

**UNDERSTANDING THE HEMODYNAMIC RESPONSE AND SENSORY
CONTRIBUTIONS TO AUTOMATIC POSTURAL CONTROL**

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ABSTRACT

The postural control-cognition dual-task literature has demonstrated greater postural stability through the examination of multiple kinetic and kinematic measures. Recently, sample entropy (SampEn) and wavelet discrete transform have supported the claim of automaticity, as higher SampEn values and a shift toward higher contribution from automatic sensory systems have been demonstrated in dual-task settings. In order to understand the cortical component of postural control, functional near-infrared spectroscopy (fNIRS) has been used to identify cortical activation under postural control conditions. However, the neural correlates of automatic postural behaviour have yet to be fully investigated. Therefore, the purpose of this study is to confirm the presence of automatic postural control through static and dynamic measurements, and to investigate the prefrontal cortex activation (PFC) when concurrently performing quiet standing and auditory cognitive tasks. Eighteen healthy young adults ($21,4 \pm 3,96$ yo), 12 females and 6 males, with no balance deficits were recruited. Participants were instructed to either quietly stand on a force platform (SM), perform three cognitive tasks while seated (SC) and perform a combination of SM and SC concurrently (DT). Results revealed automatic postural control as evidenced by lower area and standard deviation of center-of-pressure in DT conditions. As for SampEn and the wavelet analysis, greater values and a shift from vision to the cerebellum contribution were demonstrated in DT conditions. For the DNS task, a trend toward significantly lower right hemisphere PFC activation compared to left hemisphere activation in DT was evidenced, which potentially reiterate the presence of automaticity. Therefore, as demonstrated by this experiment, the simultaneous performance of a difficult cognitive task and posture yields automatic postural behaviour, and provides insight into the neural correlates of automaticity.

Keywords: Automatic postural control, functional Near-Infrared Spectroscopy, Wavelet discrete transform, Sample entropy, Dual-task

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LIST OF ABBREVIATIONS

ANOVA	Analysis of variance
AP	Anterior-posterior
AREA	Area of 95% confidence ellipse
CNS	Central nervous system
COG	Center of gravity
COP	Center of pressure
DNS	Double-number sequence
DT	Dual-task
fMRI	functional Magnetic resonance imaging
fNIRS	functional Near-infrared spectroscopy
HbO ₂	Oxygenated hemoglobin
HbR	Deoxygenated hemoglobin
ML	Medial-lateral
PFC	Prefrontal cortex
SampEn	Sample entropy
SC	Single cognitive
SD	Standard deviation
SM	Single motor
SRT	Simple reaction time
WM	Working memory

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CHAPTER ONE: INTRODUCTION

1.1 Introduction

Posture, which is mediated by the visual, vestibular and proprioceptive systems, has long been identified as attentionally demanding in young adults (Kerr, Condon & McDonald, 1985; Lajoie, Teasdale, Bard & Fleury, 1993). Woollacott and colleagues (2002) as well as Wulf *et al.* (2001) have demonstrated the presence of automatic motor control processes, when attention is withdrawn from the maintenance of balance, and directed towards a secondary task. These findings led to the development of the “constrained action hypothesis”, which suggests that an external focus promotes an automatic mode of control by using unconscious, fast, and reflexive motor control processes (Wulf, 2013). Therefore, consciously controlling postural stability constrains the motor system by interfering with the automatic motor control processes tasked with regulating said movement (Wulf, McNevin & Shea, 2001). An automatic mode of postural control can be achieved by the simultaneous execution of a secondary task, which withdraws attention from consciously attending posture, and is commonly known as a dual-task paradigm.

One of the assumptions underlying a dual-task paradigm (i.e. two tasks executed concurrently) is that performance on one or both tasks will decline when one’s resource capacity is exceeded (Woollacott & Shumway-Cook, 2002). However, when applied to the postural control-cognition domain, the paradigm fails to explain why improvements in balance during dual-task performance, with no decrements in cognitive performances, are observed compared to postural stability only (Woollacott & Shumway-Cook, 2002). A common explanation based on the “constrained action hypothesis” is that the secondary task withdraws attention from postural stability, thus promoting a more automatic mode of control. The presence of automatic postural control has been indexed using static measures of center of pressure (COP) (e.g. area of 95%

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confidence ellipse and standard deviation of COP) (Richer, Saunders, Polskaia & Lajoie, 2017).

Wulf *et al.* (2001) have showed that directing our attention on an external source when quietly standing improves our balance, underlying some automatic motor control processes. Moreover, dual-task paradigm has also lent support to the presence of automaticity of postural control.

Recently, unpublished data from our laboratory, using a wavelet frequency analysis on COP data, has revealed that when a shift from conscious to automatic control takes place during dual-task performance, there is a corresponding change in the contribution from the sensory systems (Richer & Lajoie, under review). When healthy young adults were quietly standing and simultaneously performing a cognitive task, results demonstrated a significant decrease contribution from the ultra-low band (i.e. vision), in conjunction with a significant increase contribution from the low and very low bands, which have been suggested to represent vestibular and cerebellar contributions, respectively (Quek *et al.*, 2014; Richer & Lajoie, under review).

Furthermore, the cerebellum and the vestibular system are perceived as automatic systems (Lang & Bastian, 2002; Cullen *et al.*, 2011), which supports the claim that a difficult concurrent cognitive task promotes automatic postural behaviour. Ultimately, the kinematics and kinaesthesia of postural control have been tremendously researched in the last decades, and are now well established.

Contrarily, the neural correlates of automaticity, specific to postural control, have yet to be fully investigated, as a result of the constraints imposed by commonly used neuroimaging techniques (e.g. fMRI). Poldrack and colleagues (2005) as well as Wu *et al.* (2004), through fMRI studies of sequential tapping, have demonstrated that once automaticity of a task is achieved, cortical activation decreases suggesting that the brain regions of interest work more efficiently. However, this idea of automaticity has been derived from fMRI studies, and has yet to

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be established in studies investigating cortical activation of gross motor tasks. Functional near-infrared spectroscopy (fNIRS) enables the examination of brain activity related to postural control tasks (Perrey, 2008). In relation to the field of postural control, studies using fNIRS have predominantly examined brain activation of participants walking in DT settings. Contrary to fMRI studies, increases in brain activation have been demonstrated when participants were walking and performing secondary tasks (Mirelman *et al.*, 2014; Wittenberg, Thompson, Nam & Franz, 2017; McKendrick, Mehta, Ayaz, Scheldrup & Parasuraman, 2017). However, and although some researches were not designed to investigate automaticity, authors have identified decreased brain activation when participants were quietly standing and simultaneously performing backward counting (Mirelman *et al.*, 2014), and reduced total prefrontal cortex activation, with no decrements to postural control, when concurrently performing dynamic posturography and a choice reaction time task (Rosso *et al.*, 2017). As evident with the results previously presented, no consensus with regard to the neural correlates of automaticity has been reached considering the literature presents inconsistent results.

Therefore, the purpose of the present study is to reiterate the presence of automatic postural control, through the examination of kinematics and kinesthesia measurements, when healthy young adults perform difficult cognitive tasks while standing, but also to support the idea of automaticity with the examination of cortical activation. Consequently, the purpose is threefold. The first objective is to confirm that, in healthy young adults, performing a cognitive task while standing promotes an automatic mode of postural control, through the examination of standard deviation of center-of-pressure (COP) and area. The second objective is to support, with the use of dynamic measurements such as sample entropy (SampEn) and wavelet discrete transform, the presence of automatic postural control when balance is concurrently performed with cognitive tasks. Lastly, the third objective is to determine if there is a corresponding change in cortical

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activation (i.e. HbO₂) when the contribution from the sensory systems changes during the shift from conscious to automatic postural control, which would provide further evidence for the presence of automatic postural control in healthy young adults when performing a difficult concurrent cognitive task.

1.2 Hypotheses

Based on Polskaia and Lajoie (2016) in addition to Potvin-Desrochers and colleagues (2017) findings, it is hypothesized that posture will improve under difficult dual-task (DT) conditions (i.e. decreased area and SD COP) compared to the sole execution of quiet standing (i.e. SM). Secondly, based on Potvin-Desrochers et al. (2017) results, it is hypothesized that SampEn will be significantly higher in difficult DT conditions compared to SM, thus indicating an automatic mode of postural control. It is also hypothesized that based on the aforementioned unpublished research (Richer & Lajoie, under review), there will be an increase contribution of the moderate and low bands, which allegedly and indirectly represent contributions from the vestibular system and the cerebellum respectively, in conjunction with a decrease contribution from the ultra-low band, representing contribution from the vision for the difficult DT conditions compared to SM. Lastly, based on fMRI studies examining automaticity in motor skill learning and on Rosso *et al.* (2017) findings, it is hypothesized that during the DT conditions, PFC activation (i.e. HbO₂) will decrease compared to SM.

CHAPTER TWO: LITERATURE REVIEW

2.1. *Postural control*

Posture is described as the orientation of any body segment relative to the gravitational vector, whereas balance is a generic term often used when describing the dynamics of body posture to prevent falling (Winter, 1995). More frequently used in mechanics, balance, or equilibrium, is defined as a resultant load of forces, acting upon an object, equal to zero (Pollock, Durward & Rowe, 1998). However, when it comes to postural control in humans, different definitions have been proposed. Horak (1987) describes postural control as the ability to maintain equilibrium in a gravitational field by keeping or returning the center of body mass over its base of support. Pollock and colleagues (1998) defined postural control as the act of maintaining, achieving or restoring a state of balance during any posture or activity. Nevertheless, given that humans are bipeds, and that two-thirds of their body mass is located two-thirds of their body height (Winter, 1995), we are constantly in an unstable equilibrium. One of the main functions of posture is to counteract the effect of gravity, often called a mechanical antigravity function, by maintaining the center of gravity (COG) projection inside the supporting surface (Massion, 1994). The second main function of posture is to serve as a reference frame for perception and action, more specifically the position and orientation of body segments to organize movements towards targets and their location in the external world (Mansion, 1994).

Regulation of balance and posture is dictated by three major sensory systems (i.e. vision, somatosensory and vestibular). Vision is primarily involved in planning our locomotion and in avoiding obstacles (Winter, 1995). Moreover, in conjunction with the somatosensory system (i.e. proprioceptive, cutaneous, and joint), it also provides information concerning the orientation of the body and head in relation to surfaces and objects within the external environment (Nashner, 1982). The somatosensory system is a multitude of sensors that sense the position and velocity of

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all body segments, as well as their contact with external objects, and the orientation of gravity (Winter, 1995). Finally, the vestibular system senses linear and angular accelerations (Winter, 1995), in addition to providing direct inputs to postural muscles (Nashner, 1982), and is often used to resolve conflict (Shumway-Cook & Horak, 1986). Since humans have three sensory systems regulating balance, redundancy can be present in certain instances. However, Nashner (1982) demonstrated that adjustment latencies were significantly longer when standing on a continuously tilting platform compared to a fixed support surface. It was suggested that somatosensory inputs derived from contact with a fixed surface were especially important in generating automatic postural adjustments (Nashner, 1982). Therefore, despite the availability of multiple sensory inputs, the postural information provided by the somatosensory system appears to have more weight towards the central nervous system (CNS) in healthy adults (Shumway-Cook & Horak, 1986).

To understand how the CNS modulates posture, inverted pendulum models are often used to explore human movements, and characterize postural control. When feet are positioned side-by-side, our body tends to sway in the anterior-posterior (AP) and medial-lateral (ML) planes like an inverted pendulum (Winter, 1995). In order to stay in between the margins of the base of support (BOS) once perturbed, three strategies (i.e. ankle strategy, hip strategy and stepping strategy) are used depending on the configuration of the BOS and on the size of the perturbation (Horak, 1987; Winter, 1995).

2.2. *Attentional demands of postural control*

Postural control was initially considered an automatic process requiring minimal attention (Lajoie, Teasdale, Bard & Fleury, 1993; Siu & Woollacott, 2007). However, upright standing necessitates the integration of several sources of sensory information, and has been recognized as

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attentionally demanding (Paillard, 1988; Kerr, Condon & McDonald, 1985; Lajoie, Teasdale, Bard & Fleury, 1993). Lajoie and colleagues (1993) have demonstrated increasing attentional demands with increasing balance requirements. Moreover, Kerr *et al.* (1985) have postulated that cognitive spatial processing and the maintenance of balance share similar neural mechanisms (Kerr *et al.*, 1985). In parallel with these evidences, dual-task methodologies have been used in the literature to investigate the attentional demands of multiple postural tasks. Nevertheless, contradictory results have been found with regard to the postural control-cognition domain, and their dual-task interaction. The assumptions underlying a dual-task paradigm are that attention is somewhat limited, and that if two concurrent tasks exceed total resource capacity, the performance on one or both tasks will diminish (Kahneman, 1973). Attention has been defined as a brain function that allocates cognitive processing resources to focus on information or stimuli (Styles, 2006). With regard to a dual-task paradigm, it refers more specifically to the concept of divided attention, which is the ability to process more than one response to different demands simultaneously (Styles, 2006). Research in this field has led to several neuropsychological theories regarding human information processing to elucidate the discrepancies observed in performances. The Bottle-Neck Theory (Broadbent, 1958), the Multiple Resource Models Theory (Wickens, 1991) in addition to the Capacity-Sharing Theory (Kahneman, 1973), which will be used for this proposal, lend support to why decrements in performances are seen when two tasks are performed simultaneously (Yogev-Seligmann, Hausdorff & Giladi, 2008).

The Bottle-Neck theory proposes that when two tasks share the same neural processor or networks, the processing of the second task will be delayed until the first task has been fully processed (Broadbent, 1958; Yogev-Seligmann *et al.*, 2008). On the other hand, the Multiple Resource Models Theory advocates that processing may require multiple resources. Consequently dual-task interference will not occur if two tasks do not share common resources

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(Yogev-Seligmann *et al.*, 2008). According to the Capacity-Sharing Theory, the extent to which the performance of a given task is affected by the concurrent execution of a second one (i.e. dual-task paradigm) indicates the resource demands of the primary task as well as the level of attentional resources needed to execute both tasks (Woollacott & Shumway-Cook, 2002; Yogev-Seligmann *et al.*, 2008.)

As previously stated, the postural control literature suggests that postural control is attentionally demanding in young adults, and these demands increase with increasing postural task complexity (Kerr *et al.*, 1985; Lajoie *et al.*, 1993). Contrary to preliminary findings, it has been proposed that a difficult concurrent cognitive task might actually improve balance and decrease postural sway (Riley, Baker & Schmit, 2003; Swan, Otani & Loubert, 2007).

