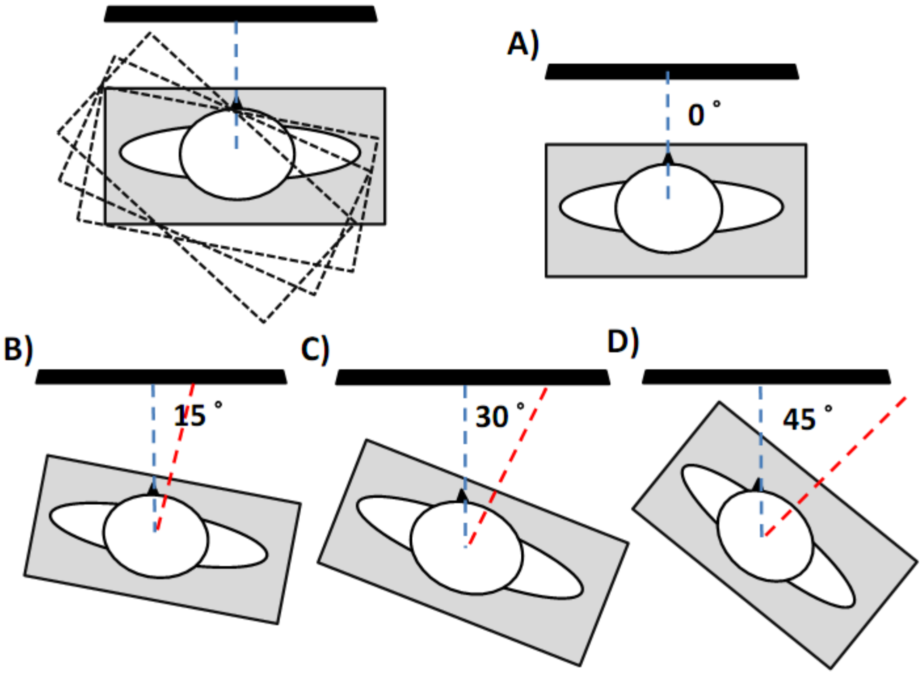

Figure 5.1. Schematic bird's-eye view of the force plate position and participant's body orientation (A: 0°, B: 15°, C: 30° and D: 45°).

In the cognitive dual-task condition, the participant performed a silent, serial arithmetic task used in previous studies (Mak, Yeh, Boulet, Cluff, & Balasubramaniam, 2011; Weeks, Forget, Mouchnino, Gravel, & Bourbonnais, 2003; Yeh, Boulet, Cluff, & Balasubramaniam, 2010). The participant’s task was to perform a series of arithmetic operations (single-digit addition or subtraction) on the two-digit number at a rate of one computation per 5s interval. Prior to a trial onset, the experimenter verbally provided the participant with a two-digit number, and then verbally announced a single digit to be added or subtracted after each 5s interval. An example series for the cognitive dual-task condition follows: “53” (two-digit number given before start of the trial) “＋2” (trial onset) “－8” (5s into trial) “－2” (10s) “＋7” (15s) “－1” (20s) “－9” (25s)=”42” (answer). The choice of single-digit numbers (1-9) and arithmetic operation (addition or subtraction) were randomly determined with the provision that the running computation always resulted in a two-digit number. Participants silently computed the running total of operations and verbalized their response following trial completion, thereby eliminating articulation effects during data collection (Yardley, Gardner, Leadbetter, & Lavie, 1999). A measure of baseline cognitive task performance was conducted while participants standing freely on the floor with no balance task.

Overall, the participants performed 3 trials in each condition for a total of 24 trials. We pseudo-randomized the order of the eight conditions (4 visual conditions × 2 cognitive conditions) within each block of trials (6 trials/ block) and the head position was different from block to block in a random order. The total time required for the experiment was ~1hr.

5.3.4-Data Analysis

The first 5s data was discarded, and only the remaining 25s of data were analyzed. We were interested in the amount of postural sway in experimental conditions, operationalized in terms of the variability of sway over the duration of each trial, with greater sway variability corresponding to greater postural instability. Moreover, we calculated mean COP velocity as this measure has been found to be sensitive to age-related differences (Prieto, Myklebust, Hoffmann, Lovett, & Myklebust, 1996). Mean COP velocity was defined as the movement amplitude over the entire trial divided by the movement time. The AP and ML sway was defined relative to the torso. The cognitive performance was measured in terms of error rate (number of errors/total numbers of math questions). A three-factor, mixed ANOVA using age group (young and older) as a between-subject factor, and head orientation (0°, 15°, 30° and 45°) and cognitive dual-task (with or without) as within-subject factors was performed on the data. We also conducted repeated measures ANOVA for each group separately to examine the effect of cognitive dual-task and body orientation. Post-hoc analysis was further performed to examine differences between each condition. Least Significance Difference (LSD) adjustment was applied to correct for multiple comparisons with the threshold significance level at $p<0.05$. The Huynh-Feldt correction to the degrees of freedom was used when violations to sphericity occurred in repeated measure tests.

5.4- RESULTS

The results section was organized as follows. We first reported the results from the mixed factorial ANOVA which added age as a between-subject factor. Second, we described the effects of body orientation and cognitive dual-task separately for each age group. SD and mean COP velocity were reported separately.

Standard Deviation (SD)

Combined two age groups. The ANOVA showed a main effect of cognitive dual-task for both ML [F (1, 22) = 6.12, $p<0.05$] and AP [F (1, 22) = 9.71, $p<0.01$] directions (Fig. 5.2). Specifically, in the ML direction, the addition of the cognitive dual-task (M=3.12, SE=0.16) reduced sway variability relative to the no secondary task condition (M=3.23, SE=0.15) ($p<0.05$). In the AP direction, the addition of the cognitive dual-task (M=4.13, SE=0.22) also reduced sway variability relative to the no secondary task condition (*M*=4.54, SE=0.24) ($p<0.05$). On the other hand, a significant body orientation main effect was only found in the AP axis [*F* (2.82, 62.10) = 3.30, $p<0.05$]. Post-hoc analysis revealed that in the AP axis, sway variability in the 15° (*M*=4.46, SE=0.30) and 30° (*M*=4.60, SE=0.27) conditions was greater than the 0° condition (*M*=3.97, SE=0.22) (both $p<0.05$). A significant main effect of age was found in ML axis [*F* (1, 22) = 13.90, $p<0.01$], but not in the AP ($p=0.18$).

Young Group. A significant body orientation main effect was found in the ML [*F* (3, 33) = 4.13, $p<0.05$], but not the AP axis ($p=0.16$). Pair-wise comparisons with LSD adjustment revealed that sway variability in the 15° (*M*=2.63, SE=0.13) and 45° (*M*=2.73, SE=0.13) conditions was increased relative to 0° condition (*M*=2.44, SE=0.11) (both $p<0.05$). Sway variability in ML axis increased when the body orientation turned relative to 0°, where the precision goal was to minimize sway in the AP axis. Main effects of cognitive dual-task were revealed in both ML [*F* (1, 11) = 7.52, $p<0.05$] and AP [*F* (1, 11) = 10.41, $p<0.01$] directions. Specifically, the addition of the cognitive dual-task reduced sway variability relative to the no secondary task condition.

Older Group. A significant body orientation main effect was found in the AP axis [*F* (3, 33) = 3.56, $p<0.05$], but not ML ($p=0.89$). Pair-wise comparisons revealed that sway variability in the 30° (M=5.17, SE=0.42) condition was increased relative to 0° condition (M=4.17, SE=0.31) (p<0.05) in the AP axis. Unlike young group, cognitive dual-task had no significant effect on both ML (p=0.27) and AP (p=0.12) directions in the older group. No significant interaction was found between body orientation and cognitive task.

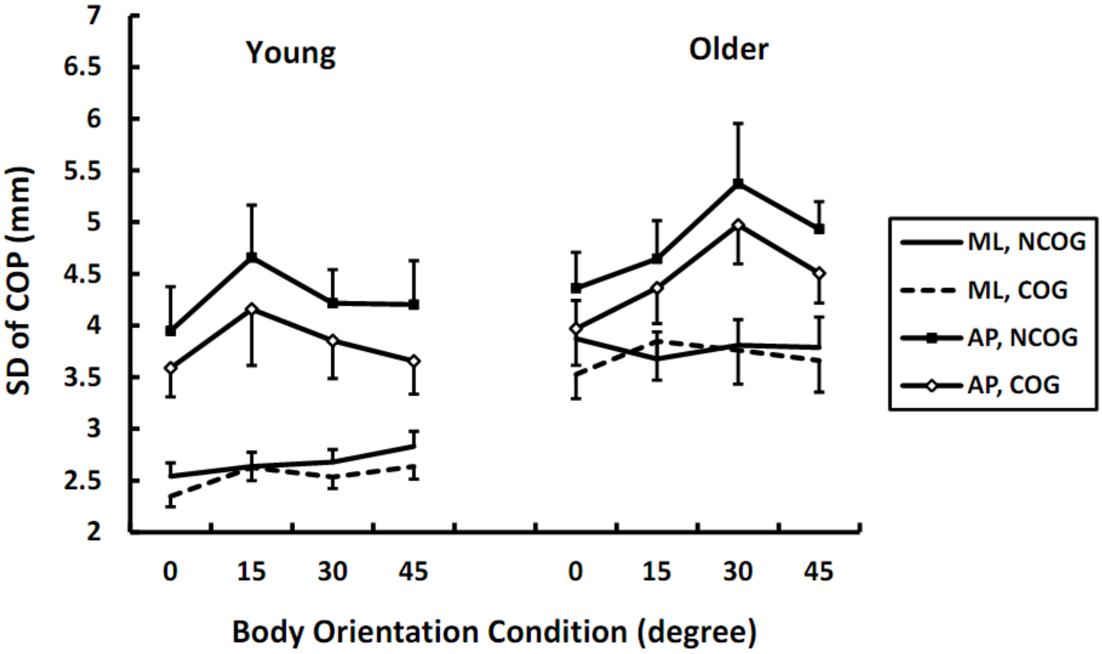

Figure 5.2. Mean COP standard deviation (mm) of ML and AP under four body orientation conditions in the presence (COG) and absence (NCOG) of the cognitive dual-task in young and older participants. Error bars represent ± 1 standard error.

Mean COP Velocity

Combined two age groups. Figure 5.3 showed main effects of body orientation in both ML [F (3, 66) = 10.51, p<0.001], and AP planes [F (2.30, 50.51) = 6.41, p<0.01].

Specifically, in the ML axis, pair-wise comparisons revealed that COP velocity in the 15° (*M*=82.04, SE=3.52), 30° (*M*=82.27, SE=3.50) and 45° (*M*=82.11, SE=3.52) condition was greater relative to 0° condition (*M*=81.35, SE=3.51) (all $p<0.01$). Moreover, a similar trend was observed in the AP axis. In particular, pair-wise comparisons revealed that COP velocity in the 15° (*M*=81.99, SE=3.36), 30° (*M*=82.18, SE=3.26) and 45° (*M*=81.77, SE=3.41) condition was increased relative to 0° condition (*M*=80.80, SE=3.47) (all $p<0.01$). However, there were no cognitive dual-task or age main effects for either the ML or AP axis (all $p>0.05$). There was no significant interaction between body orientation and cognitive task.

Young Group. A significant head orientation main effect was found in the ML axis only [F (3, 33) = 6.18, $p<0.01$]. Pair-wise comparisons revealed that COP velocity in the 15° (*M*=82.80, SE=6.12), 30° (*M*=83.29, SE=5.99) and 45° (*M*=82.67, SE=6.11) condition was increased relative to 0° condition (*M*=82.15, SE=6.08) (all $p<0.05$). Unlike SD data, cognitive dual-task had no significant main effect in both ML ($p=0.72$) and AP directions ($p=0.93$).

Older Group. Significant head orientation main effect was found in both the ML [F (3, 33) = 6.61, $p<0.01$] and AP axis [F (3, 33) = 9.14, $p<0.001$]. In the ML axis, pair-wise comparisons revealed that COP velocity in the 15° (*M*=81.28, SE=3.48), 30°

(*M*=81.27, SE=3.63) and 45° (*M*=81.56, SE=3.51) condition was increased relative to 0° condition (*M*=80.54, SE=3.48) (all $p<0.01$). A similar trend was observed in the AP axis. Pair-wise comparisons revealed that COP velocity in the 15° (*M*=80.64, SE=3.15), 30° (*M*=80.56, SE=3.19) and 45° (*M*=80.58, SE=3.20) condition was increased relative to 0° condition (*M*=79.33, SE=3.39) (all $p<0.01$). No significant main effect of cognitive dual-task on both ML ($p=0.34$) and AP direction ($p=0.82$) was observed.

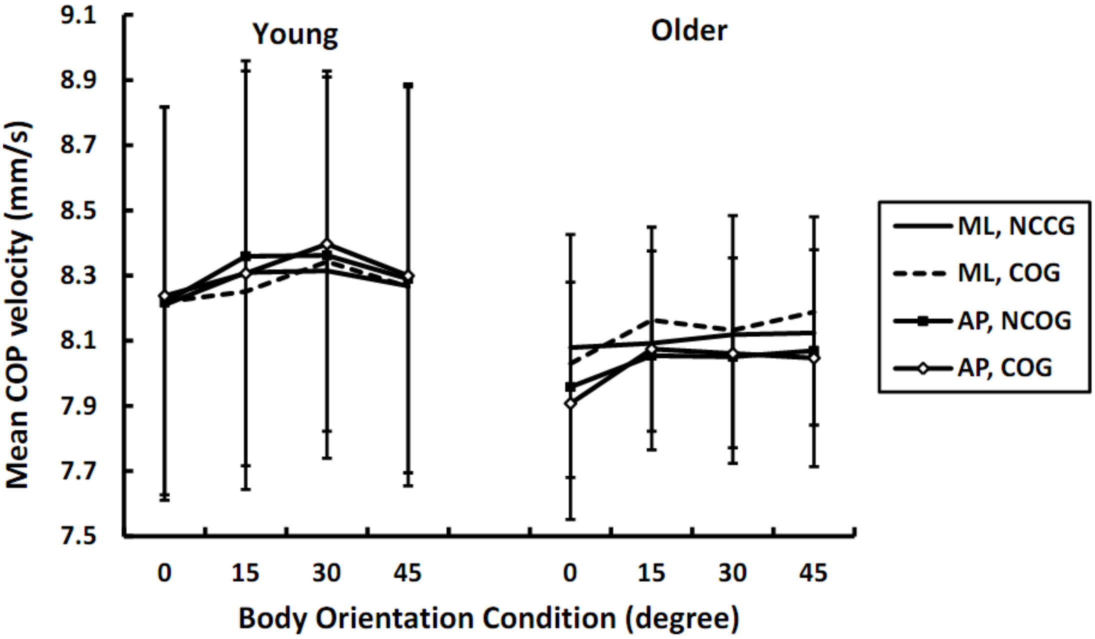

Figure 5.3. Mean COP velocity (mm/s) of ML and AP under four body orientation conditions in the presence (COG) and absence (NCOG) of the cognitive dual-task in young and older participants. Error bars represent ± 1 standard error.

Cognitive Task Performance

Cognitive performance was analyzed using independent sample *t*-test between the two age groups. The results showed there was no significant difference in terms of the error rate for the young (*M*=22.92%, SE=0.06) and older adults (*M*=25.00%, SE=0.05) during the secondary task [*t* (22) =0.26, *p*=0.80].

5.5-DISCUSSION

The current study investigated the effects of different body orientations and cognitive dual-task on the postural precision task performance in the young and older adults. Performance on the postural performance was assessed in terms of standard deviation (SD) of the COP and mean COP velocity. The results revealed three important sets of findings: (1) the SD in ML was higher for older participants compared to the young ones in accomplishing the precision task; (2) young people were able to achieve the postural precision task when the precision task required minimizing sway fluctuations. In addition, young adults were able to accomplish the task requirement by applying looser control in the ML but tighter control in the AP axis when the body orientation changed from 0° to 45°. Older people, however, did not show the same pattern. They were not able to decrease the sway variability when the task goal was to minimize sway in either ML or AP directions, and (3) cognitive dual-task performance showed a robust facilitation effect on postural control in the young adults, but not for the older ones. In particular, postural sway variability decreased significantly in both ML and AP planes while performing a secondary task in the young group. Older people, however, did not benefit from the secondary task. Together, these results of this study supported the hypothesis that sensorimotor control and attention dynamics declined with aging.

The novelty of our study was using head orientation manipulations for a visuomotor precision task to determine how the postural control system coordinates vision and proprioception to accomplish the task goal. Moreover, we used a dual-task paradigm to determine whether the existence of a cognitive dual-task could modify postural control. In the sensorimotor processing, our results were in agreement with the studies which showed that older adults have less ability to achieve the postural precision goal compared to the young group (Dault, Yardley, & Frank, 2003; Freitas & Duarte, 2012; Hatzitaki & Konstadakos, 2007). In particularly, older people had difficulty in minimizing postural sway variability compared to the young group when the task demand was to decrease COP movements. The results from SD of COP showed that the effect of body orientation was confined to the ML, but not the AP axis in the young adults. Particularly, young people were able to efficiently maintain task requirement when the precision task required minimizing fluctuations. One possible interpretation was that the control of standing balance is influenced by goal-directed behavior (Balasubramaniam et al., 2000; Riley, Balasubramaniam & Turvey, 1999). The manipulation of head orientation has been examined by Balasubramanium et al. (2000) in the context of a precision aiming task. Their results demonstrated that when aiming tasks were performed using a handheld laser pointer oriented parallel to the sagittal plane of the body, sway in the ML axis was decreased with a corresponding increase sway in the AP axis. On the contrary, the opposite results were found when the task was performed with the laser pointer oriented perpendicular to the sagittal plane. Their study suggested that postural organization is flexible to the task demands. The nature of our postural task required participants to keep the COP feedback cursor from the horizontal plane within a fixed target under different body orientation conditions. It appeared that different body orientation conditions required participants to control specifically on the ML axis. As a result, the task-based precision effects only occur in the ML axis. It would be interesting to further examine the effect when the feedback is provided in the AP axis. If task precision hypothesis stands, we should see the opposite results that reflect tighter control in the AP axis.

On the other hand, older people did not show the similar trend as the young group in terms of postural coordination to achieve the precision goal. One possibility is the decline in the somatosensory system as a function of age (Skinner, Barrack, & Cook, 1984). Researchers examining age-related declines in joint position sense at the knee found significant deterioration with increasing age for detecting motion (Bergin, Bronstein, Murray, Sancovic, & Zeppenfeld, 1995). Also, age-related changes in cutaneous sensation and proprioception showed increased thresholds of excitability of these sensory modalities in the older adults (see Shaffer & Harrison, 2007 for a review). In addition, studies have demonstrated that older adults not only needed more time to process the visual feedback (Dault et al., 2003), but also showed difficulty in integrating visual cues to produce appropriate motor action to stabilize posture (Hatzitaki & Konstadakos, 2007; Prioli, Cardozo, de Freitas Júnior, & Barela, 2006). Specifically, Prioli et al. (2006) suggested that older adults do not have problems in acquiring visual cues, but instead in how the sensory information are integrated into postural control system in order to produce appropriate motor response. Investigation of visuomotor control for upper limb aiming tasks have shown that aging deteriorate the ability to perform rapid and precise goal-directed movements (Elliott et al., 2010 for a review; Goggin & Meeuwsen, 1992; Lyons, Elliott, Swanson, & Chua, 1996; Welsh, Higgins, & Elliott, 2007). Specifically, the works on manual aiming have generally showed that age-related declines can be due to delays in detecting the movement error through sensory feedback and in producing the correction submovements (Elliott et al., 2010).