Withdrawing attention from the control of balance, and directing it to the cognitive task itself, leaves postural control to the automatic motor control processes (Swan *et al.*, 2007; Polskaia & Lajoie, 2016). Several studies have tried to measure the effect of task difficulty on postural sway. Riley and colleagues (2003) have examined how a concurrent short-term memory task would affect postural control. Participants had to stand a force platform that was covered with foam, which served as a destabilizer of posture. Prior to the beginning of the testing, by administering the Digit Memory Test, researchers quantified the difficulty level of the task through the measurement of each participant's maximum digit span (Riley *et al.*, 2003). Results were contradictory to the attention theories assuming a limited cognitive capacity, as evidenced by decrease in postural sway when participants performed the more difficult condition (Riley *et al.*, 2003). Further more, Swan *et al.* (2007) manipulated the difficulty levels of a cognitive task (i.e. Brooks' spatial task), while participant quietly stood on a force platform. In accordance with Riley and colleagues (2003) findings, results demonstrated that performing a difficult cognitive task produces a significant decrease in sway that is not observed when performing an easy

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cognitive task (Swan *et al.*, 2007). Authors have suggested that simple cognitive tasks are too easy and thus do not fully withdraw attention from balance related cues, which does not allow postural control to be mediated by the automatic motor control processes (Swan, Otani, Loubert, Sheffert & Dunbar, 2004). Consequently, the present study will use three different cognitive tasks in order to be able to compare between the different levels of cognitive demand. The first and easiest is a simple auditory reaction time (SRT; Lajoie *et al.*, 1993). Second and third cognitive tasks are working-memory task, one of which is verbal and called the N-back (Fraser *et al.*, 2016), and the other is the double-number sequence (DNS), which is a non-verbal task (Polskaia & Lajoie, 2016).

Furthermore, Woollacott and Vander Velde (2008) investigated the effects of modality (i.e. visual vs. auditory) and code (non-spatial vs. spatial) on postural interferences in young adults in a dual-task setting. Smith and colleagues (1995) have demonstrated that the performance of visual object working memory task and spatial working memory task involves different cortical regions. Thus, it appears reasonable to presume that, in a dual-task setting, a predominantly visual spatial task may affect postural control differently compared to a non-spatial (i.e. object) working memory task (Smith *et al.*, 1995). Participants were either seated or standing in a tandem Romberg position and were simultaneously executing one of three different forms of N-back task (i.e. visual-object, auditory-object and auditory-spatial) (Woollacott & Vander Velde, 2008). At comparable level of cognitive task difficulty, postural performance was significantly influenced by the type of cognitive loading (Woollacott & Vander Velde, 2008). The performance of challenging non-visual auditory-spatial task significantly increased postural sway compared to both auditory-object and visual-object tasks (Woollacott & Vander Velde, 2008). Therefore, authors suggested that using limited non-visual spatially based resources would

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be the reason why previous studies observed the conflicting results of visual dual-task interference effects on postural control (Woollacott & Vander Velde, 2008).

2.3. *Automatic postural control*

Dual-task paradigm has vastly been used to investigate the attentional demands of posture, and it has been suggested that depending on the difficulty of the postural task, balance can be automatically regulated with the help of the automatic motor control processes (Woollacott & Shumway-Cook, 2002). Automaticity is a general characteristic of the motor system and is illustrated by movements that are performed with minimal to barely any attention or cognitive control being clearly directed towards details of the movement (Bernstein, 1967). Thus, a dual-task paradigm is used to index the development of automaticity when learning a new skilled task to assess how well the primary task has been learned (Poldrack *et al.*, 2005; Wu & Hallett, 2005; Wu, Kansaku & Hallett, 2004).

The substantial body of literature on focus of attention has demonstrated that posture can indeed be improved when focusing on an external source (i.e. attention is drawn towards the effects of the movement on the environment) compared to directing attention on the body movements (i.e. internal focus) (Wulf, Hob & Prinz, 1998; Wulf *et al.*, 2001). Numerous studies have found evidence that using external focus of attention significantly enhances learning of differential tasks in comparison to using an internal focus of attention strategy (Totsika & Wulf, 2002; Wulf, Hob & Prinz, 1998; Wulf *et al.*, 2001; Wulf, Shea & Park, 2001; Wulf & Su, 2007, Wulf, Zachry, Granados & Dufek, 2007). Wulf, McNevin and Shea (2001) have suggested the constrained action hypothesis in hopes of explaining this phenomenon. The authors' proposition is that when using an internal focus strategy, we consciously control posture and this interferes with automatic motor control processes. On the other hand, focusing externally promotes a more

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automatic mode of control and allows the motor system to self-regulate (Wulf *et al.*, 2001; Wulf, 2013). This has been supported by the work of Polskaia and Lajoie (2016) when balance is simultaneously performed with a difficult concurrent cognitive task (e.g. Single and Double-number sequence (SNS/DNS)). Therefore, when quiet standing is paired with DNS, the body self-regulate posture by allocating all of the attention towards the cognitive task itself, which in turn promotes an automatic mode of postural control (Swan *et al.*, 2007; Polskaia & Lajoie, 2016).

The idea of automatic postural control has been derived from functional magnetic resonance imaging (fMRI) studies. Poldrack and colleagues (2005) have attempted to identify the changes in brain activity when automaticity of a task is achieved. A behavioural training of 2-4 hours of a single reaction time (SRT) task until automaticity was achieved has demonstrated a decrease in multiple brain regions (i.e. bilateral prefrontal and parietal regions, cerebellum, and caudate nucleus). In parallel with previous findings, their results show that automaticity is associated with specific decreases in activation of fronto-striatal network during dual-task performances (Poldrack *et al.*, 2005). Furthermore, Wu *et al.* (2004) have found that, after comparing high accuracy performances of a fine motor task, in single and dual-task conditions, there was less activity in the bilateral cerebellum, presupplementary motor area, cingulate cortex, left caudate nucleus, premotor cortex, parietal cortex, and prefrontal cortex after automaticity was reached. Researchers suggested that after automaticity is achieved, the same brain regions are used, however more efficiently, as evidenced by a decrease in activation. Nonetheless, it is still unknown whether these changes, in term of decreased cortical activation, with no deficits with regard to postural stability and cognitive performances, are observed in dual-task conditions when quiet standing and cognitive tasks are involved. Indeed, the constraints induced by fMRI do

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not enable the examination of brain activation of gross motor tasks. Therefore, the neural correlates of postural control have yet to be fully understood.

2.4. *Functional Near-Infrared Spectroscopy*

The force platform is irrevocably the primary tool for the investigation of postural control patterns such as postural sway. However, assessing brain activity associated with postural control has been proven to be more difficult due to the structural constraints associated with fMRI. Consequently, functional near-infrared spectroscopy (fNIRS) is becoming an alternative technique to gain further insight into the brain function since it provides information regarding physiological parameters without the restraints of the other neuroimaging methods (Perrey, 2008). Principles underlying fNIRS technique are that by emitting specific wavelengths (i.e. 760 and 850nm) onto the scalp, it is detected as it exits the head and quantified with the chromophores that are used to interpret the attenuated light levels as changes happen in chromophore concentration (Leff *et al.*, 2011). The attenuated light is used to calculate the relative concentration of oxy and deoxy-hemoglobin (HbO₂/HbR).

In addition, fNIRS is suitable for the examination of cortical activation of postural control. In relation to postural control, the examination of the PFC with the help of fNIRS seems fitted considering it holds motor areas involved in the planning of complex movements (Ashe, Lungu, Basford & Lu, 2006). Moreover, Mihara and colleagues (2008) have tried to elucidate the involvement of the PFC in the control of posture through the investigation of perturbation-related cortical activation. Perturbations were provided as horizontal translations (i.e. combined forward and backward translations) and participants were either warned (i.e. auditory cue) 2 seconds prior to the perturbation or not warned. Results demonstrated that the bilateral dorsolateral PFC (DLPFC) was significantly activated regardless of the auditory warning cues (Mihara, Miyai,

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Hatakenaka, Kubota & Sakoba, 2008). This finding suggests active involvement of the DLPFC in the maintenance of standing balance (Mihara *et al.*, 2008). In accordance with these results, Ferrari *et al.* (2014) have demonstrated an increased activation of the PFC while participants were performing a 5 minutes incremental tilt board balance task (ITBBT) in a semi-immersive virtual reality environment. The difficulty of the task modulated the increased cortical activity, which suggests that the PFC is bilaterally involved in attention-demanding tasks (Ferrari *et al.*, 2014). Collectively, the evidence demonstrates an important involvement of the PFC in the modulation of postural control.

Along these lines, this new non-invasive technique has been used by Mirelman and colleagues (2014) to investigate whether an increase in frontal brain activation during walking could be specific to dual-task. Twenty-three young healthy participants had to wear the device while walking at a self-selected speed, walking while counting forward and while serially subtracting 7s and standing while subtracting 7s (Mirelman *et al.*, 2014). Results showed a significant differences regarding levels of HbO₂, (i.e. increased activation when walking + 7S compared to walking only) providing direct evidence that dual-tasking while walking is associated with frontal brain activation (Mirelman *et al.*, 2014). These results extend previous findings to which demonstrate the influence of dual-task (DT) complexity on brain activation. Noteworthy to mention, authors suggested that the increased brain activation observed was not solely the product of verbalization, but also reflected the cognitive demands of dual-task while walking (Mirelman *et al.*, 2014). Interestingly, results also demonstrated a significantly lower activation in the standing + 7S condition compared to walking + 7S. Authors proposed that the motor-cognitive demands seen during walking + 7S elicit a specific response to DT, and is thus not replicated for standing + 7S because of disparities between control mechanisms of both tasks (Mirelman *et al.*, 2014).

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In addition, Fujita and colleagues (2016) aimed at better understanding the impact of frontal lobe activity and working-memory (WM) in postural control during a dual-task. They divided their participants, which were healthy young adults, into two WM groups (i.e. low span and high span) and tested the HbO₂ levels during standing single standing (S-S), standing during dual (S-D), one leg standing during single (O-S), and one leg standing during dual (O-D) STROOP. Results showed significantly higher HbO₂ levels in the DLPFC and supplementary motor area in the high-span group during dual-task (Fujita, Kasubuchi, Wakata, Hiyamizu & Morioka, 2016). Authors mention that these findings suggest that WM plays an important role in the allocation of attentional resources, and that differing WM capacities may result in different brain activation patterns, which may influence motor performances (Fujita *et al.*, 2016). Contrarily, Rosso *et al.* (2017) found significantly less activation in the regions of interest (i.e. prefrontal, temporal and motor cortices of the left hemisphere), and no change with regard to postural stability, when younger and older adults were performing an auditory choice reaction time paired with a postural task (i.e. standing with eyes closed on a dynamic posturography platform) compared to the sum of the single-task responses. Indeed, a shift from the DLPFC to the supra-marginal and superior-temporal area was seen during the dual-task performance compared to the sole execution of the cognitive task. Moreover, they observed greater reductions in the activation attributable to the postural control from the single- to dual-task conditions (Rosso *et al.*, 2017). Therefore, authors propose that in the single-posture condition, the activation may be greater than what is required to ensure sufficient postural control, which allows a decrease of activation related to posture during a dual-task condition without any impacts on postural performance (Rosso *et al.*, 2017).

In a systematic review, Wittenberg and colleagues (2017) presented multiple studies related to human balance control, which used fNIRS to examine brain activity during upright stance. An

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important point to highlight is that gait has been the main motor task performed in conjunction with different cognitive tasks to investigate the impact of a dual-task paradigm on brain activation. Regardless of the mechanical, cognitive, or sensory challenges, numerous studies revealed increased activation of the PFC in dual-task conditions compared to the sole execution of the motor task for different populations, such as chronic stroke patients (Al Yahya *et al.*, 2016), older adults (Clark, Rose, Ring & Porges, 2014b; Doi *et al.*, 2013; Holtzer *et al.*, 2011; Holtzer *et al.*, 2015; Holtzer *et al.*, 2016) and healthy young adults (Holtzer *et al.*, 2011; Mirelman *et al.*, 2014). However, they also reported multiple experiments that found contradictory findings in regards to PFC activations (i.e. decreased cortical activation; Shimada *et al.*, 2013; Beurskens, Hekmich, Rein & Bock, 2014; Lin & Lin, 2016; Wittenberg *et al.*, 2017).

Therefore, the literature presents inconsistent results and no consensus with regard to PFC activation in dual-task settings has been reached. As previously mentioned, many researches have mainly investigated gait, while discriminating the importance of evidence on the effects of a dual-task paradigm on quiet standing. Furthermore, healthy young adults have been used as a control to compare to, and not solely the main focus of the investigation. Considering the aforementioned evidences, it goes without saying that more information is needed in regards to cortical activation under quiet standing with DT paradigms in healthy younger adult population.

2.5. *Performance measurements*

As mentioned previously, postural sway is usually measured with the help of a force platform. To ensure a more comprehensive understanding of the postural control system, not only do we need to evaluate the neural correlates but also the dynamic measures of postural control in conjunction with the classic static measures. The force platform actually measures center of pressure (COP), which is the displacement of the application point of the ground reaction force

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(Roerdink, De Haart, Daffertshofer, Donker, Geurts & Beek, 2006). Commonly, the presence of automaticity has been indexed using static measures of COP (e.g., area of 95% confidence ellipse (sway area) and standard deviation of COP). The sway area measurement, thus being the area of 95% confidence ellipse (i.e. the smallest ellipse that will cover 95% of the COP displacements diagram) will determine the magnitude in which the participant's COP shifted in the AP and ML planes. The standard deviation of COP will indicate the regularity and variability of the sway exhibited by the participant. Lower sway area and lower SD of COP have been suggested to be indicative of an automatic mode of postural control (Polskaia & Lajoie, 2016; Potvin-Desrochers *et al.*, 2017).

Postural sway can also be studied under dynamical measures, one of which is sample entropy (SampEn). The SampEn is the negative natural logarithm of the conditional probability that a dataset of length N , having repeated itself for m samples within a tolerance r , will also repeat itself for $m+1$ samples, without allowing self-matches (Richman & Moorman, 2000; Ramdani, Seigle, Lagarde, Bouchara & Bernard, 2009; Roerdink, Hlavackova & Vuillerme, 2011). It essentially quantifies the regularity of a sequence of numbers, and thus provides a complexity index (Ramdani *et al.*, 2009). Related to postural sway, SampEn is used to determine the regularity of the COP signal, in the medial-lateral (ML) and anterior-posterior (AP) planes independently, by calculating the probability that two similar sequences, with the same amount of data points, remain similar when another data point is added (Potvin-Desrochers, Richer & Lajoie, 2017). Therefore, a more irregular trajectory of COP has been indexed as a reduction of cognitive involvement in postural control with recovering stroke patients, which was interpreted as an increase in efficiency or “automaticity” of postural control (Roerdink *et al.*, 2006; Donker, Roerdink, Greven & Beek, 2007; Ramdani *et al.*, 2009). Donker and colleagues (2007) found that

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withdrawing attention from postural control through a dual-task paradigm, and through visual deprivation, had an effect on COP trajectory in healthy adults. More specifically, standing with eyes closed significantly increased COP regularity, which is thought to reflect more attentional investment in regards to postural control. However, the use of a dual-task paradigm in conjunction with visual deprivation led to an irregular COP trajectory, which is indicative of automatic mode of postural control (Donker *et al.*, 2007). Furthermore, Roerdink *et al.* (2011) found more regular fluctuations of COP for standing compared to sitting, which was indicated by lower SampEn values, and thus supports the construct that a more irregular COP trajectory (i.e. as indexed by greater SampEn values) can be interpreted as an automatic mode of postural control (Donker *et al.*, 2007; Roerdink *et al.*, 2011). In the same line of thought, Stins and colleagues (2009) extended this proposition to the examination of individuals with superior skills (i.e. ballet dancers). Results demonstrated significantly higher sample entropy values, which is characterized by irregular COP trajectories, for ballet dancers compared to non-dancers. The author's proposition follows the idea of an automatic behaviour for the ballet dancers with regards to their perceptual-motor skill, which affords more automatic balance control (Stins, Michielsen, Roerdink & Beek, 2009).

Following the idea of dynamic measure, wavelet analysis corresponds to a trade-off between time localization and frequency localization, allowing the analysis of a signal over short periods of time (Bertrand, Bardet, Dabonneville, Mouzat & Vaslin., 2001; Uetake, Tanaka, Shindo & Okada, 2003). It proves to be a convenient and helpful tool when it comes to the analysis of a signal's properties at different scales, in our case at extracting more useful information from the raw data provided by the COP displacements (Lacour, Bernard-Demanze & Dimitrescu, 2008; Bertrand *et al.*, 2001). Applied to COP displacements, the wavelet discrete

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transform elaborates a time-frequency chart of body sway in both directions (i.e. AP and ML), and makes it possible to investigate balance control under static or dynamic conditions (Lacour *et al.*, 2008). Wavelet discrete transform has been demonstrated to be sensitive at detecting discontinuities and abnormalities in a continuous signal, and thus useful to analyze COP displacement diagrams (Uetake *et al.*, 2003).

COP displacements under wavelet transformation is decomposed in four independent frequency bands (*see Appendix A*), ranging from moderate to ultralow frequency, each capturing the contribution of the sensory systems regulating posture (Quek, Brauer, Clark & Treleaven, 2014). By identifying how these contributions change across conditions, it may lend new insight into automatic postural control. There is a small body of research lending support to the separation of the frequency bands, although certain bands are more established than others. Quek and colleagues (2014) proposed that the moderate band, which contains frequencies between 1.56-6.25 Hz, represents the somatosensory contributions to postural control based on results obtained from experiments on unhealthy participants (i.e. older adults with neck pain). Supporting evidence has been demonstrated by Kapteyn and de Wit (1972), who examined individuals without labyrinths and with their eyes closed, thus relying on proprioception for balance, and found that they would sway at higher frequencies. On the other hand, healthy participants who were administered a drug that slows postural reflexes presented lower frequencies of sway (Kapteyn & de Wit, 1972). Adding to these findings, Taguchi (1978) found that proprioceptive hyperactivity induces sway frequencies of 2.0-2.5 Hz.

Evidence is unfortunately lacking regarding the cerebellar contributions to postural control, and to which frequency it relates. Consequently, the frequency band suggested in this thesis is solely a proposition based on the small body of literature on wavelet discrete transform, and the frequencies related to the cerebellum's contribution. According to Queck *et al.* (2014), it would

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be the low band frequency, which contains frequencies between 0.39-1.56 Hz. Since frequencies between 0.10 and 0.39 Hz are attributed to vestibular contributions, and that participants with Friedreich's Ataxia swayed at 0.10 to 1.0 Hz with eyes opened and closed, it leaves the range of 0.39 to 1.0 Hz to cerebellar contributions (Diener, Dichgans, Bacher & Gompf, 1984). Diener and colleagues also noticed that, with their eyes closed, patients with late cortical atrophy of the anterior lobe swayed at frequencies of 2.0-4.0 Hz. The authors suggested that these patients had dysfunctional and atrophied cerebellar structures and thus, may be relying on their proprioception system when eyes closed. With this limited body of evidence, it was decided that the cerebellar contributions to posture could be approximated at 0.39 to 1.56 Hz.

Thirdly, the very-low band frequency, containing frequencies between 0.10-0.39 Hz, is alleged to represent contributions from the vestibular system (Quek *et al.*, 2014; Paillard, Costes-Salon, Lafont & Dupui, 2002; Oppenheim, Kohen-Raz, Daitz, Kohen Raz, & Azarya, 1999). The frequency range seems well established and accurate since multiple investigators have suggested contributions of the vestibular system between frequencies of 0.30-0.40 Hz (e.g. Gantchey & Popov, 1973; Patridge & Kim, 1969; Quek *et al.*, 2014; Soames & Atha, 1982). Moreover, Kapteyn and Wit (1972) investigated patients without vestibular functions, and have observed an absence of low frequencies (i.e. 0.20 Hz) of sway. Contrarily, for patients with vestibular dysfunctions, sway frequencies from the aforementioned range were solely present when stimulated. Similarly, patients with peripheral vestibular lesions, who had their eyes closed, exhibited peak sway from 0.20-0.30 Hz (Taguchi, 1978).

Lastly, the ultralow band, corresponding to frequencies under 0.10 Hz, has been associated to contributions from the visual system (Quek *et al.*, 2014; Lacour *et al.*, 2008). Being well established, this frequency band has mainly been identified under various conditions with eyes closed where participant would exhibit limited sway frequencies of 0 to 0.125 Hz (Chagdes *et al.*,

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2009). According to a review written by Berthoz and colleagues (1979), vision contributes to postural control in frequency ranges of around 0.10-0.20 Hz. However, with sway frequencies of 0.20 Hz being attributed to vestibular contributions, it has been decided that the threshold for the visual contribution to posture would be set adequately under 0.1 Hz.

Unpublished data from our laboratory has demonstrated the presence of a shift in the sensory system's contributions to postural control when in an automatic mode of postural control. Healthy younger and older adults stood with feet together on a force platform, and concurrently performed a cognitive task. Results have demonstrated a significant increase in the relative contributions of the very-low and low bands, which allegedly represent contributions from the vestibular system and cerebellum, respectively. Moreover, authors have also identified a concurrent significant decrease in the contributions of the ultra-low band, which represents inputs from the visual system, when participants were executing both tasks (i.e. cognitive and posture) compared to the sole execution of the postural task. The cerebellum plays an important role in the acquisition and execution of automatic movements (Lang & Bastian, 2002). Greater cerebellar activation when a practiced movement was performed at a later time has been demonstrated (Shadmehr & Holcomb, 1997). Authors have suggested that a practiced movement relies on cortical and subcortical motor areas as less attention-demanding movements may rely more on adequate internal representations of the motor pattern (Shadmehr & Holcomb, 1997). As for the vestibular system, Cullen and colleagues (2011) have demonstrated a reduction of to the quantity of vestibular inputs when movements were actively controlled compared to passive movements, which are the results of changes in the environments (i.e. unexpected motion). The aforementioned results suggest that conscious movements display fewer inputs from the vestibular system. Therefore, a more automatic mode of postural control, promoted by the simultaneous execution of a difficult cognitive task and posture, is hypothesized to yield a shift

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towards a greater contribution from the cerebellum and the vestibular system, with a concurrent decrease in contribution from the visual system.

Based on the literature reviewed, knowledge of postural control regarding kinematic and kinesthesia data is well established and has been repeatedly studied in the last few decades. However, with the limitations imposed by the commonly used neuroimaging devices (e.g. fMRI) that prohibits the examination of gross motor function, there are still several gaps to fill regarding attentional resources that are related to posture and how they may change when under dual-task protocol.

CHAPTER THREE: MANUSCRIPT

Understanding the hemodynamic response and sensory contributions to automatic postural control

HEMODYNAMIC RESPONSE AND SENSORY CONTRIBUTION OF AUTOMATICITY

Understanding the Hemodynamic Response and Sensory Contributions to Automatic Postural Control

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ABSTRACT

The postural control-cognition dual-task literature has demonstrated greater postural stability through the examination of multiple kinetic and kinematic measures. Recently, sample entropy (SampEn) and wavelet discrete transform have supported the claim of automaticity, as higher SampEn values and a shift toward increased contributions from automatic sensory systems have been demonstrated in dual-task settings. In order to understand the cortical component of postural control, functional near-infrared spectroscopy (fNIRS) has been used to identify cortical activation under postural control conditions. However, the neural correlates of automatic postural behaviour have yet to be fully investigated. Therefore, the purpose of this study is to confirm the presence of automatic postural control through static and dynamic measurements, and to investigate the prefrontal cortex activation (PFC) when concurrently performing quiet standing and auditory cognitive tasks. Eighteen healthy young adults ($21,4 \pm 3,96$ yo), 12 females and 6 males, with no balance deficits were recruited. Participants were instructed to either quietly stand on a force platform (SM), perform three cognitive tasks while seated (SC) or perform both aforementioned tasks concurrently (DT). Results revealed automatic postural control as evidenced by lower area and standard deviation of center-of-pressure in DT conditions. As for SampEn and the wavelet analysis, greater values and a shift from vision to a cerebellum contribution were demonstrated in DT conditions. For the DNS task, a trend toward significantly lower right hemisphere PFC activation compared to left hemisphere activation in DT was evidenced, which potentially reiterate the presence of automaticity. Therefore, as demonstrated by this experiment, the simultaneous performance of a difficult cognitive task and posture yields automatic postural behaviour, and provides insight into the neural correlates of automaticity.

Keywords: Automatic postural control, functional Near-Infrared Spectroscopy, Wavelet discrete transform, Sample entropy, Dual-task

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1. *Introduction*

Postural control has long been identified as attentionally demanding in healthy young adults (Kerr, Condon & McDonald, 1985; Lajoie, Teasdale, Bard & Fleury, 1993). The assumptions underlying the capacity-sharing theory are that attention is limited, and that if the concurrent execution of two tasks exceeds resource capacities, performance on one or both task will diminish (Woollacott and Shumway-Cook, 2002). However, contradictory findings have been demonstrated in the literature with regard to the simultaneous execution of two tasks (i.e. dual-task paradigm) when posture is involved. The paradigm fails to explain the observed improvements in postural stability that have been observed in a dual-task setting (Polskaia & Lajoie, 2016; Richer, Saunders, Polskaia & Lajoie, 2017; Potvin-Desrochers, Richer *et al.*, 2017). Research in the field of attentional focus has demonstrated the presence of automatic motor control processes when attention is withdrawn from the control of posture, and directed towards an external source (Wulf, 2013). The “constrained action hypothesis” proposed by Wulf and colleagues (2001) suggests that allocating attention away from postural control allows automatic mechanisms to regulate posture unconstrained. Since its proposition, authors have expanded the hypothesis to the domain of cognitive tasks. Results have demonstrated that a difficult cognitive task performed simultaneously with posture elicits an automatic mode of postural control as reflected by greater stability (Polskaia & Lajoie, 2016; Richer *et al.*, 2017; Potvin-Desrochers *et al.*, 2017). Therefore, the presence of automatic postural control has been indexed in dual-task settings through the examination of multiple kinetic and kinematic measures (i.e. Area of 95% confidence ellipse and standard deviation (SD) of center-of-pressure (COP) (Richer *et al.*, 2017).

Recently, dynamic measurements such as sample entropy (SampEn) and wavelet discrete transform have been used to investigate COP excursions to provide evidences of automaticity (Potvin-Desrochers *et al.*, 2017; Richer & Lajoie, under review). They provide a more detailed

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analysis as they capture the variations present in a time series (Stergiou & Decker, 2011).

SampEn indexes the statistical regularity of the COP signal (Richman & Moorman, 2000), and is indicative of the degree of automaticity of postural control (Donker, Roerdink, Greven & Beek, 2007; Potvin-Desrochers *et al.*, 2017). Consequently, an irregular COP signal, indexed by high SampEn values, combined with greater postural stability is reflective of an automatic mode of postural control (Richman & Moorman, 2000; Donker *et al.*, 2007; Potvin-Desrochers *et al.*, 2017). Wavelet discrete transform decomposes the COP signal into different frequencies bands, which are believed to reflect the contribution of the sensory systems modulating posture (Lacour, Bernard-Demanze & Dimitrescu, 2008). The combined frequencies from 1.56 to 6.25Hz have been associated to the somatosensory system's contribution to postural control, and represent the moderate band (Quek, Brauer, Clark & Treleaven, 2014; Kapteyn & de Wit, 1972; Taguchi, 1978). The low band, which contains frequencies from 0.39 to 1.56Hz, allegedly represents contributions from the cerebellum (Quek *et al.*, 2014; Diener, Dichgans, Bacher & Gompf, 1984). As for the very-low and ultra-low bands, they respectively comprise frequencies between 0.10 to 0.39Hz and lower than 0.10Hz, and reflect contributions from the vestibular and the visual systems (Quek *et al.*, 2014; Soames & Atha, 1982; Oppenheim, Kohen-Raz, Daitz, Kohen Raz, & Azarya, 1999; Chadges *et al.*, 2009; Lacour *et al.*, 2008). It has been suggested that the lower contribution from the vision, and the concurrent greater contribution from the cerebellum and vestibular system observed in dual-task conditions represent a shift from conscious to automatic postural behaviour (Richer & Lajoie, under review; Lang & Bastian, 2002; Cullen, Brooks, Jamali, Carriot & Massot, 2011). Therefore, SampEn and wavelet can provide support to the presence of automatic postural control under dual-task performances.

The idea of automaticity has been derived from fMRI experiments looking into brain activation of behavioural motor task (Wu, Kansaku & Hallet, 2004; Poldrack *et al.*, 2005).

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Studies have demonstrated that once automaticity of a task is achieved, cortical activation decreases on the assumption that the brain regions work more efficiently (Wu *et al.*, 2004; Poldrack *et al.*, 2005). However, due to the structural constraints induced by fMRI, these findings have not been replicated with gross motor tasks. Functional near-infrared spectroscopy (fNIRS), a portable neuroimaging technique that monitors the hemodynamic response of the brain on the basis of neurovascular coupling (Leff *et al.*, 2011), has been used in multiple studies looking into the attentional demands of gait (for review see Wittenberg, Thompson, Nam & Franz, 2017; Pinti *et al.*, 2018). Unfortunately, the cortical demands of quiet standing have mostly been overlooked or purposely used as a comparison tool. Mirelman and colleagues (2014) had intended to investigate if an increase in frontal brain activation was specific to dual-task walking. Nevertheless, they demonstrated lower PFC activation while participants were standing and simultaneously counting backwards by seven (Mirelman *et al.*, 2014). Paralleling this line of evidence, Rosso *et al.* (2017) have found lower prefrontal cortex (PFC) activation in a dual-task setting compared to the sum of both single tasks with no decrements to postural stability. Results in the literature seem to indicate a decrease in brain activity when a postural control-cognition paradigm is used to create dual-task interference. However, it has yet to be linked to automatic postural behaviour since the neural correlates of automaticity have not been fully understood.

Therefore, the purpose of this study was threefold. The first objective was to confirm the presence of automatic postural control yielded by the concurrent execution of difficult cognitive tasks and quiet standing (Dual-task (DT)), through the examination of static measurements such as area and SD of COP. The second objective was to support the presence of automaticity in DT with the investigation of dynamic measurements of postural sway such as SampEn and wavelet discrete transform. Lastly, the third objective was to identify if there was a corresponding change in brain activation (i.e. lower cortical activation) in the prefrontal cortex when the DT condition

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elicits an automatic mode of postural control. The first hypothesis was that DT would promote greater stability as reflected by lower area and SD of COP compared to single motor (SM). The second hypothesis was that SampEn values would increase, and thus indicate automaticity of postural control, under DT conditions compared to SM. It was also hypothesized that a shift between the contributions of the sensory systems would reflect a change from conscious to an automatic mode of postural control under the DT conditions compared to SM. Lastly, it was hypothesized that during DT, PFC activation would decrease compared to SM.