Another explanation could be the age-related decline in postural muscle response characteristics. Specifically, older adults demonstrated temporal delay in postural muscle activation (Halstead, Myklebust, & Myklebust, 1997; Toledo & Barela, 2010) and less postural muscle recruitment compared to the young adults (Lin & Woollacott, 2002). These results showed differences in reaction times between postural and voluntary muscles between the young and older adults. This resulted in an increase in the time between postural and voluntary responses in older adults. It is possible that deterioration of the postural control system limits the speed of initial stabilization and thus delays the onset of the voluntary response (Woollacott, & Shumway-Cook, 1988). Thus, variations in muscle response between young and older adults may be a result of differences in movement execution. Collectively, due to the age-related sensorimotor and visuomotor deficits, older adults may have difficulty to accomplish a visually-based postural tracking task, which required proper integration of sensory feedback and motor response.

These age-related differences, however, were not observed in the COP velocity measure. Previous research assessing the mean COP velocity has found it to be sensitive to age (Prieto et al., 1996). In general, older people show greater COP velocity compared to the young adults. However, this effect was not observed in our results. Interestingly, even though there was no statistically significant, there was a trend indicating that younger participants had greater mean COP velocity than the older ones in both the ML and AP directions (Fig. 5.3). A possible explanation was the different nature of the postural task: most studies measures COP velocity while no specific task goal was provided (Hewson, Singh, Snoussi, & Duchene, 2010; Prieto et al., 1996), whereas our postural task required participants to move the instantaneous COP feedback cursor within a fixed target. In order to fulfill the visuomotor precision task, young participants may use a tighter control strategy which they increased ankle joint stiffness to produce higher frequency of corrective adjustments (Carpenter, Frank, Silcher, & Peysar, 2001). This strategy demonstrated better movement efficiency as confirmed by the higher COP velocity in both ML and AP planes. However, no muscle activities of lower limb muscles were recorded to confirm this hypothesis. Nevertheless, the increased COP velocity does not necessarily account for postural instability; increased movement speed may indicate a better control of dynamic tracking task. This explanation is consistent with the findings of Hernandez et al.

(2012) for a dynamic tracking task which required participants to move their COP front and back in the AP axis to a target zone with an auditory cue. In that case, their results showed that young women had greater movement speed than older women. The authors concluded that age-related difference in movement speed can be due to increase in neuromuscular noise and decrease in the efficiency of movements in older adults (Hernandez et al., 2012).

In addition to the age-dependent sensorimotor decline, the differences in central cognitive processing during the postural precision task also demonstrated age-related changes in cognitive dynamics. Results from the young group indicated that postural sway variability decreased in both ML and AP directions with the secondary counting task. Older people, however, did not show this dual-task reduction in sway variability. Previous studies that examined the influence of cognitive performance on postural control have generated inconsistent and sometimes contradictory results. Secondary task manipulations during unperturbed balance are found to increase variability of postural sway, which is commonly interpreted as decreasing postural stability (Maki & McIlroy, 1996; Mitra & Fraizer, 2004; Mitra, 2003; Pellecchia, 2003). This effect is found to be more common and greater in older people compared to the young people (Brauer et al., 2001; Redfern et al., 2001; Shumway-Cook et al., 1997). Conversely, cognitive dual-task was also found to reduce sway variability in healthy young adults (Andersson, Hagman, Talianzadeh, Svedberg, & Larsen, 2002; Dault et al., 2003; Riley, Baker, & Schmit, 2003; Yeh et al., 2010), or that sway variability was unaffected during cognitive performance (Dault, Frank, & Allard, 2001; Marsh & Geel, 2000). Some of these inconsistent observations and lack of consensus on the role of cognition in postural control can be attributed to differences in experimental design, such as the type of postural and cognitive tasks used or the measures used to assess postural sway (see Fraizer & Mitra, 2008 for a review).

In the present study, our results demonstrated that performing a secondary cognitive dual-task improved postural control in the young group, but not the older group. Two main hypotheses have been proposed to explain these results. First, the decreased postural sway variability in young adults could be due to co-contraction of ankle agonist and antagonist muscles, which would result in a tighter control of postural sway (Dault et al., 2001). This strategy would increase muscle activities in order to act as a compensatory response, and it is less attention demanding. Second, adding a secondary task could allow the attention shift away from the control of posture because consciously controlling posture can be detrimental in performance (Vuillerme, Nougier, & Teasdale, 2000). Introducing a secondary task may divert the participants' attentional resources to focus onto this counting task and to fully delegate postural control to an automatic process, reducing sway variability. When performing the counting task, the postural control may be governed by low-level reflexive mechanisms in order to facilitate the concurrent task performance (Torres-Oviedo, Macpherson, & Ting, 2006). In this study, however, no muscle activities of lower limb muscles were recorded to confirm the muscle co-contraction hypothesis. Therefore, we suggested that cognitive performance may shift attention away from controlling posture and increasing the automatic processing of posture in the young adults.

In older adults, however, impaired attentional dynamics may affect postural performance in dual-task situations (Maki, Zecevic, Bateni, Kirshenbaum, & McIlroy, 2001). Specifically, Maki et al. (2001) suggested that an impaired ability of the attention switching may adversely affect the execution of dual-task. Other investigations also demonstrated that reduced ability to flexibly allocate attention between a postural and secondary task in dual-task situations contributes to an increased risk of falling in older people (Siu & Woollacott, 2007; Yogev-Seligmann et al., 2010). In addition, the capacity sharing theory suggested that attentional resources are limited in capacity, so that postural control and cognitive activity compete for attentional resources and cause deterioration of at least one of the tasks. Specifically, if one task demands more information processing, there will be less capacity available to allocate to the other concurrent task. In the current study, older people were able to maintain cognitive performance, but not the postural task, compared to the young group. Many studies confirmed this view and showed that performance of an attentional demanding secondary task deteriorated postural control in the older adults (Brauer et al., 2001; Brown et al., 1999; Redfern et al., 2001; Shumway-Cook et al., 1997; Teasdale et al., 1993). This model may explain the decreased postural performance when older people in dual-task conditions; however, it failed to account for the increased posture control in the young group in our study. Together, these findings may suggest that a seemingly automatic task like standing may require additional cognitive resources in late adulthood due to a reduction in attentional capacity (Huxhold, Li, Schmiedek, & Lindenberger, 2006) and impaired attentional dynamics (Maki et al., 2001).

In conclusion, the current study revealed two age-related alterations between young and older adults. First, the assembly of a postural organization for the postural precision task is well-organized in young adults in order to accomplish the task goal. Older people showed decreased ability to coordinate posture in a postural precision task. Second, by using the dual-task paradigm, we have confirmed that fulfillment of a cognitive task in a postural precision task increased postural control in the young adults. However, older people did not benefit from the secondary task during the precision task due to the impaired attentional dynamics.

The current study extended previous investigations in three ways. First, we used a functional head orientation positions (from 0° to 45°) to examine the effects on postural control in the older and younger population. Second, we provided a real-time visual feedback while standing, as opposed to simply asking participants to look at a fixed target (e.g., Balasubramaniam et al., 2000; Chen & Stoffregen, 2012). Lastly, we combined a secondary task during standing in order to expand our understanding of the role of attention during a visuomotor postural task. Together, the present results provide insight into age-related differences in sensorimotor strategies in a postural precision task, as well as in a cognitive dual-task. Age-related changes in postural control may degrade the flexible coordination of the sensory feedback and motor execution. Furthermore, diminished cognitive and attentional capacities may alter postural performance in dual-task conditions.

Despite the age-induced changes, visuomotor control ability seemed to improve with practice (Hatzitaki & Konstadakos, 2007), which highlights the adaptive visuomotor plasticity of the aging brain. A recent study demonstrated that balance training with visual feedback during external perturbations can improve postural corrective responses through improved neuromuscular coordination of the involved muscles, and adaptive neural modifications on the spinal and cortical levels facilitated by voluntary activity (Sayenko et al., 2012). Although the results are derived from healthy young people, this training protocol could potentially be examined as an intervention to reverse age-related impairment in future investigations.

5.6-REFERENCES

Andersson, G., Hagman, J., Talianzadeh, R., Svedberg, A., & Larsen, H. C. (2002). Effect of cognitive load on postural control. *Brain Research Bulletin, 58,* 135–139.

Balasubramaniam, R., Riley, M. A, & Turvey, M. T. (2000). Specificity of postural sway to the demands of a precision task. *Gait and Posture, 11,* 12–24.

Bemben, M. G. (1999). Age related physiological alterations to muscles and joints and potential exercise interventions for their improvement. *The Journal of the Oklahoma State Medical Association, 92,* 13-20.

Bennett, S., Schenk, R. & Simmons, E.D. (2002). Active range of motion utilized in the cervical spine to perform daily functional tasks. *Journal of Spinal Disorders & Techniques, 15,* 307–311.

Bergin, P. S., Bronstein, A. M., Murray, N. M., Sancovic, S., & Zeppenfeld, D. K. (1995). Body sway and vibration perception thresholds in normal aging and in patients with polyneuropathy. *Journal of Neurology, Neurosurgery, and Psychiatry, 58,* 335–340.

Brauer, S. G., Woollacott, M., & Shumway-Cook, A. (2001). The interacting effects of cognitive demand and recovery of postural stability in balance-impaired elderly persons. *The Journals of Gerontology, 56A,* M489–M496.

Brown, L. A., Shumway-Cook, A., & Woollacott, M. (1999). Attentional demands and postural recovery: the effects of aging. *The Journals of Gerontology, 54A*, M165–M171.

Campanelli, L. C. (1996). Mobility changes in older adults: Implications for practitioners. *Journal of Aging and Physical Activity, 4,* 105–118.

Carpenter, M., Frank, J., Silcher, C., & Peysar, G. (2001). The influence of postural threat on the control of upright stance. *Experimental Brain Research*, *138*, 210–218.

Carpenter, M. G., Murnaghan, C. D., & Inglis, J. T. (2010). Shifting the balance: evidence of an exploratory role for postural sway. *Neuroscience*, *171*, 196–204.

Chen, F.-C., & Stoffregen, T. A. (2012). Specificity of postural sway to the demands of a precision task at sea. *Journal of Experimental Psychology: Applied*, *18*, 203–212.

Dault, M. C., de Haart, M., Geurts, A. C. H., Arts, I., & Nienhuis, B. (2003). Effects of visual center of pressure feedback on postural control in young and elderly healthy adults and in stroke patients. *Human Movement Science*, *22*, 221–236.

Dault, M. C., Frank, J. S., & Allard, F. (2001). Influence of a visuo-spatial, verbal and central executive working memory task on postural control. *Gait and Posture*, *14*, 110–116.

Dault, M. C., Yardley, L., & Frank, J. S. (2003). Does articulation contribute to modifications of postural control during dual-task paradigms? *Cognitive Brain Research*, *16*, 434–440.

Elliott, D., Hansen, S., Grierson, L. E. M., Lyons, J., Bennett, S. J., & Hayes, S. J. (2010). Goal-directed aiming: two components but multiple processes. *Psychological Bulletin*, *136*, 1023–44.

Fraizer, E. V, & Mitra, S. (2008). Methodological and interpretive issues in posture-cognition dual-tasking in upright stance. *Gait and Posture*, *27*, 271–279.

Freitas, S. M. S. F., & Duarte, M. (2012). Joint coordination in young and older adults during quiet stance: effect of visual feedback of the center of pressure. *Gait and Posture*, *35*, 83–87.

Goggin, N. L., & Meeuwsen, H. J. (1992). Age-related differences in the control of spatial aiming movements. *Research Quarterly for Exercise and Sport*, *63*, 366–372.

Halstead, G., Myklebust, J., & Myklebust, B. (1997). Changes in voluntary reaction time with age: implications for falls in the elderly. *Proceedings of the 19th International Conference of the IEEE Engineering in Medicine and Biology Socity*, 1683–1685.

Hatzitaki, V., & Konstadakos, S. (2007). Visuo-postural adaptation during the acquisition of a visually guided weight-shifting task: age-related differences in global and local dynamics. *Experimental Brain Research, 182*, 525–535.

Hernandez, M. E., Ashton-Miller, J. A, & Alexander, N. B. (2012). The effect of age, movement direction, and target size on the maximum speed of targeted COP movements in healthy women. *Human Movement Science*, *31*, 1213–1223.

Hewson, D., Singh, N., Snoussi, H., & Duchene, J. (2010). Classification of elderly as fallers and non-fallers using centre of pressure velocity. *Proceedings of the 32nd International Conference of the IEEE Engineering in Medicine and Biology Socity*, 3678–3681.

Huxhold, O., Li, S.-C., Schmiedek, F., & Lindenberger, U. (2006). Dual-tasking postural control: aging and the effects of cognitive demand in conjunction with focus of attention. *Brain Research Bulletin*, *69,* 294–305.

Lacour, M., Bernard-Demanze, L., & Dumitrescu, M. (2008). Posture control, aging, and attention resources: models and posture-analysis methods. *Clinical Neurophysiology*, *38*, 411–421.

Lin, S.-I., & Woollacott, M. H. (2002). Postural muscle responses following changing balance threats in young, stable older, and unstable older adults. *Journal of Motor Behavior, 34*, 37–44.

Lyons, J., Elliott, D., Swanson, L. R., & Chua, R. (1996). The use of vision in manual aiming by young and older adults. *Journal of Aging and Physical Activity, 4,* 165–178.

Maigne, J.Y. (2000) Cervicothoracic and thoracolumbar spinal pain syndromes. In Singer, K.P., Giles, L.G.F. (eds) Clinical anatomy and management of thoracic spine pain. *Oxford: Butterworth-Heinemann*, 157-168.

Mak, L., Yeh, T. T., Boulet, J., Cluff, T., & Balasubramaniam, R. (2011). Interaction between delayed visual feedback and secondary cognitive tasks on postural control in older adults. *Science & Motricité, 88*, 81–88.

Maki, B. E., & McIlroy, W. E. (1996). Influence of arousal and attention on the control of postural sway. *Journal of Vestibular Research:Equilibrium & Orientation*, *6*, 53–59.

Maki, B. E., Zecevic, A., Bateni, H., Kirshenbaum, N., & McIlroy, W. E. (2001). Cognitive demands of executing postural reactions: does aging impede attention switching? *Neuroreport*, *12,* 3583–3587.

Marsh, A. P., & Geel, S. E. (2000). The effect of age on the attentional demands of postural control. *Gait and Posture*, *12*, 105–113.

McDowd, J. M. (1997). Inhibition in attention and aging. *The Journals of Gerontology*, *52B*, 265–273.

Mitra, S. (2003). Postural costs of suprapostural task load. *Human Movement Science*, *22*, 253–270.

Mitra, S., & Fraizer, E. (2004). Effects of explicit sway-minimization on postural–suprapostural dual-task performance. *Human Movement Science, 23,* 1–20.

Murnaghan, C. D., Horslen, B. C., Inglis, J. T., & Carpenter, M. G. (2011). Exploratory behavior during stance persists with visual feedback. *Neuroscience, 195*, 54–59.

Pellecchia, G. L. (2003). Postural sway increases with attentional demands of concurrent cognitive task. *Gait and Posture, 18*, 29–34.

Prieto, T. E., Myklebust, J. B., Hoffmann, R. G., Lovett, E. G., & Myklebust, B. M. (1996). Measures of postural steadiness: differences between healthy young and elderly adults. *IEEE transactions on Biomedical Engineering, 43,* 956-966.

Prioli, A. C., Cardozo, A. S., de Freitas Júnior, P. B., & Barela, J. A. (2006). Task demand effects on postural control in older adults. *Human Movement Science, 25*, 435–46.

Redfern, M. S., Jennings, J. R., Martin, C., & Furman, J. M. (2001). Attention influences sensory integration for postural control in older adults. *Gait and Posture*, *14*, 211–216.

Redfern, M. S., Yardley, L., & Bronstein, A M. (2001). Visual influences on balance. *Journal of Anxiety Disorders*, *15*, 81–94.

Riley, M. A., Balasubramaniam, R., & Turvey, M. T. (1999). Recurrence quantification analysis of postural fluctuations. *Gait and Posture, 9*, 65–78.

Riley, M. A., Balasubramaniam, R., & Mitra, S. (1998). Visual influences on center of pressure dynamics in upright posture. *Ecological Psychology*, *10*, 65–91.

Riley, M. A., Mitra, S., Stoffregen, T., & Turvey, M. (1997). Influences of body lean and vision on unperturbed postural sway. *Motor Control,1,* 229–246.

Riley, M. A., Baker A. A., Schmit, J. M. (2003). Inverse relation between postural variability and difficulty of a concurrent short-term memory task. *Brain Research Bulletin*, *62*(3), 191–195.

Sayenko, D. G., Masani, K., Vette, A. H., Alekhina, M. I., Popovic, M. R., & Nakazawa, K. (2012). Effects of balance training with visual feedback during mechanically unperturbed standing on postural corrective responses. *Gait and Posture*, *35,* 339–344.

Shaffer, S. W., & Harrison, A. L. (2007). Aging of the somatosensory system: a translational perspective. *Physical Therapy, 87,* 193-207.

Shumway-Cook, A., Woollacott, M., Kerns, K. A., & Baldwin, M. (1997). The effects of two types of cognitive tasks on postural stability in older adults with and without a history of falls. *The Journals of Gerontology*, *52A*, M232–M240.

Siu, K.-C., & Woollacott, M. H. (2007). Attentional demands of postural control: the ability to selectively allocate information-processing resources. *Gait and Posture, 25,* 121–126.

Skinner, H, B., Barrack, R. L., & Cook, S. D. (1984) Age-related decline in proprioception. *Clinical Orthopaedics and Related Research, 184,* 208-211.

Stoffregen, T. A., Smart, L. J., Bardy, B. G., & Pagulayan, R. J. (1999). Postural stabilization of looking. *Journal of Experimental Psychology: Human Perception and Performance, 25,* 1641–1658.

Teasdale, N., Bard, C., Larue, J., & Fleury, M. (1993). On the cognitive penetrability of posture control. *Experimental Aging Research, 19,* 1–13.

Toledo, D. R., & Barela, J. A. (2010). Sensory and motor differences between young and older adults: somatosensory contribution to postural control. *Revista Brasileira Fisioterapia, 14,* 267–275.

Torres-Oviedo, G., Macpherson, J. M., & Ting, L. H. (2006). Muscle synergy organization is robust across a variety of postural perturbations. *Journal of Neurophysiology, 96,* 1530–1546.

Tousignant, M., Smeesters, C., Breton, A.M., Breton, É., & Corriveau, H. (2006). Criterion validity study of the cervical range of motion (CROM) device for rotational range of motion on healthy adults. *Journal of Orthopaedic and Sports Physical Therapy 36,* 242–248.

Vuillerme, N., Nougier, V., & Teasdale, N. (2000). Effects of a reaction time task on postural control in humans. *Neuroscience Letters, 291,* 77–80.

Wade, M. G., & Jones, G. (1997). The role of vision and spatial orientation in the maintenance of posture. *Physical Therapy, 77,* 619–628.

Weeks, D. L., Forget, R., Mouchnino, L., Gravel, D., & Bourbonnais, D. (2003). Interaction between attention demanding motor and cognitive tasks and static postural stability. *Gerontology*, *49*, 225–232.

Welsh, T. N., Higgins, L., & Elliott, D. (2007). Are there age-related differences in learning to optimize speed, accuracy, and energy expenditure? *Human Movement Science*, *26*, 892–912.

Woollacott, M. H. & Shumway-Cook, A. (1988) Development of posture and gait across the lifespan. *Columbia: University of South Carolina Press*, 155-225.

Yardley, L., Gardner, M., Leadbetter, A., & Lavie, N. (1999). Effect of articulatory and mental tasks on postural control. *Neuroreport*, *10*, 215–219.