2. *Methods*

2.1. *Participants*

Eighteen right-handed young healthy adults (Twelve females and six males, 21.44 ± 3.96 years) participated in this sub study. This study is part of larger project aiming to examine cerebral oxygenation differences in younger and older adults under different cognitive loads during quiet standing and walking. This sub study presents the postural effect of automaticity when quiet standing is concurrently performed with cognitive tasks. In order to partake in this experiment, participants had to have no neurological or musculoskeletal damage, nor any hearing problems that could impair their ability to perform the balance or the cognitive tasks. At the beginning of the session, all participants provided written informed consent, and filled out the following questionnaires: the Short Physical Performance Battery test, the Beck's Depression Inventory and the Digit Symbol Substitution Test (DSST) (*Table 1*). This study was approved by the University of Ottawa Research Ethic Board.

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2.2. Apparatus

Area of 95% confidence ellipse and standard deviation of center-of-pressure (COP) in the anterior-posterior (AP) and medial-lateral (ML) directions were collected, at a sampling rate of 500Hz, with an AMTI OR6-6-1000 force platform (Waterloo, MA, USA). The recordings for the auditory tasks were presented through headphones with a media player.

As for the cerebral activation, the portable functional near-infrared spectroscopy (fNIRS) OCTAMON by Artinis was used to assess the relative oxygenated and deoxygenated hemoglobin (HbO₂/HbR) levels of the prefrontal cortex (PFC) by an eight-channel continuous-wave spectrometer. The 760 and 850nm wavelengths were continuously emitted in order to capture changes in levels of HbR and HbO₂, respectively. The inter-optode distance was set at 35mm and the sampling rate was 10Hz. For the purpose of this study, only HbO₂ levels were used for the statistical analysis because of its higher sensitivity to task-related changes (Miyai *et al.*, 2001). The fNIRS was fitted on the participant's forehead using the modified International 10/20 EEG system.

2.3. Postural task

Participants stood on the force platform with feet together, arms comfortably hanging on each side, and were fixating at an eye-level target 3m ahead. They were asked to refrain from moving as much as possible, and foot placement was standardized across all participants. They either had to solely quietly stand with their eyes opened (SM), or simultaneously execute one of three cognitive tasks while standing (DT).

2.4. Auditory cognitive tasks

Three different cognitive tasks were selected for the present study. The first and easiest was an auditory simple reaction time task (SRT) where participants had to respond 'TOP', as fast as possible, after hearing a high pitch beat (Lajoie *et al.*, 1993). Between five and seven stimuli were presented per trial. The second cognitive task was the N-back, which is a verbal auditory working-memory task used to manipulate memory load (Herff *et al.*, 2014). Participants were presented with a series of one-digit numbers (e.g. 3, 6, 3, 7, etc.), presented at 2.2-s interval, and participants had to say out loud the number they heard two numbers back (e.g. in the example above, when hearing 7, participants had to say 6). The 2-back was chosen for its high difficulty level compared to the 1-back as shown by Fraser *et al.* (2016). The third cognitive task was the double-number sequence (DNS), which was a non-verbal working-memory task, and was considered the most difficult (Richer *et al.*, 2017). Participants were presented with an auditory recording of three-number digits, presented at 2-s intervals (e.g., 342, 404, 506, etc.). They were given two target digits prior to the beginning of each trial, and were asked to silently count, without some sort of counting aid, the separate total number of times the single digits were presented in the sequence (e.g., count the number of 3s and 4s). At the end of each trial, the participants were prompted to provide their answer. The DNS task has been proven effective at removing the attention from postural control because of its difficulty level (Richer *et al.*, 2017). Swan and colleagues (2004) have demonstrated that an easy task, in our case the SRT task, does not provide the level of difficulty necessary to distract from the control of posture, and thus does not leave the regulation of balance to the automatic motor control processes. Therefore, it was decided to have the participants perform more difficult tasks (i.e. N-back and DNS). Moreover, since articulation creates movements (Dault, Yardley & Frank, 2003), the use of a non-verbal and

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a verbal difficult WM task seemed appropriate to ensure reliable findings. The cognitive tasks were counterbalanced through all participants to minimize order effect.

2.5. Procedure

Each participant underwent three different runs, one run for each cognitive task. A run consisted of 12 trials (i.e. 10-s baseline, 35-s active condition), for a total of 36 trials of 45-s. Participants were either asked to quietly stand on the force platform (i.e. Single Motor (SM)), execute one of three cognitive tasks while seated (i.e. Single COG (SCOG)), and simultaneously stand on the force platform and perform the given cognitive tasks (i.e. Dual-task (DT)). Every run went as follows: two trials of Single COG, two trials of Single Motor, four trials of Dual-task (i.e. Cognitive + Posture), followed by two trials of Single motor and ended with two trials of Single COG (*see Appendix B for an example of a run*).

2.6. Data Analysis

2.6.1. Postural data

Static measurements

SD of COP in AP and ML directions as well as area of 95% confidence ellipse (area) data were extracted from the force platform and exported to Matlab (MathWorks Inc., MA, USA). All SM trials were averaged out to ensure consistency when comparisons between conditions were required.

Dynamic measurements

Matlab was also used to calculate sample entropy values from the COP data following the same procedure as in Potvin-Desrochers *et al.*, 2017. The data was first downsampled to 100Hz and, was then processed with the subsequent formula (Richman & Moorman, 2000):

$$\text{SampEn}(m, r, N) = -\log\left(\frac{A(r)}{B(r)}\right)$$

Where m represents the number of data points to compare in a sequence, N is the length of the data sequence, and $A(r)$ and $B(r)$ correspond to the total number of concordant sequences according to the level of tolerance r in the suitable dimensional space (i.e. m for $B(r)$ and $m + 1$ for $A(r)$; Richman & Moorman, 2000). Parameters were set to $m = 2$ and $r = 0.2 * \text{SD}$ (Potvin-Desrochers *et al.*, 2017 ; Richer & Lajoie, under review).

With regard to the wavelet analysis, the wavelet toolbox in Matlab (MathWorks Inc., MA, USA) was used to analyse the COP data collected with the force platform. As in Richer and colleagues (in review), the data was downsampled from 500Hz to 100Hz. Subsequently, the signal was processed using the discrete wavelet transform, more specifically a 12-level Symlet-8 wavelet with one-dimension multisignal analysis. The contribution percentage of each band was totalled through Microsoft Excel, where the independent signals were combined in the following four frequency bands: (1) moderate (1.56–6.25 Hz), (2) low (0.39–1.56 Hz), (3) very-low (VL; 0.10–0.39 Hz), and (4) ultralow (UL ; <0.10 Hz; Quek *et al.*, 2014).

2.6.2. *fNIRS data analysis*

Once more, Matlab was used to process and analyse the fNIRS data with the use of HomER processing package for NIRS (version 2; MathWorks Inc., MA, USA; Huppert, Diamond, Franceschini & Boas, 2009). First, the raw optical intensity measurements were converted into optical density. Secondly, each channel was inspected to detect the presence of motion artefact, as reflected by optical density higher than 0.2 (AMP_{Thres}) over 0.1seconds (t_{Motion}). If present, the motion artefact was masked for 0.2seconds (t_{Mask}) before and after its presence. The data was then band-pass filtered with a fourth order Butterworth filter of a low-pass of 0.5Hz and a high-pass of 0.01Hz, in order to remove any cardiac oscillations and

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systemic noises (Cooper *et al.*, 2012). Subsequently, a principle component analysis (PCA) was applied to correct for remaining motion artefacts, and was deemed the most effective technique to remove the variability present in the signal (Cooper *et al.*, 2012). Finally, the optical density measurements were converted into relative concentration using the modified Beer-Lambert law, and were then block-averaged over a time range of -15seconds and 30seconds. Following the work of Rosso and colleagues (2017), we subtracted the relative levels of HbO₂ for SCOG to the relative levels of activation for DT to compare the proportion of activation related to postural control (e.g. $DT (HbO_2)_{diff} = DT SRT - SCOG SRT$ and is then compared to SM).

2.7. Statistical analysis

All data (i.e. SD of COP, area of 95% confidence ellipse and HbO₂) are expressed in means with their respective standard deviation. Each DT condition will be referred to as SRT, N-back and DNS to make it simpler for the statistical analysis comprehension. In order to answer the first hypothesis, a one-way analysis of variance (ANOVA) with repeated measures on Conditions (SM, SRT, N-back, DNS) was performed for area. In addition, two one-way ANOVAs with repeated measures on Conditions (SM, SRT, N-back, DNS) were performed, one per direction, for the SD of COP. With regards to the second hypothesis, two one-way ANOVAs with repeated measures on Conditions (SM, SRT, N-back, DNS) were performed, again one for each direction, for the SampEn values. Furthermore, a multivariate analysis of variance (MANOVAs) with repeated measures on Conditions (SM, SRT, N-back, DNS) with a 4-level factor, which corresponds to the bands (Moderate, Low, Very-Low, Ultra-Low), was performed for each direction for the discrete wavelet transform. Lastly, for the third hypothesis, a three-way ANOVAs with repeated measures on Hemisphere (Right, Left) x Channels (1-4) x Conditions (SM, DT) were performed for the HbO₂ levels for each cognitive task. To support that no

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difference in cognitive performances occurred from SC to DT, a paired t-test comparing the mean numbers of rejected trials was performed for each cognitive task. Mauchly's Test of Sphericity was performed to ensure normality, and if violated, Greenhouse-Geisser p value was reported. When necessary, LSD post-hoc test was performed to determine the location of significance. Statistical significance was set at $p < 0.05$.

3. Results

Cognitive performances

The paired t-tests revealed no significant differences between the mean numbers of rejected trials for SC and DT for all cognitive tasks.

[See Table 2]

Static measurements

There was a significant main effect of condition for area ($F(3,51) = 3.43, p < .05, \eta^2_p = 0.168$). Results of the LSD post-hoc test revealed that the N-back promoted greatest reduction in area compared to SM ($p = 0.001$). However, SRT ($p = .912$) and DNS ($p = .198$) did not yield significantly different areas compared to SM. As for SD of COP in the ML direction, the one-way ANOVA revealed a main effect of conditions ($F(3,51) = 8.642, p < .001, \eta^2_p = 0.337$). The LSD post-hoc test identified significantly lower variability for every DT condition compared to SM. Moreover, the N-back resulted in higher stability, as evident by a larger decrease in SD of COP, compared to SRT ($p = .024$) but was not significantly different from DNS ($p = .447$). As for SD of COP in the AP direction, no main effect of condition was found ($F(3,51) = 2.246, p > .05, \eta^2_p = 0.117$).

[See Table 3]

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These findings are in line with the body of literature demonstrating increased stability, as reflected by a reduction in area and SD of COP, promoted by difficult concurrent cognitive tasks (e.g. Polskaia and Lajoie, 2016; Potvin-Desrochers *et al.*, 2017; Richer *et al.*, 2017).

Dynamic measurements

The one-way ANOVA revealed a significant main effect of condition for SampEn values in the ML direction ($F(3,51) = 13.338, p < .001, \eta^2_p = 0.440$). Results of the LSD post-hoc test revealed significantly higher SampEn values for each DT condition compared to SM ($p_s < .01$). However, the cognitive tasks were not significantly different from one another ($p_s > .05$). As for the SampEn values in the AP direction, no significant main effect of condition was identified ($F(3,51) = 6.35, p > .05, \eta^2_p = 0.036$).

[See Figure 1]

With regard to the wavelet analysis, the MANOVA in the ML plane revealed a statistical difference in conditions for the contribution of the different bands ($F(12,6) = 3.798, p = .056, \eta^2_p = 0.884$). The LSD post-hoc test identified higher contribution from the moderate and low bands, which allegedly represent the somatosensory system and cerebellum contributions in postural control, for the three cognitive tasks compared to SM ($p_s < .05$). However, there was no significant difference between the conditions for the contribution of the VL band, hence the contribution of the vestibular system did not change. Lastly, the contribution of the vision, represented by the UL band, was significantly lower as identified by the LSD post-hoc test for the three conditions compared to SM ($p_s < .05$), resulting in a more automatic mode of postural control. The N-back promoted significantly greater changes in contribution of the sensory systems when compared to SRT ($p < .05$) but was not significantly different from DNS. As for

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the AP plane, the MANOVA did not identify any significant change in the contribution of the sensory systems between the different cognitive tasks ($F(12,6) = 2.069, p > .05, \eta^2_p = 0.805$).

[See Figure 2]

In summary, the wavelet analysis partially demonstrated an automatic mode of postural control yielded by the simultaneous execution of the cognitive tasks and posture as reflected by significantly lower contribution from the vision, and greater contributions from the somatosensory system and the low band, which appears to reflect contributions from the cerebellum. Moreover, the N-back elicited higher cognitive demands as demonstrated by greater changes in between contributions of the sensory systems. As for SampEn, all three cognitive tasks promoted an automatic mode of postural control as reflected by significantly higher SampEn values.

fNIRS

As for the cortical activation (HbO_2), the three-way ANOVA with regard to the SRT task revealed no significant main effect ($F(3,51) = 0.51, p > .05, \eta^2_p = 0.029$). The N-back task did not promote an automatic mode of postural control as revealed by the lack of main effect ($F(3,51) = 0.497, p > .05, \eta^2_p = 0.028$). Lastly, any main effects for the DNS task were superseded by a significant Hemisphere x Condition interaction ($F(1,17) = 5.183, p < .05, \eta^2_p = 0.234$). The LSD post-hoc test revealed a significant trend towards a decreased activation in the right hemisphere compared to the left solely under DT ($p = .063$). Therefore, the DNS task partially promoted an automatic mode of postural control, as reflected by a trend toward significantly lower relative concentration of HbO_2 in the right hemisphere compared to the left hemisphere, when participants were dual-tasking.

[See Figure 3]

4. Discussion

The purpose of the present study was threefold. The first objective was to support the presence of automatic postural control when concurrently performing quiet standing and difficult cognitive tasks, through static measurements such as area and SD of COP. We predicted that an automatic mode of postural control would be evidenced by reduced sway area and SD of COP. The present findings confirm this hypothesis seeing as a significant reduction in area from SM to DT for the N-back task was found as well as lower SD of COP in the ML direction for every cognitive task. The SRT task yielded unforeseen lower SD of COP as it was considered an easy cognitive task. However, the aforementioned task may not have elicited high levels of automaticity considering there was no significant change in sway area. As for the N-back task, its cognitive load appeared to be greater since it promoted greater stability for both static measurements, which is indicative of automaticity.

Therefore, this work lends support to the body of literature on automatic postural control resulting from the simultaneous execution of quiet standing and difficult cognitive tasks. The observed reduction of postural sway yielded by the concurrent performance of these cognitive tasks is in line with the idea of automaticity (Polskaia & Lajoie, 2016; Richer *et al.*, 2017; Potvin-Desrochers *et al.*, 2017). Indeed, the cognitive loads generated by the cognitive tasks were effective at removing the attention from consciously controlling posture as reflected by the significantly lower variability, thus promoting the presence of automatic postural control processes (Wulf, 2013).

The second objective was to provide further evidence of the presence of automatic postural control through the examination of dynamic measurements, such as SampEn and discrete wavelet transform. The predicted increase in SampEn values and shift between the sensory systems modulating posture when participants would perform standing simultaneously

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with difficult cognitive tasks was confirmed. Results demonstrated increased SampEn values in the ML plane when participants were performing every cognitive task while standing. As for the wavelet discrete transform, each cognitive task prompted a shift towards a lower contribution from the visual system, with a concurrent greater contribution from the frequencies that are allegedly representing the cerebellum and the somatosensory system. Therefore, the aforementioned shift between the sensory systems can possibly be attributed to a shift from a conscious to an automatic mode of postural control (Lang & Bastien, 2002; Cullen *et al.*, 2011; Richer et Lajoie, in review).

The present findings are in agreement with the body of literature on automatic postural control examining postural stability through sample entropy (Potvin-Desrochers *et al.*, 2016; Richer & Lajoie, under review). Indeed, SampEn reflects the amount of cognitive involvement dedicated to postural control, and is thought to be representative of an automatic mode of postural control when high values are observed (i.e. irregular COP signal) (Stins *et al.*, 2009; Donker *et al.*, 2007; Potvin-Desrochers *et al.*, 2016). The literature demonstrates that higher SampEn values when healthy adults concurrently perform standing and difficult cognitive tasks are indicative of a shift of attention towards the cognitive task, which allows the automatic processes to regulate posture unconstrained (Potvin-Desrochers *et al.*, 2017). Therefore, findings of the present experiment suggest that the cognitive demands of the SRT, N-back and DNS tasks are sufficiently high to distract from consciously controlling postural, and thus leaving the automatic processes to work unconstrained (Wulf, 2013).

As for the wavelet discrete transform, results are partially in line with the literature as they reflected a shift from a conscious system (i.e. vision) to an automatic one (i.e. cerebellum) when participants were dual-tasking, but did not demonstrate any shift towards an increased contribution from the band possibly reflecting the vestibular system's contribution (Richer &

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Lajoie, under review). Lang and Bastian (2002) have demonstrated the important role of the cerebellum in the acquisition and execution of automatic movements. While directing their attention away from the movement production, cerebellar impaired patients compared to healthy controls were not able to learn and perform a novel movement in an automatic state after practice. Therefore, the cerebellum has been suggested to play an important role for shifting movement performance from an attentionally demanding state to a more automatic fashion (Lang & Bastian, 2002). As demonstrated in this experiment, our dual-task paradigm is believed to have partially promoted automaticity, as evident by lower contribution from the vision and a greater contribution from frequencies that are hypothesized to represent the cerebellum's contribution to postural control (Quek *et al.*, 2014). Furthermore, the dynamic measurements are in line with the static measurements of postural sway, and thus reinforce the suggestion of an automatic postural control in a postural control-cognition dual-task paradigm.

Lastly, the third objective was to determine if an automatic mode of postural control was reflected through cortical activation. We expected a decrease in the relative concentration levels of HbO₂ of the PFC when participants were performing difficult concurrent cognitive tasks with posture. The hypothesis was partially confirmed considering the trend toward significantly lower activation was only seen in the right PFC hemisphere compared to the left hemisphere when participants were performing the DNS task simultaneously with quiet standing. The neural correlates of automaticity have been derived from functional magnetic resonance imaging (fMRI) studies, which reported lower prefrontal cortex activation when automaticity of a task was achieved (Wu *et al.*, 2004; Poldrack *et al.*, 2005). They have identified training-related decrease in brain activation of the prefrontal regions once the task was fully learned. Furthermore, Rosso and colleagues (2017) have demonstrated lower brain activation using fNIRS, with greater brain activation reduction attributable to postural control, when young adults were dual-tasking. In

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accordance with our findings, when compared to the sum of both single tasks, the dual-task activation was lower than anticipated (Rosso *et al.*, 2017). Consequently, lower brain activation, as observed in the right PFC when participants were simultaneously performing standing with DNS, could be indicative of automatic postural control.

The trend toward significantly lower PFC activation found solely in the right hemisphere when participants were performing the DNS task simultaneously with quiet standing is in line with Fujita and colleagues (2016) findings. Indeed, authors found greater activation in the right dorsolateral prefrontal cortex (rDLPFC) in the high-span group compared to the low-span group when participants were performing a difficult postural task (i.e. one-leg standing) concurrently with a cognitive task. They attributed the difference between groups due to inferior working-memory capacities for the low-span group as reflected through difficulties in attention allocation (Fujita *et al.*, 2016). Furthermore, Fujita *et al.* (2016) mentioned the important role the DLPFC plays in body positioning in physical activity performance. The literature has reported lateralization of postural control, where the right hemisphere is believed to play a dominant role in postural control compared to the left hemisphere (Ugur, Gücüyener, Uzuner, Özkan & Özdemir, 2000; Karnath & Broetz, 2003). Findings of the present study are thus consistent with previous results as the DNS task yielded sufficient cognitive demands to distract from consciously controlling posture (Richer *et al.*, 2017). The aforementioned was revealed by significantly lower right PFC activation in a dual-task setting. Although speculative, it may indicate an automatic mode of postural control reflected by a transfer from cortical to subcortical brain regions (Floyer-Lea & Matthews, 2004).

However, the N-back used in the present study was likewise used for its difficulty level (Fishburn, Norr, Medvedev & Vaidya, 2014; Fraser *et al.*, 2016), and appeared to create sufficient cognitive demands to promote an automatic mode of postural control as demonstrated

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in the present study with the static and dynamic measurements of COP. However, no significant decrease in brain activation was observed. One possible explanation for this finding is the verbalization required to complete the task. Binder and colleagues (1997) have identified multiple brain regions involved in language processing, one of which was the left prefrontal cortex. Therefore, we propose that the task in itself, being a verbal working-memory task, might have caused the discrepancy observed between the results of the two difficult cognitive tasks in the present study. Supporting this idea is the meta-analysis conducted by Owen and colleagues (2005) comparing results of brain activation for verbal and non-verbal N-back tasks. Evidences support the implication of the dorsolateral prefrontal cortex and of the ventrolateral prefrontal cortex in working-memory task, and their activation in both aforementioned tasks (Owen, McMillan, Laird & Bullmore, 2005). However, the overall activation for the non-verbal n-back task was less salient and extensive compared to the verbal n-back activation (Owen *et al.*, 2005). Consequently, the lower brain activation yielded by automatic postural behaviour might be disguised by the activation resulting from the verbalization of the task, and not be caused by insufficient levels of cognitive demands needed for the successful completion of the task.

Unexpectedly, SRT yielded lower sway variability, higher SampEn values, and a shift in the sensory system's contribution compared to SM. However, no difference in sway area was promoted by the performance of this easy discrete cognitive task, and the changes elicited were trivial compared to the ones promoted by the simultaneous execution of N-back or DNS with quiet standing. The aforementioned results may indicate lower levels of automaticity elicited by SRT in a dual-task fashion. One of the limitations of this study is that the cognitive tasks used were not standardized. Therefore, even if the SRT task was deemed easy, comparison between the tasks cognitive demands is not possible. Finally, the observation of cortical activation changes was limited to the prefrontal cortex because of the fNIRS used in the present study. It is

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thus impossible to know if changes in brain activation of deeper cortices (Wu *et al.*, 2004; Poldrack *et al.*, 2005) occurred when participant were shifting from conscious control to an automatic mode of postural control.

5. *Conclusion*

In conclusion, the present experiment suggests the presence of automatic postural control, through the examination of static and dynamic measurement of postural sway, yielded by the simultaneous execution of a difficult cognitive task and quiet standing. Additionally, a concurrent trend toward significantly lower brain right hemisphere PFC activation compared to the left hemisphere when dual-tasking further supports the claim of automaticity. We suggest that the DNS task promotes sufficient cognitive demands to distract from the conscious control of posture, and thus enables the automatic processes to modulate posture unconstrained (Wulf, 2013). This work provides new insight into automatic postural control by examining the effect of automaticity on brain activation, while highlighting the importance of using both static and dynamic measurements when analyzing postural sway.

Acknowledgements

The authors report no conflicts of interest.

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Table 1.

Mean scores (SD) for all of the questionnaires filled prior to the beginning of the testing

Test	Scores
Short Physical Performance Battery test	11.5 (0.65)
Beck's Depression Inventory	2.3 (2.8)
Digit Symbol Substitution Test (DSST)	75.7 (22.4)

Table 2.

Mean number of rejected trial (SD) of each cognitive task for the single performance of the cognitive tasks (SC) and for their performance while quietly standing (DT)

Tasks	Rejected trials	
	SC	DT
SRT	0.00 (0.00)	0.00 (0.00)
N-Back	0.06 (0.22)	0.0 (0.0)
DNS	0.11 (0.45)	0.11 (0.31)

Table 3.

Mean (SD) of each postural stability measures across all conditions.

Outcome measures	SM	SRT	N-back	DNS
Area (cm²)	6.104 (3.143)	6.013 (5.031)	3.771* (1.286)	4.990 (3.528)
SD of COP in ML (cm)	0.516 (0.150)	0.460** (0.130)	0.413** (0.076)	0.430** (0.116)
SD of COP in AP (cm)	0.623 (0.192)	0.642 (0.392)	0.485 (0.103)	0.607 (0.302)

Significantly different than SM (*p< .05 ; **p< .01).

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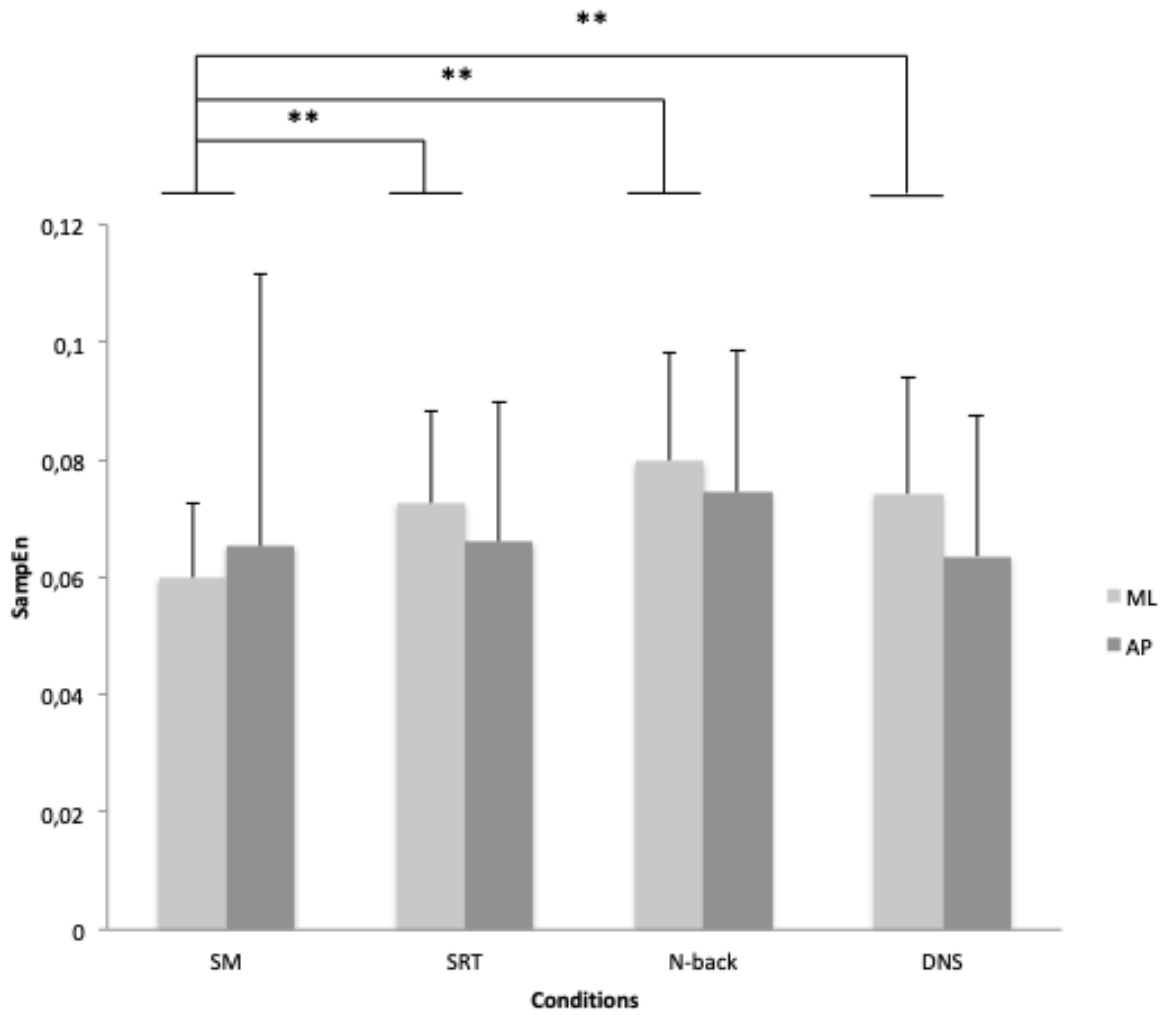


Figure 1. Mean and SD of SampEn values in the ML and AP direction for all conditions. (**p < .01).

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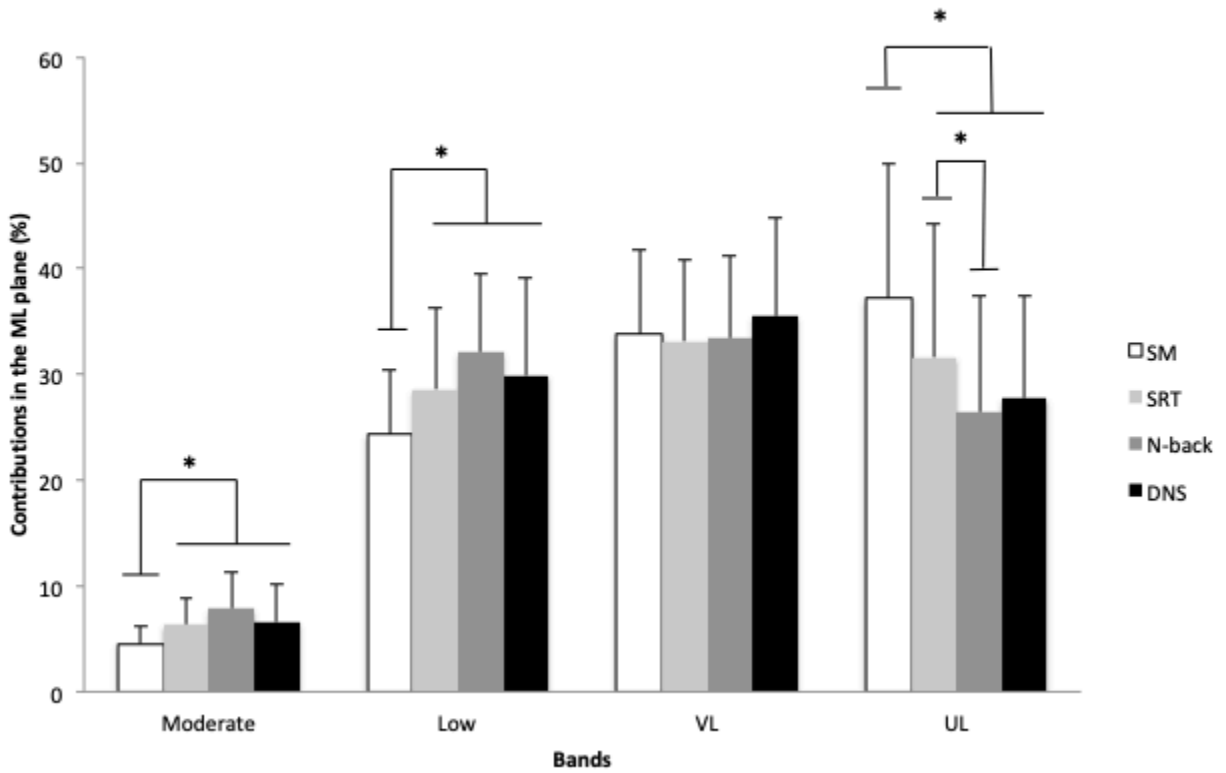


Figure 2. Mean contribution in percentage (%) and SD of each frequency band across all conditions in the ML direction (* $p < .05$).