Yeh, T. T., Boulet, J., Cluff, T., & Balasubramaniam, R. (2010). Contributions of delayed visual feedback and cognitive task load to postural dynamics. *Neuroscience Letters*, *481*, 173–177.

Yeh, T. T., Cluff, T., & Balasubramaniam, R. (revised and resubmitted). Increased reliance on visual feedback for balance control in older adults. *PLoS ONE*.

Yogev-Seligmann, G., Rotem-Galili, Y., Mirelman, A., Dickstein, R., Giladi, N., & Hausdorff, J. M. (2010). How does explicit prioritization alter walking during dual-task performance? Effects of age and sex on gait speed and variability. *Physical Therapy*, *9*, 1–7.

Chapter 6- General Discussion

6.1 –THESIS SUMMARY

The ability to stand, to walk and to perform daily activities in a safe manner depends on a complex interaction of the individual with the task and the environment. In addition, the ability to control the body’s position in space emerges from a complex interaction of musculoskeletal and higher level neural systems. An understanding of the components of the postural control system and age-related changes within the system is necessary. Developing a thorough understanding of knowledge in controlling balance for older adults is an urgent area in a growing aging society.

This thesis has examined the roles of visual feedback, cognitive processing and sensorimotor strategies in the control of unperturbed posture. The four studies presented in this thesis used a dual-task paradigm to investigate age-related changes in relation to the secondary task and context-dependent factors attributed to human postural control. Our postural task involved visuomotor tracking, which required participants to position a feedback cursor (representing their COP) in a fixed target. On some trials, participants performed a concurrent silent arithmetic task together with the postural task.

Broadly, we hypothesized that deterioration of peripheral sensorimotor systems, as well as reduced flexibility in central information processing, likely serve as co-mechanisms for the age-related difference in postural control. This hypothesis was examined in Chapters 2 and 3. Based on these experimental results we further examined task demand under different attentional focus instructions and age (Chapter 4). Lastly, we expanded our investigation to include different task demands to determine how the postural control system coordinates vision and proprioceptive feedback to accomplish different task goals under dual-task conditions (Chapter 5). The following sections provide a summary of each study and outline future research directions.

6.2-CONTRUBUTIONS OF DELAYED VISUAL FEEDBACK, COGNTIIVE LOAD AND AGE TO POSTURAL DYNAMICS

In Chapter 2 and 3, we imposed artificial delays on visual information in young (Chapter 2) and older adults (Chapter 3). We examined the relative contributions of visual feedback delay and cognitive task load on the low and high frequencies in postural dynamics. We implemented a two-timescale model for postural control, decomposing sway variability into distinct frequency components by low and high-pass filtered COP time series.

Chapter 2 examined the extent to which sway variability was influenced by the interplay between delayed visual feedback and cognitive task performance in an upright postural task in young adults. Specifically, we examined whether the magnitude of sway variability attributable to imposed visual delay and cognitive load influenced postural control independently. We found that sway variability computed from both low and high-pass filtered COP time series increased as a function of the visual delay. In contrast, a concurrent cognitive task only reduced the variability in the high-pass filtered COP time series. The results showed that our secondary cognitive task makes distinct contributions to postural dynamics (Yeh, Boulet, Cluff, & Balasubramaniam, 2010).

Chapter 3 extended the findings from Chapter 2 and examined age-related changes in postural dynamics during delayed visual feedback and under secondary cognitive load. The main finding of the study was that postural sway variability caused by delayed visual feedback was substantially larger for older adults than young adults. That said, while delayed visual feedback increased postural sway variability in both young and older adults, these increases were markedly larger for the older adults. This result provided direct evidence that older adults rely more on visual information to control their posture compared to the young ones.

Another notable finding was that delayed visual feedback increased the variability of low and high-frequency postural deviations in both age groups, corresponding to previous findings in Chapter 2. Furthermore, we found that simultaneous cognitive task performance had different effects on COP variability between the two age groups: the cognitive task improved postural performance (decrease COP sway variability of both unfiltered and high-pass filtered COP time series) in the group of young participants, but had no effect on task performance for the older adults.

Taken together, the findings from Chapter 3 supports and extends the idea that older adults rely more on visual information to guide and correct posture (Horak, Shupert, & Mirka, 1989; Pyykkö, Jäntti, & Aalto, 1990; Teasdale, Stelmach, Breunig, & Meeuwsen, 1991; Wade, Lindquist, Taylor, & Treat-Jacobson, 1995) – even when visual information about the task was delayed by as much as 900ms.

Collectively, we demonstrated that postural displacements are composed of two independent timescale components: a fast stochastic component and slow feedback control. We found that visual feedback delays resulted in increased sway variability compared to the veridical visual feedback about the COP position in both age groups. This was linked to increased variability in both the slow and fast component of postural sway. Our results also demonstrated that reduced sway variability in the dual-task cognitive condition in young adults is attributable to reduced amplitude in the fast component that defines moment-to-moment COP fluctuations.

Our interpretation of this finding is that delayed visual feedback may disrupt the relationship between the predicted consequences of postural corrections and feedback displayed during the task. Indeed, a number of modeling studies have suggested that sway variance during unperturbed standing arises from estimation errors about the body's orientation (Kiemel, Oie, & Jeka, 2002; van der Kooij & de Vlugt, 2007). These estimation processes are thought to use knowledge about the body's dynamics and descending motor commands to predict the state of the body, and combine these predictions with sensory feedback to form accurate body state estimates. We suggest that delayed visual feedback may create uncertainty about the task because it creates conflict between feedback and predictions about the state of the body.

Another important finding was that visual feedback delays destabilized posture to a greater extent in older than younger subjects. One possible explanation for this finding was that age-related declines in peripheral sensory function cause older adults to rely more on visual information during postural control. Indeed, it has been suggested that normal aging delays sensory reweighting processes, and causes postural instability when visual feedback is altered during postural control (Eikema, Hatzitaki, Konstantakos, & Papaxanthis, 2013). Moreover, a number of studies have shown that older adults have persistent increases in postural sway when they are exposed to visual motion stimuli, suggesting that older adults are unable to suppress unreliable visual cues (Jeka, Allison, & Kiemel, 2010; O’Connor, Loughlin, Redfern, & Sparto, 2008).

We found that fast postural deviations were reduced when young adults performed the secondary cognitive task. On the other hand, seemingly automatic motor tasks like standing balance may require additional cognitive resources in late adulthood due to generalized decreases in sensorimotor (Wade & Jones, 1997) and cognitive-attention functions (Lacour, Bernard-Demanze, & Dumitrescu, 2008; McDowd, 1997), therefore contributing to a trend to increase in postural sway variability when older adults maintain standing balance while they are engaged in secondary tasks.

Together, Chapter 2 and 3 provided convergent evidence on important features of age-related changes in postural control under delayed visual feedback and secondary task performance. First, young adults demonstrated that reduced postural sway variability in the dual-task condition is attributed to reduced amplitude in the high frequency time scales component of postural sway. Yet, older adults did not benefit from the secondary dual-task; the cognitive dual-task did not influence the moment-to-moment COP fluctuations. Second, our findings demonstrated the increased role of vision with age in postural control. Visual feedback delays destabilized posture to a greater extent in older, compared to younger subjects (Yeh, Cluff, & Balasubramaniam, Chapter 3).

There are some important caveats to note about the filtering method that we used to separate the fast and slow timescales in postural control. Following previous work by van den Heuvel et al. (2009), we used a frequency-based method to identify control mechanisms that underlie stance regulation. It would be useful to see the present results corroborated by employing other methods used to infer dual time-scale postural mechanisms such as the rambling/trembling decomposition (Zatsiorsky & Duarte, 2000), or dynamical systems analysis using higher dimensional embedding (Donker, Roerdink, Greven, & Beek, 2007). Our studies nevertheless provide groundwork that can guide future experiments to further explore a completely understanding of the roles of vision and secondary performance on postural dynamics.

6.3- SUPRAPOSTURAL TASK GOAL MODIFIES POSTRUAL CONTROL WITH ATTENTIONAL FOCUS

Chapter 4 determined whether directing focus of attention internally on postural control could be enhanced by performing a concurrent cognitive task (e.g., silent counting) in young and older adults. Our experiment was inspired by attentional focus research which demonstrated that an external focus of attention is beneficial for motor performance and learning, whereas an internal focus of attention degrades motor performance and inhibits motor learning (Wulf, McNevin, & Shea, 2001; Wulf & Prinz, 2001). In Chapters 2 and 3 we reported that a cognitive task reduced postural sway variability in the young adults. Our focus in Chapter 4 was to determine whether the cognitive task would improve postural control by devoting less attention internally. We expected that a cognitive dual-task would influence postural control in younger and older adults differently. Specifically, given the evidence of age-related declines in sensorimotor and cognitive-attention functions (Li & Lindenberger, 2002), we hypothesized that older adults would improve less than the younger ones in postural control while performing a cognitive dual-task in both focus of attention conditions.

We used an innovative experimental procedure to ascertain that participants were adhering to the specific instructional constraints under each condition. Our manipulation check showed that only young adults followed our experimental instructions. Older participants could not adhere to the instructions and seemed to rely on the visual cue to control posture even when they were asked to focus on their body movements. The finding that older people failed to adopt the internal focus of attention may suggest that age-related decline impaired attentional dynamics. It is possible that older adults experience impaired ability to inhibit and redirect attention allocated to distraction tasks (Maki, Zecevic, Bateni, Kirshenbaum, & McIlroy, 2001; McDowd, 1997; Siu, Lugade, & Chou, 2008a; Siu, Chou, Mayr, van Donkelaar, & Woollacott, 2009). It is also possible that age-related changes in peripheral sensory function cause older people to rely more on visual information during postural control (Eikema et al., 2013). The latter explanation supports our previous study suggesting that an increasing reliability in older adults on their visual system to maintain postural control (Chapter 3).

On the other hand, analyses of the sway variability in *young* adults showed an increased postural control under external focus condition, as well as under dual-task conditions. Therefore, the finding from young adults supported the “constrained action hypothesis” (Wulf & Prinz, 2001; Wulf et al., 2001) that an external focus of attention (focus on the movement effect) enhanced balance performance relative to an internal focus of attention (focus on the movement itself). Moreover, our finding provided further evidence to support the finding from previous work (Nafati & Vuillerme, 2011) that devoting less attention internally by performing a cognitive dual-task enhanced postural control in young adults.

According to the attentional focus literature (Wulf & Prinz, 2001; Wulf et al., 2001), an internal focus has been considered to compromise postural control by inducing a conscious type of control, causing an individual to constrain their motor system by interfering with the relatively automatic control process. Nevertheless, an imposed cognitive dual-task may be acting as an external focus which promotes an automatic mode of control in order to facilitate postural control. That is to say, when participants did the silent counting while focusing internally, some of the attention was allocated from the body movement to the counting task. By devoting less attention or little conscious control in the body movement, the postural system may utilize a reflexive control process during the cognitive dual-tasking. In order to achieve the dual-task goals, the participants should flexibly allocate attention between the postural and the silent counting task. Our finding indicated that younger participants have the ability to allocate their attention flexibly between focus of attention externally/internally and the silent counting task. This result is consistent with previous findings which showed that younger adults are able to flexibly update information in the dual-task paradigm that required them to switch attentional focus according to specific instructions (Mayr, & Liebscher, 2001; Siu & Woollacott, 2007).

Collectively, our results suggested that while there is consistent evidence showing the benefits of an external focus compared to an internal focus (McNevin &

Wulf, 2002; Wulf & Prinz, 2001), the relationship between focus of attention and its effect on postural control in *older* individuals requires further investigation. Although we could not draw conclusions about whether the internal focus of attention has a negative effect on postural control in older adults, our study demonstrated that these focus-related experiments are difficult to control, especially in older people. Future investigation may use manipulation checks in concert with participant self-ratings to ensure proper adherence to focus of attention instructions.

6.4- AGE-RELATED DECLINES IN SENSORIMOTOR STRATEGIES AND COGNITIVE DYNAMICS

Optimal sensorimotor integration is needed to maintain the precision of a visuomotor postural task (Balasubramaniam, Riley, & Turvey, 2000; Riley, Balasubramaniam & Turvey, 1999a). Furthermore, cognitive resources have been suggested to be involved in maintaining balance, especially in the older adults (Marsh & Geel, 2000). Chapter 4 showed that the control of standing balance was influenced by specific instructions or goal-directed behavior and this direction-specific minimization of sway variability affects only in the direction that met the task goal.

In Chapter 5, we asked whether older and younger adults differ in employing sensorimotor strategies in a dual-task situation. The experimental manipulations in

Chapter 5 provided specific task goals when we manipulated body orientations. We hypothesized that postural instability would be greater in older adults to those observed in the young persons. A secondary hypothesis was that the assembly of postural organization in mediolateral (ML) and anteroposterior (AP) sway variability would respond differently to precision demands under different body orientations in both age groups.

Our results revealed three important findings: (1) postural control decreased in older participants compared to the young ones in accomplishing the precision task, (2) young people were able to achieve the postural precision task when the precision task required minimizing sway fluctuations. Older people, however, did not show the same pattern. They were not able to maintain the precision when the task goal was to minimize sway, and (3) cognitive dual-task performance showed a robust facilitation effect on postural control in the young adults, but not for the older ones. Together, these results of this study supported the hypothesis that sensorimotor control and attention dynamics declined with aging.

Chapter 5 revealed two age-related alterations between young and older adults. First, compared to younger adults, older people showed decreased ability to coordinate posture in a visuomotor tracking task. Older adults may have difficulty to accomplish a visually-based postural tracking task which required integration of sensory feedback and motor response due to age-related sensorimotor and visuomotor deficits. Second, simultaneous execution of a cognitive task together with a postural precision task improved postural control in the younger, but not older adults. We suggest that the additional cognitive task shifted attention away from, and increased the automatic processing, of posture in the young adults. An impaired ability of the attention switching in older adults however, may adversely affect the execution under dual-task situations.

This study extended previous investigations in three ways. First, a functional body orientation positions (from 0° to 45°) were used to examine the effects on postural control in the older and younger population. Second, we provided a real-time visual feedback while standing, as opposed to simply ask participants to look at a fixed target (e.g., Balasubramaniam et al., 2000; Chen & Stoffregen, 2012). Lastly, we combined a secondary task during standing in order to expand our understanding of the role of attention during a visuomotor postural task.

Together, these results provided insight into age-related differences in sensorimotor strategies in a postural precision task, as well as in a cognitive dual-task. Age-related changes in postural control may degrade the flexible coordination of the sensory feedback and motor execution. Furthermore, diminished cognitive and attentional capacities may alter postural performance in dual-task conditions. We propose that deterioration of peripheral sensorimotor systems and reduced flexibility in central information processing are responsible for these age-related differences in postural control.

6.5- AGE-RELATED CHANGES UNDER DUAL-TASK SITUATIONS

We outlined four dual-task models/theories in the general introduction section. Several different theoretical perspectives have been proposed to explain the relationships between postural control and cognitive demand under dual-task situations. So far, there is no consensus on the model/theory that best explains the relationship between postural control and dual-tasking (Yogev-Seligmann, Hausdorff, & Giladi, 2008).

A consistent finding of the thesis was that in healthy young adults, postural control improves under dual-task conditions (Chapters 2-5). In contrast, postural control in older adults did not benefit from the cognitive task. Specifically, under dual-task conditions, older participants showed a trend toward decreased postural control under delayed visual feedback conditions (Chapter 3). However, in Chapter 5, another group of older adults showed a trend toward increased postural control under different body orientation conditions. Considering these mixed results together, we discussed the findings separately in young and older adults with the dual-task models/theories below. We also describe some methodological limitations in the thesis.

6.5.1 - Dual-tasking in healthy young adults

Our studies reproduced the phenomenon that postural sway variability decreased when a young person performs a secondary cognitive task (Andersson, Hagman, Talianzadeh, Svedberg, & Larsen, 2002; Dault, Frank, & Allard, 2001; Riley, Baker, & Schmit, 2003; Vuillerme, Nougier, & Teasdale, 2000).

Our findings from young adults contradict attention theories that assure a limited central capacity of cognitive resources (Kahneman, 1973). The *central resource capacity model* assumes that performing a task requires a given portion of this capacity. If two tasks performed simultaneously require more than the total capacity, the performance on one or both tasks will decline (Kahneman, 1973). In line with our finding, a number of studies have also provided little support for this model by showing the secondary task increased postural control under dual-task situations (Andersson et al., 2002; Dault, Yardley, & Frank, 2003; Riley et al., 2003).

The *inverted U-relationship model* described by Yerkes-Dodson law (1908) postulates that nature of the relationship is highly task-dependent. With simple tasks, the relationship between arousal and performance is a linear function, whereas with difficult tasks, the relationship becomes an inverted U-shaped function. Thus, under conditions of high arousal, people show a high level of performance in simple tasks, but with performance degraded in difficult tasks. In this thesis, silent counting as a secondary task did not interfere with the visual or somatosensory feedback for postural control. In addition, this task did not induce articulatory confounds on postural control (Yardley, Gardner, Leadbetter, & Lavie, 1999). In our view, this cognitive task may provide an optimal level of arousal which promotes postural control by shifting the focus of overt attention away from the postural task (Huxhold, Li, Schmiedek, & Lindenberger, 2006; McNevin & Wulf, 2002; Riley, Stoffregen, Grocki, & Turvey, 1999b). This explanation is consonant with the constrained action hypothesis (Wulf et al., 2001) that focusing attention externally enables the postural control system to self-organize automatically. In this thesis, however, we could not determine how much cognitive load was actually added to the cognitive process in each participant due to the lack of individually tailored secondary tasks (Simoneau, Billot, Martin, Perennou, & Van Hoecke, 2008). It may be that some people are good at math, so the task load was relatively low compared to others. However, we assumed that the silent counting, which required single digit addition or subtraction, needed relatively low cognitive demand in young adults. The average error rate for the cognitive performance in all four experiments was about 13%; this may imply that the cognitive load provided a relatively low cognitive load in young participants. Thus, the low cognitive demands increased the arousal level in a way that produced optimal postural regulation. Considering this, future studies may use individually-tailored secondary tasks to determine each participant's math ability in order to accurately identify the level of difficulty of the cognitive task. Also, future investigations can extend current knowledge and manipulate the difficulty of the cognitive task to further test the inverted U-relationship model.

Stoffregen et al. (1999) proposed a *postural facilitation viewpoint* which suggested that performance of a postural task with a suprapostural task may increase or decrease postural control depending on the relationship between the two tasks. Postural stability may be increased if the task requires head stabilization or gaze control, and vice versa. Our finding showed that a cognitive task increased postural control, which contradicted the facilitation viewpoint. Stoffregen et al. (2007) suggested that postural control was facilitated during the performance of a visually demanding task (a signal-detection task), but not a task without precise control of the oculomotor system (mental arithmetic task). In contrast to their finding, our results showed enhanced postural control with the mental arithmetic task (Chapters 2-5). Even though we used different postural tasks for each study, they were all visuomotor tracking tasks in general. We demonstrated that silent counting had an additional effect to enhance postural control under dual-task conditions. Thus, we suggested that postural changes with the demand of a suprapostural task can be facilitated with a mental arithmetic task. Our interpretation is that, the role of the postural system is to minimize sway to the extent that it facilitates concurrent task performance. When performing cognitive tasks one could make the case that posture control is more likely relegated to low-level subsystems that are governed by reflexive and compensatory mechanisms (Torres-Oviedo, Macpherson, & Ting, 2006).