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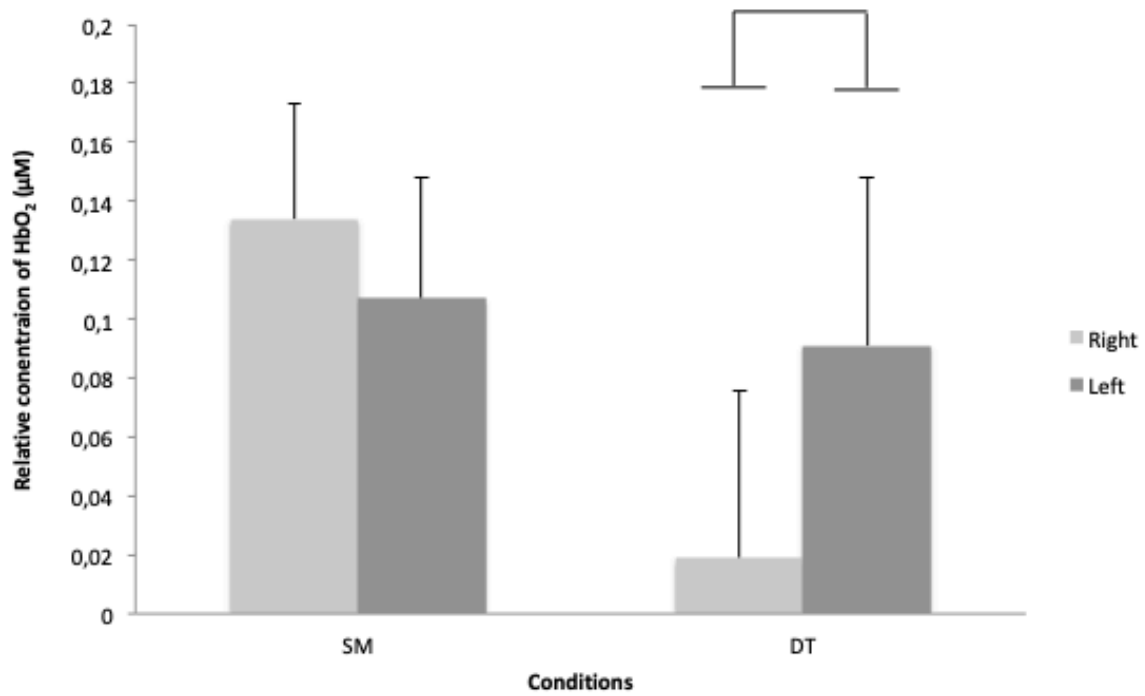


Figure 3. Relative concentration of HbO₂ (µM) and SD for the right and left hemispheres under SM and DT conditions for the DNS task. (*p < .05).

CHAPTER FOUR: GENERAL DISCUSSION

The purpose of the present experiment was to provide further evidence of the presence of automatic postural behaviour elicited by a cognition-posture dual-task paradigm through static and dynamics measurements of center-of-pressure excursions, and to investigate the neural correlates of automaticity with fNIRS. Therefore, the first objective was to demonstrate greater stability during the difficult dual-task condition as evidenced by lower sway area and standard deviation (SD) of center-of-pressure (COP), also referred to as sway variability. The second objective was to reiterate the presence of automaticity in a dual-task setting with higher sample entropy (SampEn) values and a wavelet discrete transform analysis. Lastly, the third objective was to investigate the involvement of the prefrontal cortex (PFC) during single and dual-task conditions. Therefore, it was hypothesized that the simultaneous execution of quiet standing and a difficult cognitive task would elicit lower area and SD of COP. With regard to the second hypothesis, we predicted higher SampEn values and a shift in the contribution of the sensory systems from a conscious (i.e. vision) to automatic systems (i.e. vestibular and cerebellum) for difficult dual-task performances. Lastly, we hypothesized that lower PFC activation would reflect an automatic mode of postural control yielded by the concurrent execution of a difficult cognitive task and quiet standing.

4.1. Effects of a dual-task paradigm on static and dynamic measures of COP

Contrary to what was hypothesized, lower sway area was only observed when participants were quietly standing and concurrently performing the N-back task. Although marginal, the DNS yielded lower sway area compared to SM and SRT. The N-back and the DNS tasks were both chosen for their cognitive loads, which have been proven to yield adequate demands to distract from consciously controlling posture (Fraser *et al.*, 2016; Richer *et al.*, 2017). However, in terms

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of area, the DNS task did not elicit significantly greater stability compared to the sole execution of posture (SM). As for SD of COP in the ML plane, all cognitive tasks promoted greater stability compared to SM as reflected with lower sway variability. Surprisingly, the SRT task, which was deemed an easy discrete cognitive task, produced lower SD of COP. However, seeing it did not promote any difference in sway area in a DT setting, its automatic property remains uncertain. Nevertheless, the N-back appeared again to yield greater cognitive demands, as evidenced by lower variability compared to SRT, but was not significantly different from DNS. Therefore, the static measurements of the present experiment established the presence of automatic postural control when concurrently performing a difficult cognitive task and quiet standing, which confirms the first hypothesis, and parallels the literature (Polskaia & Lajoie, 2016; Richer *et al.*, 2017; Potvin-Desrochers *et al.*, 2017).

As for the dynamic measurements, SampEn reiterated the proposition of automaticity when concurrently executing quiet standing and a difficult cognitive task, confirming the second hypothesis. SampEn values were significantly higher in the ML plane for each cognitive condition compared to the quiet standing alone. Unexpectedly, no significant difference was found between the effect of the SRT task, deemed easy, and the N-back and DNS tasks, which were chosen for their high cognitive demands as previously mentioned (Fraser *et al.*, 2016; Richer *et al.*, 2017). Furthermore, no difference was revealed between the SampEn values for the DT conditions and SM in the AP plane. Higher SampEn values have been indicative of a shift towards an automatic mode of postural as it reflects the amount of cognitive involvement allocated to the control of posture (Stins *et al.*, 2009; Potvin-Desrochers *et al.*, 2017). Thus, it is suggested that the cognitive tasks yielded enough cognitive distractions, and allowed the automatic processes to modulate postural control (Wulf, 2013).

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The wavelet discrete transform suggests the presence of automatic postural control when simultaneously performing all three cognitive tasks with quiet standing as it revealed a shift from conscious to automatic sensory systems. SRT, N-back and DNS in DT settings elicited a significant shift between a lower contribution from the moderate and UL bands, reflecting the proportion of regulation related to the somatosensory and visual systems, and a greater contribution from the low band, which is believed to reflect the contribution of the cerebellum (Quek *et al.*, 2014). As previously stated, the aforementioned shift is thought to represent a shift from a conscious to an automatic mode of postural control (Richer & Lajoie, under review; Cullen *et al.*, 2002). Furthermore, the N-back promoted higher cognitive demands compared to SRT as it produced a significantly greater shift between the sensory systems contributions as revealed by the LSD post-hoc test, but was not significantly different from the shift promoted by the DNS cognitive load. Consequently, the second hypothesis that a postural control-cognition dual-task would yield automatic postural behaviour was confirmed, and further supports the proposition of automaticity.

4.2. *Type and difficulty levels of the cognitive tasks*

Surprisingly, the SRT task yielded lower sway variability, higher SampEn values, and a shift from conscious to automatic sensory systems compared to SM, all of which are believed to be indicative of automatic postural control. Considered an easy discrete cognitive task, the SRT task may have promoted lower levels of automaticity seeing as sway area did not change under DT, and the changes were marginal compared to the N-back and DNS tasks. SRT was selected for its low difficulty level, as the cognitive load elicited by the task is minimal. A possible explanation for the discrepancies observed in the cognition-postural dual-task domain is the difficulty level and type (i.e. discrete and continuous) of cognitive tasks used (Pellecchia, 2003;

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Huxhold, Lie, Schmiedek & Lindenberger, 2006). It was initially believed that difficult cognitive tasks would produce postural instability as it resulted in increased postural sway when participants were standing on a compliant surface (Pellecchia, 2003). Contrary to the original findings, difficult cognitive tasks promoted greater stability because their cognitive demand retained focus and prevented participants from consciously controlling balance (Riley *et al.*, 2010; Polskaia & Lajoie, 2016; Richer, Polskaia & Lajoie, 2017; Richer *et al.*, 2017; Potvin-Desrochers *et al.*, 2017). As demonstrated by Richer and colleagues (2016), a cognitive task elicited greater stability as evidenced by a reduction in sway area and variability, and an increase in mean power frequency compared to internal and external focus of attention. Moreover, Polskaia and Lajoie (2016) have confirmed the presence of significantly lower sway area and sway variability for auditory moderate and difficult cognitive tasks compared to an easy auditory cognitive task. Therefore, we did not anticipate any significant difference promoted by the simultaneous execution a simple postural task (i.e. quiet standing with feet together) and SRT compared to SM. Unexpectedly, although in line with findings in the literature, the performance of SRT in a dual-task setting yielded higher SampEn values (Potvin-Desrochers *et al.*, 2017) and lower sway variability (Lajoie, Richer, Jehu & Tran, 2016) compared to the quiet standing only. Consequently, the findings of the present work suggest the SRT demand to be sufficient in diverting the attention from consciously controlling posture. Nevertheless, the attention is momentarily directed to the cognitive task since it is a discrete auditory task with a low cognitive load. Therefore, compared to the other more complex tasks, we surmise that the SRT elicits lower levels of automaticity.

Also of concern is the type of cognitive task used to allocate the attention away from the control of posture. A continuous cognitive task provides less opportunity to consciously control posture, where a discrete cognitive task is filled with lapses of time between stimuli, during which

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participants may allocate attention to postural control (Lajoie *et al.*, 2016; Lajoie *et al.*, 2017; Potvin-Desrochers *et al.*, 2017). However, when compared to the quiet standing only, where participants are required to refrain from moving as much as possible, and are likely to direct most of their attention on the postural task, SRT has been found to produce lower SD of COP and higher SampEn values as stated previously (Lajoie *et al.*, 2016; Potvin-Desrochers *et al.*, 2017).

Previous work has implied that the act of articulation increases instability as reflected by higher postural sway (Dault, Yardley & Frank, 2003). Although the SRT and N-back tasks required intermittent and verbal articulation, their simultaneous execution with quiet standing resulted in higher stability. This was evidenced by reduced sway area for the N-back, lower sway variability, higher SampEn values, and a shift from conscious to automatic sensory systems for both tasks compared to SM. We presume that the improvements observed in postural stability are an effect of the processing demands elicited by the performance of the tasks, which distract from allocating attention onto postural control, and are indicative of an automatic mode of postural control (Wulf, 2013; Polskaia & Lajoie, 2016; Lajoie *et al.*, 2016; Richer *et al.*, 2017; Potvin-Desrochers *et al.*, 2017).

4.3. *Effects of a dual-task paradigm on PFC activation*

The third and last hypothesis predicted lower PFC activation in a difficult dual-task setting compared to quiet standing only, which would suggest an automatic mode of postural control. As the fMRI literature has demonstrated, the motor networks become more efficient once automaticity of a task is achieved as reflected by lower brain activation (Wu *et al.*, 2004; Poldrack *et al.*, 2005). However, the results of the present study partially confirmed the hypothesis as the sole decrease in cortical activation observed was a trend toward significantly lower right PFC hemisphere activation compared to the left hemisphere for the concurrent

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execution of quiet standing and DNS. The statistical analyses did not reveal any significant difference in cortical activation between SM and DT for the SRT and N-back tasks. As for the DNS, a significant hemisphere by condition interaction was found. The LSD post-hoc test identified a significant trend between the right and left hemispheres in the dual-task setting. More specifically, DNS promoted significantly lower PFC activation in the right hemisphere compared to the activation in the left hemisphere. Therefore, the cortical activation partly confirms the presence of automaticity of postural control as the decrease in relative concentration in HbO₂ levels was only observed in the right PFC compared to the left hemisphere, when participants were simultaneously performing quiet standing and DNS.

4.4. *Cortical activation related to working-memory tasks*

The prefrontal cortex has been demonstrated to be involved in locomotion and postural control (Mihara *et al.*, 2008, 2012). The bilateral dorsal lateral prefrontal cortices have been implicated in maintaining standing balance (Mihara *et al.*, 2008, 2012). Moreover, the different roles played by both PFC hemispheres are well documented in the literature (Pérennou, Amblard, Laassel & Pélissier, 1997; Tulving, 2002). For instance, the literature has reported lateralization of postural control, in where the right hemisphere is thought to be prominently involved in postural control compared to the left hemisphere (Ugur, Gücüyener, Uzuner, Özkan & Özdemir, 2000; Karnath & Broetz, 2003; Takeuchi, Mori, Suzukamo, Tanaka & Izumi, 2016). Results of a study looking into smartphone use while walking has established that the left PFC inhibited inappropriate action, while the right PFC was involved in a conservative basic gait pattern for gait stability (Takeuchi *et al.*, 2016). To further support this claim, the right hemisphere has been found to be dominantly involved in the visual contribution for head stabilization in space (Pérennou *et al.*, 1997). Therefore, authors have postulated that the right hemisphere plays a

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prevalent role in the control of body stability. This claim supports our findings of lower right PFC activation in a difficult DT fashion, which suggests an automatic mode of postural control, and is presumed to reflect a shift from cortical to subcortical regions (Floyer-Lea & Matthews, 2004).

Another fundamental distinction between the two hemispheres is their role in relation to language processing and production. As mentioned in Chapter three, one possible explanation for the lack of finding when concurrently performing balance and the N-back task may be the verbal requirements of this difficult cognitive task. Owen and colleagues (2005) demonstrated a pattern in activation in where the following regions are activated during the completion of the N-back task: lateral premotor cortex, dorsal cingulate and medial premotor cortex, dorsolateral and ventrolateral PFC, frontal pole, and bilateral and medial posterior parietal cortex. However, for non-verbal data, there is a lack of left PFC activation, which suggests an important involvement of the left hemisphere in language processing (Owen, McMillan, Laird & Bulmore, 2005). In parallel, previous literature has demonstrated extensive left hemisphere lateralization of activation in response to language task that is well beyond the traditional Broca's area, which includes the lateral and medial portions of the left PFC (Binder *et al.*, 1997). Therefore, we advocate that the lateralization of brain activation related to verbalization may have concealed the effect of a difficult dual-task paradigm on cortical activation. This could explain the inconsistencies observed in PFC activation when participants were simultaneously performing the N-back with quiet standing compared to the DNS task, which does not require verbal response during the trial.

The PFC is not only involved in postural control (Mihara *et al.*, 2008, 2012), but is also centrally involved in higher cognitive activities such as planning, problem solving, and language as previously stated (Cohen *et al.*, 1994; Goldberg, Podell & Lovell, 1994). Further evidence has

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provided insight into his important role for the maintenance and manipulation of information held temporarily in mind, also referred to as working memory (D'Esposito *et al.*, 1995; Rypma & D'Esposito, 1999; Owen *et al.*, 2005). The literature provides considerable evidence on the differential roles played by both hemispheres with regard to working memory. Moreover, authors have postulated the encoding to be associated with left PFC activation, whereas the right PFC is involved in episodic memory retrieval (Tulving, Kapur, Craik, Moscovitch & Houle, 1994; Raye, Johnson, Mitchell & Nolde, 2000; Tulving, 2002). Using an event-related potential protocol, left frontal activation was demonstrated and associated with early encoding stages (Ruchkin, Johnson Jr, Grafman, Canoune & Ritter, 1992). Moreover, left PFC lateralization activation was observed during verbal encoding (Opitz, Mcklinger & Friederici, 2000). Consequently, the left PFC has been identified as implicitly related to the cognitive selection driven by the encoding phase of working memory (Goldberg *et al.*, 1994).

As for the DNS and N-back task, their continuous nature requires constant reshuffling of the contents held in working memory because different stimuli are simultaneously presented and stored (Cohen *et al.*, 1994; D'Esposito, *et al.*, 1998). Results of the present experiment parallel the literature as we observed greater left PFC activation in the dual-task setting compared to the right PFC (*Figure 3*), which could be associated with the encoding processes related to working memory since participants are presented with novel material (Tulvin *et al.*, 1994; Raye *et al.*, 2000; Tulving, 2002). Therefore, our findings support the asymmetry and differential roles played by both hemispheres, all of which may explain the discrepancies observed between the brain activation of the right and left PFC.

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4.5. *Is automaticity the preferable state of postural control?*

This study has lent support to the presence of automatic postural control under difficult dual-task conditions as evidenced with greater stability, lower sway variability, higher values of SampEn and a shift from conscious to automatic sensory systems. With regard to brain activation, reduced relative concentrations of HbO₂, believed to reflect automaticity, were solely identified between the right and left hemispheres when DNS was performed. Nevertheless, it is of necessity to enquire if automatic postural control is consistently favourable compared to consciously controlling posture.

Typically, automaticity is referred to as a process that occurs in the absence of attention, intention and awareness, but is also economical, elegant and occurs without uncertainty (Saling & Phillips, 2007). It has long been postulated that working in an automatic fashion would result in faster responses, and would result in greater cerebral activation (Saling & Phillips, 2007). With regard to postural control, the automatic motor control processes are often described as fast, reflexive and self-organized mechanisms, which ultimately allow greater postural stability (Wulf *et al.*, 2001; McNevin, Shea & Wulf, 2003). However, contrary to expectations, the examination of automatic behaviours did not reveal increases in global brain activation, but instead decreases of PFC activation were observed as well as a shift from cortical to subcortical regions (Floyer-Lea & Matthews, 2004; Puttemans, Wenderoth & Swinnen, 2005; Seitz & Roland, 1992). As presented earlier in this document, fMRI studies have demonstrated lower brain activation of the same brain regions once automaticity of a task was achieved (Wu *et al.*, 2004; Poldrack *et al.*, 2005). Following the same line of thinking, we advocate the decreases observed in the present study to be associated with automaticity of postural control. Therefore, it has been suggested that automatic processing is less fussy, less hesitant and more direct, which makes it more efficient and elegant than controlled processing (Saling & Phillips, 2007).

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On the other hand, extensive evidence has demonstrated a shift in brain activation pattern of automaticity compared to controlled processing. Puttemans and colleagues (2005) identified increased activation in the primary motor cortex, posterior cingulate zone, putamen, and right anterior cerebellum when a new bimanual coordination task was at an automated stage. Conversely, learning-related decreases in the bilateral opercular area, bilateral ventrolateral PFC, right ventral premotor and supramarginal gyrus, and anterior cingulate sulcus were observed in post-test compared to the initial stage of learning (Puttemans *et al.*, 2005). Authors have thus proposed that a gradual shift from cortical to subcortical involvement reflects the development of an internally, feedforward-driven executive mode, which is associated with acquisition of automaticity (Puttemans *et al.*, 2005; Seitz & Roland, 1992; Saling & Phillips, 2007). Therefore, it has been postulated that strengthening of the neural connections with skill acquisition is consequently less uncertain, and is simply more efficient.

As for automatic postural control, evidence in the literature has suggested lower postural sway, lower sway variability, greater SampEn values as well as a shift between the contribution of the sensory systems to be indicative of automaticity (Stins *et al.*, 2009; Potvin-Desrochers *et al.*, 2017; Richer *et al.*, 2017). Although counterintuitive, withdrawing attention from consciously controlling posture with a secondary task has demonstrated greater stability, and has prompted the modulation of posture by the automatic motor control processes (Wulf, 2013). However, recent findings have lent support to the possibility of viewing automaticity of sway as a continuum. Richer and colleagues (2017, 2018) have identified, through a wavelet analysis, a greater shift in the contribution of the sensory systems when participants were performing the double-number sequence (DNS) compared to its easier version, the single-number sequence (SNS). Likewise, the performance of a continuous cognitive task (i.e. SNS and DNS) compared to an external focus of attention has yielded greater postural control improvements, as evidenced

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by the static and dynamic measurements used (Polskaia, Richer, Dionne & Lajoie, 2015; Richer & Lajoie, under review). In parallel, continuous cognitive task have been demonstrated to elicit higher stability compared to external focus of attention (Richer *et al.*, 2017). Therefore, automatized postural control varies throughout the aforesaid conditions, and is believed to be best considered as a continuum (Richer, 2018).

Consequently, we advocate for automatic postural control, which is associated with higher postural stability and lower attentional demands, to be more efficient, and thus a superior mode of postural control compared to conscious control. As demonstrated in the cognition-postural control domain and focus of attention literature, withdrawing conscious attention from postural control leaves the automatic motor control processes to work unconstrained, and ultimately promotes higher postural stability (Wulf, 2013; Polskaia *et al.*, 2015; Potvin-Desrochers *et al.*, 2017; Richer *et al.*, 2017). Furthermore, as evidenced by the neuroimaging literature, automatic processing is simple, elegant, efficient, and demands less resources (Saling & Phillips, 2007), and should thus be prioritized in a healthy adult population.

4.6. *Baseline activity*

Unexpectedly, the sole execution of quiet standing, referred to as SM, did not elicit the same amount of PFC activation for each cognitive task. An analysis of variance on hemispheres by conditions revealed a trend toward significant differences between cortical activation for conditions ($F(2,34) = 2.738$, $p = .079$). As evident in Figures 4 and 5, SM for the SRT run yielded lower PFC activation compared DNS. Therefore, the baseline activity used to compare cortical activation was distinct for every cognitive task, and is thus not optimal. One possible explanation for the aforementioned results is the increased activation related to the instruction given prior to the execution of a task. Specifically, pre-task activation has been associated to the preparation of

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a specific task (Sakai & Passingham, 2002). Preparation for the performance of a task has been identified in the PFC, and is reflected by greater activation when verbally cued to start walking (Suzuki, Miyai, Ono & Kubota, 2008), when auditory perturbation-related cues are presented (Mihara *et al.*, 2008), or dependent on the items to be remembered (Sakai & Passingham, 2002). Therefore, evidence has suggested the presence of a preparatory phase to be associated with specific neural activities in the PFC (Suzuki *et al.*, 2008). Moreover, the literature has provided evidence of greater brain activation with increasing task difficulty (Barch *et al.*, 1997; Jonides, Schumacher, Smith & Lauber, 2008; Herff *et al.*, 2014). Consequently, the observed differences in cortical activation for the identical postural task may be explained by the preparation since participants were only instructed to stand as still as possible, and no instruction was given with regard to what they should be focusing on. Therefore, participants may have been preparing for one of the two difficult cognitive tasks ahead, which would have resulted in higher brain activation.

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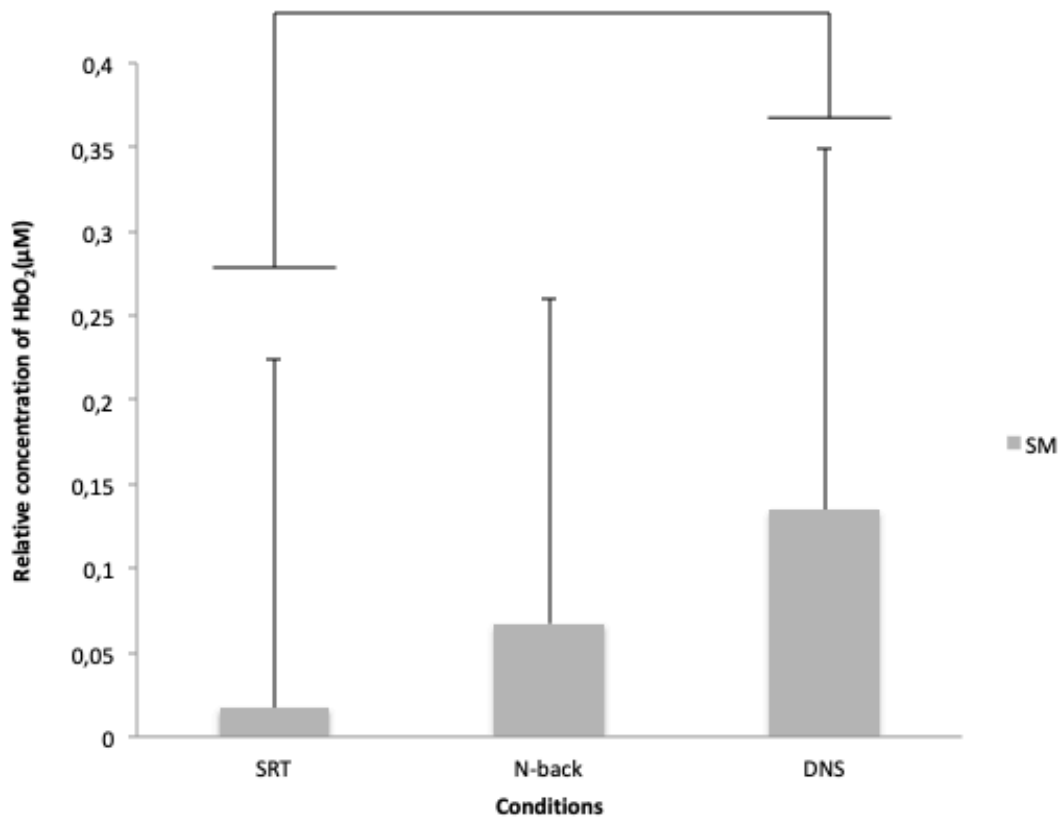


Figure 4. Right hemisphere relative HbO₂ concentration (μM) and SD for quiet standing only (SM).

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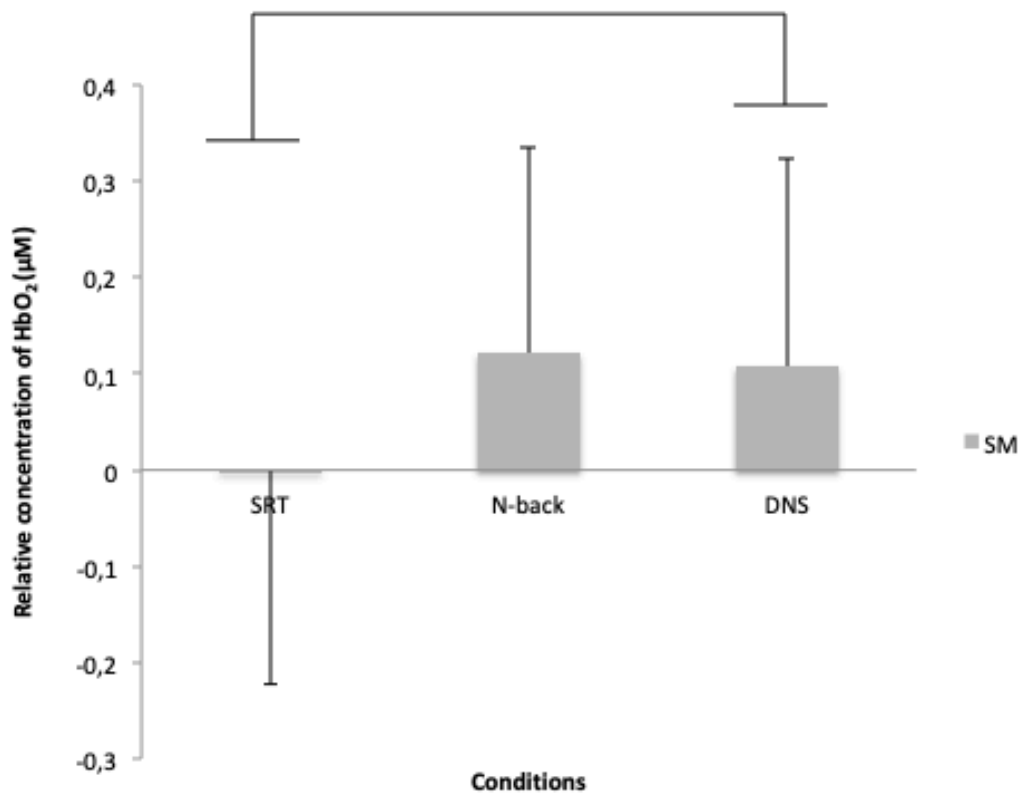


Figure 5. Left hemisphere relative HbO₂ concentration (µM) and SD for quiet standing only (SM).

CHAPTER FIVE: CONCLUSION

5.1. Summary of findings

The present experiment suggests the presence of automatic postural control, as evidenced by lower sway area and lower sway variability in the ML direction, when participants were concurrently performing quiet standing and N-back. As for SRT and DNS performed in a dual-task setting, the sole significant reduction was observed in sway variability in the ML direction. The dynamic measurements of COP excursions revealed greater SampEn values and a shift in contribution from conscious to automatic sensory systems for each cognitive task executed concurrently with quiet standing. Once more, the N-back elicited greater automaticity compared to SRT, as supported by lower contribution from frequencies representing the contribution of the visual system (Quek *et al.*, 2014). Therefore, the static and dynamic measurements suggest the presence of automaticity when the cognitive tasks are performed in a dual-task paradigm (Polskaia & Lajoie, 2016; Potvin-Desrochers *et al.*, 2017; Richer *et al.*, 2017). Furthermore, the N-back appears to have yielded higher automatic postural control seeing all the COP variables are in accordance. As for the neural correlates of automaticity, this study has identified a trend toward significantly lower right PFC activation compared to the left hemisphere when concurrently performing standing and DNS. The aforementioned results are believed to reflect automatic postural control as evidenced in the literature by lower cortical activation once automaticity of a task has been achieved (Wu *et al.*, 2004; Poldrack *et al.*, 2005; Floyer-Lea & Matthews, 2004). Consequently, the present work appears to suggest the presence of automatic postural control through static and dynamics measurements, and has provided insight into the neural correlates of automated standing.