Lastly, the *task prioritization model* suggests that older people prioritize posture over concurrent cognitive tasks, while young adults prioritize secondary tasks under dual-task situations (Shumway-Cook, Woollacott, Kerns, & Baldwin, 1997). Our results showed that young adults maintained optimal cognitive performance under dual-tasking situations. This finding suggests that performance on a secondary task may take priority in situations where postural control is relatively easy to maintain or is less likely to evoke the risk of falling. When the cognitive attention is necessary, it might be that attention shifts to the cognitive task where postural control would be delegated to highly automatic processes and thus decreased sway variability. Vuillerme & Nafati (2007) suggested that directing attention to postural control discouraged the use of automatic control process and hampered the efficiency for controlling posture. Together, these results thus provided support for the “constrained action hypothesis” (e.g., McNevin, Shea, & Wulf, 2003; Wulf & Prinz, 2001) that accounts for detrimental effect associated with an attentional focus directed towards the body movements themselves.

In addition, the co-contraction strategy has been proposed to explain reduced sway variability. Specifically, when cognitive attention was required, a postural control strategy can be invoked in which joints are “stiffened” by the surrounding musculature to restrain postural sway (Dault et al., 2001; Ehrenfried, Guerraz, Thilo, Yardley, & Gresty, 2003; Weeks, Forget, Mouchnino, Gravel, & Bourbonnais, 2003). This muscle co-contraction strategy can reduce cognitive load on postural control since the independent commands produced for controlling each joint would be reduced. Therefore, the co-contraction strategy requires less attentional capacity for postural control. Unfortunately, our studies did not measure muscle activities from lower limb agonist and antagonist muscles to assess this hypothesis. Nevertheless, in

Chapters 2 and 3, our results demonstrated that reduced sway variability in the dual-task conditions is attributable to reduced amplitude in the *fast* component of COP time series. Ankle joint stiffness is reflected by increased frequency, reduced amplitude of COP excursions (Winter, Patla, & Prince, 1998). This is consistent with our data and it is possible that postural sway variability decreased due to an increased activity of ankle musculature in dual-task situations. This plausible mechanism needs to be corroborated in future studies using electromyography or biomechanical analyses of the ankle joint.

Collectively, we suggested that healthy young subjects with good postural reserve (i.e., balance control) and hazard estimation (i.e., self-awareness) toward the environment and the situation may prioritize the cognitive tasks as long as the postural threat is relatively low.

6.5.2 - Dual-tasking in healthy older adults

Compared to young adults, who showed a consistent postural control enhancement with a cognitive task, older adults exhibited no significant changes in postural control while dual-tasking. However, the cognitive performance degraded when older people performed under dual-task situations. It is likely that the “posture first” principle was used in our healthy older adults by which they reallocated attentional resources to the postural stability at the expense of the cognitive performance. This result supported previous studies that, compared to younger people, older people tended to prioritize postural control over cognitive performance under dual-task situations (Berger & Bernard-Demanze, 2011; Brauer, Woollacott, & Shumway-Cook, 2002; Shumway-Cook, Brauer, & Woollacott, 2000). Maintaining an optimal postural control could be a preferential strategy developed by the older adults when performing both the postural and the cognitive tasks. Therefore, an unconscious “posture first” strategy could be a key to avoid hazards and reduce risk of falls in healthy older persons.

Age-related deterioration in postural control has been attributed to decreases in sensory or motor system function. However, parallel research in the area of cognition suggested that attentional allocation deficits may be other intrinsic factor (Lajoie, Teasdale, & Bard, 1993; Siu, Chou, Mayr, van Donkelaar, & Woollacott, 2008b). For example, in Chapter 4, the finding that older people failed to adopt the internal focus of attention may suggest that age-related decline impaired attentional dynamics. It is possible that older adults experience impaired ability to inhibit and redirect attention allocated to distraction tasks (Maki et al., 2001; McDowd, 1997; Siu et al., 2008a; Siu et l., 2009). It is also possible that age-related changes in peripheral sensory function cause older people to rely more on visual information during postural control (Eikema et al., 2013). Over-reliance on visual information in older adults when the visual feedback was delayed was also demonstrated in Chapter 3. The ability to switch attention flexibly was predictive of the ability to adhere to instructional set. Older adults appeared to exhibit vulnerability toward a reduced ability to switch attention between postural control and a secondary cognitive task. Attentional allocation ability might degrade with aging. Given that age-related declines exist in many areas such as cognitive and sensorimotor functioning, the relation between postural control and attentional focus in older people is complex. Our results supported the hypothesis that healthy older adults have a reduction of ability to flexibly allocate attention between two tasks compared to the young adults.

In sum, our finding suggested that healthy aging may contribute to decrements in flexible allocation of attention. Therefore, postural instability may not due to balance deficits in isolation, but the inability to effectively allocate attention under dual-task conditions.

6.6- CONCLUDING REMARKS

According to Horak’s six-resource framework (2006), older people tend to increase the risk of fall because of specific, unique constrains on their postural control system.

Among the six resources for controlling posture, this thesis primarily focused on the influence of attention, sensory and motor strategies on postural control. Taken all four studies together, this thesis sheds light on three age-related declines. We also provide knowledge about the role of attention, sensory reweighting and movement strategies with aging and postural control in Horak's framework (Fig. 6.1).

1) Older people have reduced ability to allocate attention in dual-task situations (Chapters 3, 4 and 5).
2) Older people increase sensory weight to vision (Chapters 3 and 4).
3) Older people have less ability to coordinate sensorimotor strategies to maintain postural control (Chapter 5).

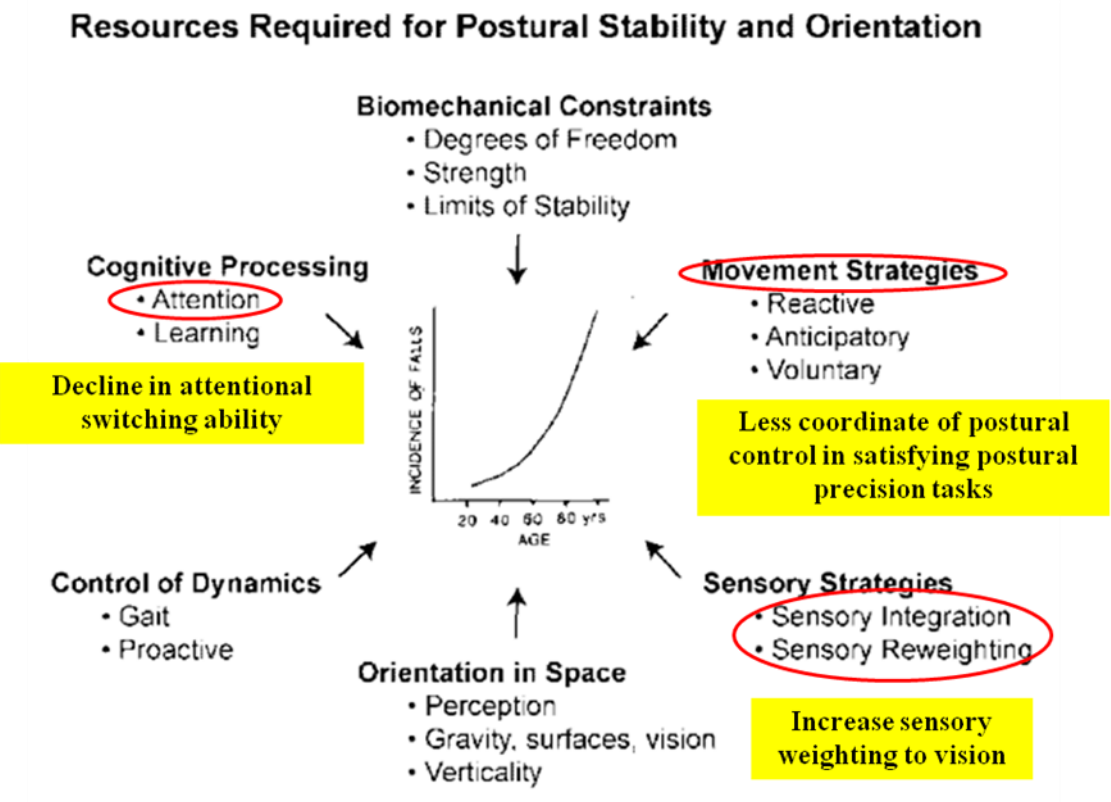

Figure 6.1 Schematic representation of the six resources of postural control on the incidence of falls in the elderly. The three highlighted points are summarized from the thesis which provide novel insights to age-related declines (adapted from Horak, 2006).

In summary, the thesis adds to current understanding of the role of sensorimotor processing, attentional influence and age in the control of posture. We have provided an innovative approach for the investigation of timescale mechanisms for postural control. We have also demonstrated the increased role of visual feedback in postural control in older adults. In addition, this thesis provides new insight to the age-related difference under dual-task performance. Lastly, we have provided evidence of deterioration of peripheral sensorimotor systems and reduced flexibility in central information processing are responsible for the age-related differences. These findings encourage future work to investigate whether these age-related declines could be reversed by dual-task balance training.

6.7-REFERENCES

Andersson, G., Hagman, J., Talianzadeh, R., Svedberg, A., & Larsen, H. C. (2002). Effect of cognitive load on postural control. *Brain Research Bulletin*, *58*, 135–139.

Balasubramaniam, R., Riley, M. A, & Turvey, M. T. (2000). Specificity of postural sway to the demands of a precision task. *Gait and Posture*, *11*, 12–24.

Berger, L., & Bernard-Demanze, L. (2011). Age-related effects of a memorizing spatial task in the adults and elderly postural control. *Gait and Posture*, *33*, 300–302.

Brauer, S. G., Woollacott, M., & Shumway-Cook, A. (2002). The influence of a concurrent cognitive task on the compensatory stepping response to a perturbation in balance-impaired and healthy elders. *Gait and Posture*, *15*, 83–93.

Chen, F.-C., & Stoffregen, T. A. (2012). Specificity of postural sway to the demands of a precision task at sea. *Journal of Experimental Psychology. Applied*, *18*, 203–212.

Dault, M. C., Frank, J. S., & Allard, F. (2001). Influence of a visuo-spatial, verbal and central executive working memory task on postural control. *Gait and Posture*, *14*, 110–116.