5.2. *Limitations*

In addition to the limitations stated in Chapter three, we can only speculate to a shift from cortical to subcortical regions when in an automatic mode of postural control since our fNIRS device only allowed the examination of the PFC. Accordingly, we can not be certain of the aforementioned fact, and would need to investigate the effects of a difficult dual-task paradigm with an apparatus that allows a more complete examination of total brain activation. Realistically, the emitted infrared light travels in a banana-shape, and has a penetration depth of approximately 2 to 3 centimeters into the tissue (Perrey, 2008). Therefore, the examination of deeper brain regions has yet to be fulfilled with such equipment.

Although the present study has revealed numerous significant findings, an important limitation of this study is the high inter-subject and intra-subject variability present in the data (Minati, Visani, Dowell, Medford & Critchley, 2011; Wittenberg *et al.*, 2017). It has been demonstrated that at a subject level, there is a high variability in the shape and timing of the hemodynamic response (Hocke *et al.*, 2018), and in the distribution of activated regions within the PFC (D'Esposito *et al.*, 1995; Sato *et al.*, 2005). As for inter-subject variability, unaccounted anatomical differences may result in less precise positioning (Perrey, 2008; Minati *et al.*, 2011). Consequently, our data contains high variability, as evidenced by the high standard deviation related to relative HbO₂ concentration (*Figures 3, 4 & 5*), and could potentially explain our limited findings with regard to reduced PFC activation in a difficult dual-task setting.

5.3. *Practical implications*

The present work has further reiterated the presence of automatic postural control when concurrently performing quiet standing and difficult cognitive tasks, and its kinetic and kinematic properties are now extensively established. Likewise, it has provided evidence of the cortical activation required to quietly stand, which was absent from the current literature. Although more research is necessary, it has lent insight into the neural correlates of postural automaticity, and has identified a similar decrease in PFC activation as seen in fMRI studies when an automatized stage of movement has been reached. This work also validates the use of fNIRS as an effective portable neuroimaging tool to investigate cortical activation of gross motor tasks. Lastly, this experiment solidifies the claim of lower cortical activation suggested by the body of literature once automaticity has been achieved.

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APPENDIX A. WAVELET TRANSFORM AND FREQUENCY RANGE

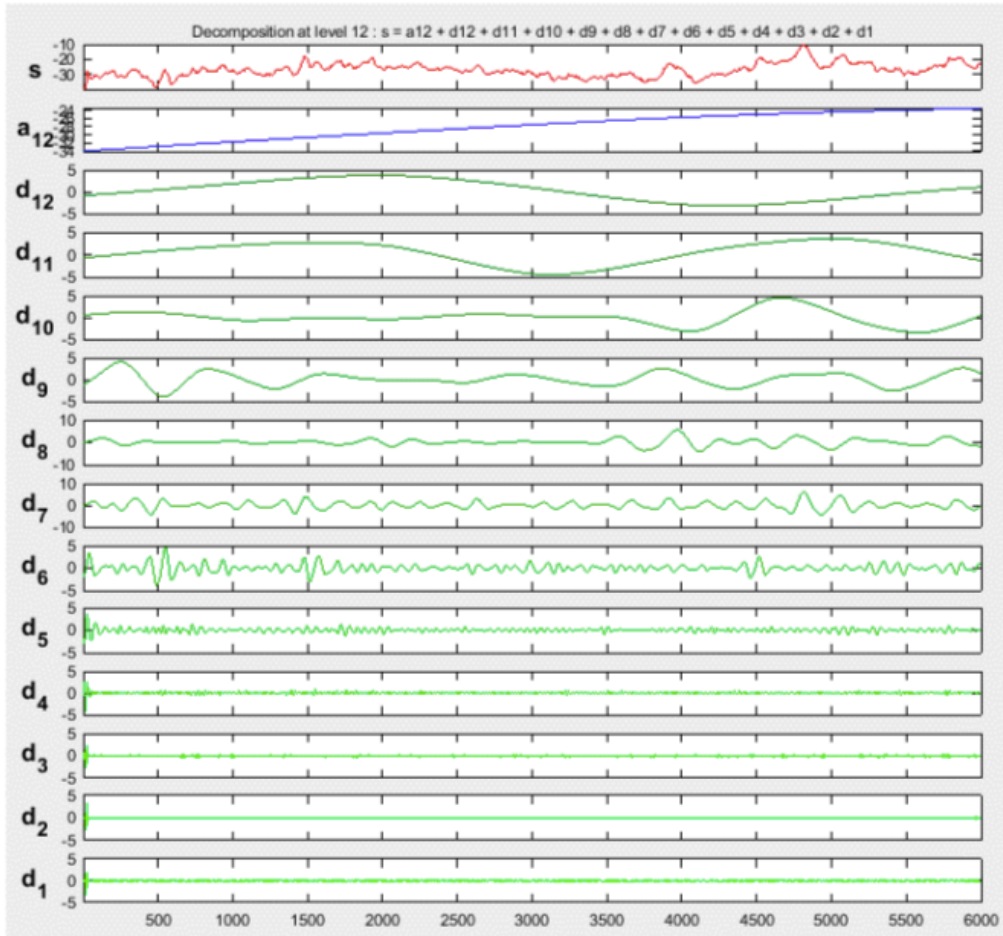


Figure 6. Example of a 12-level decomposition of a COP signal in quiet standing for a young adult participant, s represents the original COP signal and d1-d12, the details of decomposition at each level. (Figure taken from Richer et Lajoie, 2018a).

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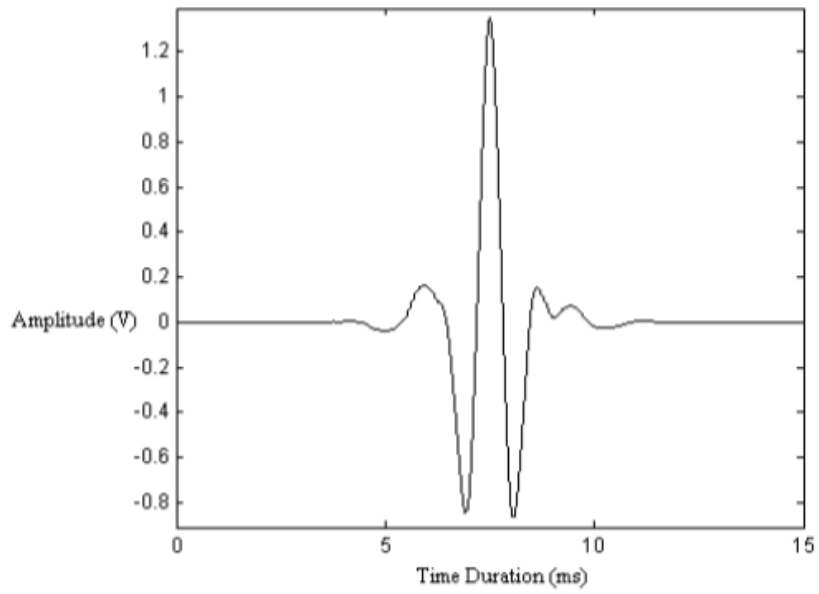


Figure 7. Example of a Symlet-8 wavelet (Hunter *et al.* 2010).

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Table 2.

Frequency content of each level of decomposition of the discrete wavelet transform. (Table taken from Richer, 2018).

DECOMPOSITION LEVEL	FREQUENCY RANGE (HZ)
1	50.0-100
2	25.0-50.0
3	12.5-25.0
4	6.25-12.5
5	3.13-6.25
6	1.56-3.13
7	0.78-1.56
8	0.39-0.78
9	0.19-0.39
10	0.10-0.19
11	0.05-0.10
12	0.02-0.05

*APPENDIX B. EXAMPLE OF A RUN***PROTOCOL A: STATIC BALANCE**

Participant ID:

Date:

PRAC #	SRT	BLOCK	SEQUENCE	RESPONSE #	NOTES
INSTRUCTIONS: Once you hear experiment details, relax and stare straight at the target. For this task you will sit . You will hear 3 initial warning beeps. The last of the three beeps is a higher pitch, when you hear this it means the task will start. The task will be the following: you will hear beeps in the headphones at random intervals. When you hear a beep, respond by saying the word "TOP" as fast as possible.					
Once the participant scores > 5/7 (~70%) continue to Block6 Single Motor.					
SINGLE COG	1		b		
	REST (15 S)				
SINGLE COG	2		c		
	REST (15 S)				
SINGLE COG	3		b		
	REST (15 S)				
SINGLE COG	4		c		
	REST (15 S)				
SINGLE COG	5		b		
	REST (15 S)				
INSTRUCTIONS: Once you hear experiment details, relax and stare straight at the target with your feet together on the square. After the initial warning beeps for the beginning of the trial, remain standing with your feet together. Please stand with your hands relaxed at your sides and look straight ahead at the target on the wall. Please refrain from moving during the trial.					
SINGLE MOTOR	6		a		
	REST (15 S)				
INSTRUCTIONS: Once you hear experiment details, relax and stare straight at the target. After the initial warning beeps for the beginning of the trial, respond to beeps by saying "TOP" as quickly as possible and simultaneously remain standing and staring straight ahead. <i>If at any point you are fatigued or feel like you are losing your balance, please let us know and we can stop the experiment for a break.</i>					
DT	7		b		
	REST (15 S)				
DT	8		c		
	REST (15 S)				

Figure 8. Example of a SRT run of a static protocol of a healthy young adult.

APPENDIX C. HEALTH QUESTIONNAIRE

1. In the last year have you participated in a cognitive study? (If yes, at least 6 months should have passed between the ending of the previous study and this study)
2. What is your mother tongue?
3. What is your age?
4. What is your date of birth?
5. What is your highest level of education? (Degree and number of years)
6. Are you right or left handed? Right handed ___ Left Handed ___
7. In the last 6 months did you have surgery (or another medical intervention) that required general anesthesia? (If yes, write the date of the anesthesia and we will see them after the delay)
8. Do you have vision or hearing problems that have not been corrected or an abnormal loss for your age?
9. Have you ever had frequent or requiring migraines?
10. Have you ever had neurological or psychiatric problems? If so which ones?
11. Have you ever had a head injury? When?
12. Have you ever lost consciousness?
13. Have you had tremors or involuntary movements?
14. Have you ever had motor problems (walking or manipulating objects) (If severe, exclusion)?
15. Have you ever had dizziness or problems with maintaining your balance (If yes, ask more questions: of what nature, when, frequency, etc.)?
16. Have you ever had an injury to your lower extremities (hip, knee, ankle)?
17. Do you have a cardiovascular condition?
18. Do you have high blood pressure?
19. Do you have diabetes?
20. Do you have arthritis?
21. Do you have epilepsy?
22. Do you have a thyroid condition?
23. Have you ever fallen while walking?
24. What is your weekly consumption of alcohol?
25. Have you ever had alcohol or drug abuse problems?
26. Do you smoke?
27. Do you have problems with concentration or attention?
28. Do you have problems with your memory?
29. Do you have problems finding your words while talking?
30. Have the people close to you noticed a significant difference in these three areas: attention, memory, trouble finding words?
31. Are you physically active regularly (more than 2 times per week) besides activities of daily living? What are these activities?
32. Do you take medication? If yes, do these medications make you feel drowsy or affect your mental state? (List the medications, name and dosage, that are taken regularly)

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APPENDIX D. SHORT PHYSICAL PERFORMANCE BATTERY (SPPB)

1. Repeated Chair Stands

Instructions: Do you think it is safe for you to try and stand up from a chair five times without using your arms? Please stand up straight as quickly as you can five times, without stopping in between. After standing up each time, sit down and then stand up again. Keep your arms folded across your chest. Please watch while I demonstrate. I'll be timing you with a stopwatch. Are you ready? Begin Grading: Begin stop watch when subject begins to stand up. Count aloud each time subject arises. Stop the stopwatch when subject has straightened up completely for the fifth time.

Also stop if the subject uses arms, or after 1 minute, if subject has not completed rises, and if concerned about the subject's safety.. Record the number of seconds and the presence of imbalance. Then complete ordinal scoring.

Time: _____sec (if five stands are completed)

Number of Stands Completed: 1 2 3 4 5

Chair Stand Ordinal Score: _____

0 = unable

1 = > 16.7 sec

2 = 16.6-13.7 sec

3 = 13.6-11.2 sec

4 = < 11.1 sec

2. Balance Testing

Begin with a semi-tandem stand (heel of one foot placed by the big toe of the other foot).

Individuals unable to hold this position should try the side-by-side position. Those able to stand in the semi-tandem position should be tested in the full tandem position. Once you have completed time measures, complete ordinal scoring.

a. Semi-tandem Stand

Instructions: Now I want you to try to stand with the side of the heel of one foot touching the big toe of the other foot for about 10 seconds. You may put either foot in front, whichever is more comfortable for you. Please watch while I demonstrate.

Grading: Stand next to the participant to help him or her into semi-tandem position. Allow participant to hold onto your arms to get balance. Begin timing when participant has the feet in position and lets go.

Circle one number

2. Held for 10 sec

1. Held for less than 10 sec; number of seconds held _____

0. Not attempted

b. Side-by-Side stand

Instructions: I want you to try to stand with your feet together, side by side, for about 10 sec. Please watch while I demonstrate. You may use your arms, bend your knees, or move your body to maintain your balance, but try not to move your feet. Try to hold this position until I tell you to stop.

Grading: Stand next to the participant to help him or her into the side-by-side position. Allow participant to hold onto your arms to get balance. Begin timing when participant has feet together and lets go.

Grading

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2. Held of 10 sec

1. Held for less than 10 sec; number of seconds held _____

0. Not attempted

c. Tandem Stand

Instructions: Now I want you to try to stand with the heel of one foot in front of and touching the toes of the other foot for 10 sec. You may put either foot in front, whichever is more comfortable for you. Please watch while I demonstrate.

Grading: Stand next to the participant to help him or her into the side-by-side position. Allow participant to hold onto your arms to get balance. Begin timing when participant has feet together and lets go.

Grading

2. Held of 10 sec

1. Held for less than 10 sec; number of seconds held _____

0. Not attempted

Balance Ordinal Score: _____

0 = side by side 0-9 sec or unable

1 = side by side 10, <10 sec semitandem

2 = semitandem 10 sec, tandem 0-2 sec

3 = semitandem 10 sec, tandem 3-9 sec

4 = tandem 10 sec

3. 8' Walk (2.44 meters)

Instructions: This is our walking course. If you use a cane or other walking aid when walking outside your home, please use it for this test. I want you to walk at your usual pace to the other end of this course (a distance of 8'). Walk all the way past the other end of the tape before you stop. I will walk with you. Are you ready?

Grading: Press the start button to start the stopwatch as the participant begins walking.

Measure the time take to walk 8'. Then complete ordinal scoring.

Time: _____ sec

Gait Ordinal Score: _____

0 = could not do

1 = >5.7 sec (<0.43 m/sec)

2 = 4.1-6.5 sec (0.44-0.60 m/sec)

3 = 3.2-4.0 (0.61-0.77 m/sec)

4 = <3.1 sec (>0.78 m/sec)

Summary Ordinal Score: _____

Range: 0 (worst performance) to 12 (best performance). Shown to have predictive validity showing a gradient of risk for mortality, nursing home admission, and disability.