Dault, M. C., Yardley, L., & Frank, J. S. (2003). Does articulation contribute to modifications of postural control during dual-task paradigms? *Cognitive Brain Research*, *16*, 434–440.

Donker, S. F., Roerdink, M., Greven, A. J., & Beek, P. J. (2007). Regularity of center-of-pressure trajectories depends on the amount of attention invested in postural control. *Experimental Brain Research*, *181*, 1–11.

Ehrenfried, T., Guerraz, M., Thilo, K. V, Yardley, L., & Gresty, M. A. (2003). Posture and mental task performance when viewing a moving visual field. *Cognitive Brain Research*, *17*, 140–153.

Eikema, D. J. A, Hatzitaki, V., Konstantakos, V., & Papaxanthis, C. (2013). Elderly adults delay proprioceptive reweighting during the anticipation of collision avoidance when standing. *Neuroscience*, *234*, 22–30.

Horak, F B, Shupert, C. L., & Mirka, A. (1989). Components of postural dyscontrol in the elderly: a review. *Neurobiology of Aging*, *10*, 727–38.

Horak, F. B. (2006). Postural orientation and equilibrium: what do we need to know about neural control of balance to prevent falls? *Age and Ageing*, *35*, ii7–ii11.

Huxhold, O., Li, S.-C., Schmiedek, F., & Lindenberger, U. (2006). Dual-tasking postural control: aging and the effects of cognitive demand in conjunction with focus of attention. *Brain Research Bulletin*, *69*, 294–305.

Jeka, J. J., Allison, L. K., & Kiemel, T. (2010). The dynamics of visual reweighting in healthy and fall-prone older adults. *Journal of Motor Behavior*, *42*, 197–208.

Kahneman, D. (1973) Attention and effort, Englewood Cliffs, NJ: Prentice Hall

Kiemel, T., Oie, K. S., & Jeka, J. J. (2002). Multisensory fusion and the stochastic structure of postural sway. *Biological Cybernetics*, *87*, 262–277.

Lacour, M., Bernard-Demanze, L., & Dumitrescu, M. (2008). Posture control, aging, and attention resources: models and posture-analysis methods. *Clinical Neurophysiology*, *38*, 411–421.

Lajoie, Y., Teasdale, N., & Bard, C. (1993). Attentional demands for static and dynamic equilibrium. *Experimental Brain Research*, 97, 139–144.

Li, K. Z. H., & Lindenberger, U. (2002). Relations between aging sensory/sensorimotor and cognitive functions. *Neuroscience and Biobehavioral Reviews*, *26*, 777–783.

Maki, B. E., Zecevic, A, Bateni, H., Kirshenbaum, N., & McIlroy, W. E. (2001). Cognitive demands of executing postural reactions: does aging impede attention switching? *Neuroreport*, *12*, 3583–3587.

Marsh, A. P., & Geel, S. E. (2000). The effect of age on the attentional demands of postural control. *Gait and Posture*, *12*, 105–113.

Mayr, U., & Liebscher, T. (2001). Age differences in the selection of mental sets: the role of inhibition, stimulus ambiguity, and response-set overlap. *Psychology and Aging*, *13*, 47-69.

McDowd, J. M. (1997). Inhibition in attention and aging. *The Journals of Gerontology* , *52B*, 265–273.

McNevin, N. H., Shea, C. H., & Wulf, G. (2003). Increasing the distance of an external focus of attention enhances learning. *Psychological Research*, *67*, 22–29.

McNevin, N. H., & Wulf, G. (2002). Attentional focus on supra-postural tasks affects postural control. *Human Movement Science*, *21*, 187–202.

Nafati, G., & Vuillerme, N. (2011). Decreasing internal focus of attention improves postural control during quiet standing in young healthy adults. *Research Quarterly forEexercise and Sport, 82,* 634–643.

O’Connor, K. W., Loughlin, P. J., Redfern, M. S., & Sparto, P. J. (2008). Postural adaptations to repeated optic flow stimulation in older adults. *Gait and Posture, 28,* 385–391.

Pyykkö, I., Jäntti, P., & Aalto, H. (1990). Postural control in elderly subjects. *Age and Ageing*, *19*, 215–221.

Riley, M. A., Balasubramaniam, R., & Turvey, M. T. (1999a). Recurrence quantification analysis of postural fluctuations. *Gait and Posture*, *9*, 65–78.

Riley, M. A., Stoffregen, T., Grocki, M., & Turvey, M. T. (1999b). Postural stabilization for the control of touching. *Human Movement Science, 18*, 795–817.

Riley, M. A., Baker A. A., & Schmit, J. M. (2003). Inverse relation between postural variability and difficulty of a concurrent short-term memory task. *Brain Research Bulletin*, *62*, 191–195.

Shumway-Cook, A., Brauer, S., & Woollacott, M. (2000). Predicting the probability for falls in community-dwelling older adults using the Timed Up & Go Test. *Physical Therapy*, *80*, 896–903.

Shumway-Cook, A., Woollacott, M., Kerns, K. A., & Baldwin, M. (1997). The effects of two types of cognitive tasks on postural stability in older adults with and without a history of falls. *The Journals of Gerontology*. *Series A*, *52*, M232–M240.

Simoneau, E. M., Billot, M., Martin, A., Perennou, D., & Van Hoecke, J. (2008). Difficult memory task during postural tasks of various difficulties in young and older people: a pilot study. *Clinical Neurophysiology*, *119*, 1158–65.

Siu, K.-C., Lugade, V., & Chou, L.-S. (2008a). Dual-task interference during obstacle clearance in healthy and balance-impaired older adults. *Aging Clinical and Experimental Research*, *20*, 349–354.

Siu, K.-C., Chou, L.-S., Mayr, U., van Donkelaar, P., & Woollacott, M. H. (2008b). Does inability to allocate attention contribute to balance constraints during gait in older adults? *The Journals of Gerontology*, *63A*, 1364–1369.

Siu, K.-C., Chou, L.-S., Mayr, U., van Donkelaar, P., & Woollacott, M. H. (2009). Attentional mechanisms contributing to balance constraints during gait: the effects of balance impairments. *Brain Rresearch, 1248,* 59–67.

Siu, K.-C., & Woollacott, M. H. (2007). Attentional demands of postural control: the ability to selectively allocate information-processing resources. *Gait and Posture, 25*, 121–126.

Stoffregen, T. A, Hove, P., Bardy, B. G., Riley, M., & Bonnet, C. T. (2007). Postural stabilization of perceptual but not cognitive performance. *Journal of Motor Behavior, 39*, 126–138.

Stoffregen, T. A., Smart, L. J., Bardy, B. G., & Pagulayan, R. J. (1999). Postural stabilization of looking. *Journal of Experimental Psychology: Human Perception and Performance*, *25*, 1641–1658.

Teasdale, N., Stelmach, G. E., Breunig, A., & Meeuwsen, H. J. (1991). Age differences in visual sensory integration. *Experimental Brain Research*, *85*, 691–696.

Torres-Oviedo, G., Macpherson, J. M., & Ting, L. H. (2006). Muscle synergy organization is robust across a variety of postural perturbations. *Journal of Neurophysiology, 96,* 1530–1546.

van den Heuvel, M. R. C., Balasubramaniam, R., Daffertshofer, A., Longtin, A., & Beek, P. J. (2009). Delayed visual feedback reveals distinct time scales in balance control. *Neuroscience Letters*, *452*, 37–41.

van der Kooij, H., & de Vlugt, E. (2007). Postural responses evoked by platform pertubations are dominated by continuous feedback. *Journal of Neurophysiology, 2*, 730–743.

Vuillerme, N., Nougier, V., & Teasdale, N. (2000). Effects of a reaction time task on postural control in humans. *Neuroscience Letters, 291*, 77–80.

Vuillerme, N., & Nafati, G. (2007). How attentional focus on body sway affects postural control during quiet standing. *Psychological research*, *71*, 192–200.

Wade, M. G., & Jones, G. (1997). The role of vision and spatial orientation in the maintenance of posture. *Physical Therapy*, *77,* 619–628.

Wade, M. G., Lindquist, R., Taylor, J. R., & Treat-Jacobson, D. (1995). Optical flow spatial orientation and the control of posture in the elderly. *The Journals of Gerontology, 50B*, P51–58.

Weeks, D. L., Forget, R., Mouchnino, L., Gravel, D., & Bourbonnais, D. (2003). Interaction between attention demanding motor and cognitive tasks and static postural stability. *Gerontology*, *49*, 225–232.

Winter, D., Patla, A., & Prince, F. (1998). Stiffness control of balance in quiet standing. *Journal of Neurophysiology*, *80*, 1211–1221.

Wulf, G, & Prinz, W. (2001a). Directing attention to movement effects enhances learning: a review. *Psychonomic Bulletin & Review*, *8*, 648–660.

Wulf, G., Mcnevin, N., & Shea, C. H. (2001b). The automaticity of complex motor skill learning as a function of attentional focus. *The Quarterly Journal of Experimental Psychology, 54A*, 1143–1154.

Yardley, L., Gardner, M., Leadbetter, A, & Lavie, N. (1999). Effect of articulatory and mental tasks on postural control. *Neuroreport*, *10*, 215–219.

Yeh, T. T., Boulet, J., Cluff, T., & Balasubramaniam, R. (2010). Contributions of delayed visual feedback and cognitive task load to postural dynamics. *Neuroscience Letters*, *481*, 173–177.

Yeh, T. T., Cluff, T., & Balasubramaniam, R. (revised and resubmitted). Increased reliance on visual feedback for balance control in older adults. *PLoS ONE*.

Yerkes, R., & Dodson, J. (1908). The relation of strength of stimulus to rapidity of habit-formation. *Journal of Comparative Neurology and Psychology, 18*, 459–482.

Yogev-Seligmann, G., Hausdorff, J. M., & Giladi, N. (2008). The role of executive function and attention in gait. *Movement Disorders, 23*, 329–342.

Zatsiorsky, V. M., & Duarte, M. (2000). Rambling and trembling in quiet standing. *Motor Control, 4*, 185–200.