

Postural control mechanisms in young and older adults

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Abstract

Recent findings have suggested that the type of postural control seems to change, with certain conditions promoting a more conscious control and others, a more automatic control. It has been proposed that by withdrawing attention from postural control, external focus and cognitive task conditions allow automatic mechanisms to control sway more efficiently. The present dissertation aimed to investigate whether two types of postural control exist and to provide evidence for these two types of postural control in healthy young and older adults. In experiment 1, the effect of attentional focus and cognitive tasks was examined in healthy older adults. It was found that the cognitive task yielded improvements in stability compared to focus conditions, which highlighted the fact that automaticity is possible in this group. In experiment 2, the effect of attentional focus and cognitive tasks was once again observed in older adults, this time by including electromyographic recordings of lower leg muscles to examine if changes were due to stiffening. Although improvements were observed in external focus and cognitive task conditions compared to baseline and internal focus, no change occurred in muscle activity which lends further support to the idea that changes are due to automaticity. Finally, dynamic measures of sway were used to help interpret the changes that occurred in attentional focus and cognitive task conditions in both young and older adults. The wavelet transform revealed a change in sensory contributions to postural control in cognitive task conditions. There was a shift to increased contributions from the cerebellum and the vestibular system, and a decrease in visual contributions, compared to other conditions. Sample entropy revealed changes in complexity of sway, with cognitive tasks presenting more complex, irregular and efficient sway in both groups compared to baseline standing and attentional focus conditions. Finally, the rambling-trembling decomposition highlighted increases in the spinal reflex contributions to sway in external focus and difficult

cognitive task conditions in young adults, while no change occurred in older adults. Results of these experiments provide the evidence of two types of postural control; a more automatic type in cognitive task conditions and a more conscious type in baseline and internal focus conditions. The external focus elicited some changes that could have indicated automaticity, but clear differences were still present between this condition and the cognitive tasks, which suggest automaticity of sway should be viewed as a continuum.

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Preface

The present dissertation presents an investigation on the automaticity of sway. The three research objectives were formulated with my supervisor, Dr. Yves Lajoie. For the first experiment, I was responsible for participant recruitment, data collection, data analysis, and preparation of the manuscript. Research assistance in participant recruitment, data collection and data analysis was provided by two undergraduate students, Sarah Kosacky and Sepideh Sanaee. Further assistance was provided by Nadia Polskaia, who worked with me through all steps of the project including preparation of the manuscript and is therefore co-author on the corresponding paper. Nadia gives her consent to the inclusion of the paper in this dissertation. Dr. Lajoie helped oversee this project and provided guidance throughout, particularly during preparation of the manuscript. He also gives consent to the inclusion of this paper in the dissertation.

For the second experiment, I was once again responsible for all steps of the project. Two undergraduate students, Kien Ly and Noémy Fortier, were involved and greatly assisted in participant recruitment, data collection, and data analysis. The preparation of the manuscript was primarily done by myself, with revisions by Dr. Lajoie, who once again helped oversee the project and assisted with technical issues that arose with the equipment. All three co-authors give consent to the inclusion of this manuscript in the dissertation.

Data from the second experiment was used for the third experiment. Additionally, data collected in another experiment was also used. In this experiment, I once again participated in all steps of the research process including participant recruitment, data collection, data analysis and manuscript preparation. I received assistance from two undergraduate students, Andrew Athanathious and Annabelle Phillion, who assisted in participant recruitment, data collection, and

data analysis, and two master's students, Deanna Saunders and Nadia Polskaia, who also participated in all steps of the experiment. With data collected in these two previous studies, I completed secondary analyses. Since these were new analyses to our laboratory, myself and Dr. Yves Lajoie worked extensively on learning the procedures for these analyses. I then completed the data analysis and manuscript preparation. Dr. Lajoie helped by revising the manuscript before submission. He gives consent to the inclusion of this manuscript in the dissertation.

In summary, I was fully involved in each experiment presented in this dissertation. I was involved in conception, ethics proposal, participant recruitment, data collection and analysis, statistical analysis, and manuscript preparation. The following provides a summary of the three manuscripts that are included in this dissertation, as well as the article containing the data set which served for secondary analysis in the third experiment.

Experiment 1: Published

Richer, N., Polskaia, N., & Lajoie, Y. (2017). Continuous Cognitive Task Promotes Greater Postural Stability than an Internal or External Focus of Attention in Older Adults. *Experimental Aging Research*, 43,1, 21-33.

Experiment 2: Submitted for publication

Richer, N., Ly, K., Fortier, N., & Lajoie, Y. Improvements in postural control in external focus and cognitive task conditions are unlikely due to stiffening in healthy older adults. Submitted to *Gait & Posture*, January 2018.

Experiment 3: To be submitted for publication

Richer, N., & Lajoie, Y. Automaticity of postural control while dual-tasking revealed in young and older adults.

Related published manuscript:

Richer, N., Saunders, D., Polskaia, N., & Lajoie, Y. (2017). The effects of attentional focus and cognitive tasks on postural sway: stiffening or automaticity? *Gait & Posture*, 54, 45-49.

List of Abbreviations

COP	Centre of pressure
AP	Anterior-posterior
ML	Medial-lateral
MMSE	Mini Mental State Examination
SD	Standard deviation
FFT	Fast Fourier transform
MPF	Mean power frequency
ANOVA	Analysis of variance
TA	Tibialis anterior
MG	Medial gastrocnemius
EMG	Electromyography
SNS	Single number sequence
DNS	Double number sequence
Area	Area of 95% confidence ellipse

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Chapter 1 – Introduction

Postural control was once considered an automatic process, with no cognitive involvement (Woollacott & Shumway-Cook, 2002). Multiple dual-task studies have since argued that static postural control requires cognitive involvement (Teasdale, Bard, Larue, & Fleury, 1993; Lajoie, Teasdale, Bard, & Fleury, 1993; Lajoie, Teasdale, Bard, & Fleury, 1996; Maylor & Wing, 1996; Kerr, Condon, & McDonald, 1985; Remaud, Boyas, Caron, & Bilodeau, 2012). Recent findings have suggested that both ideas may be correct; the type of postural control seems to change, with certain conditions promoting a more automatic control and others a more conscious control (Wulf, 2007). For example, attentional focus has been suggested to impact automaticity of postural control (McNevin, Shea, & Wulf, 2003; Wulf, Shea, & Park 2001; Wulf & Prinz, 2001; Wulf, McNevin, & Shea 2001). When participants are instructed to focus on the effects of their movements, as opposed to movement production, they present improved performance and faster reaction times (Wulf *et al.*, 2001a). The constrained action hypothesis suggests that an external focus is beneficial to postural control since it is associated to a more automatic control (McNevin *et al.*, 2003; Wulf *et al.*, 2001a; Wulf & Prinz, 2001; Wulf *et al.*, 2001b). By focusing on external cues, individuals allow the motor system to self-organize and maintain posture in a more automatic, efficient way (McNevin *et al.*, 2003; Wulf *et al.*, 2001a; Wulf & Prinz, 2001; Wulf *et al.*, 2001b). Research has demonstrated that an external focus of attention is associated with not only faster reaction times, but also a higher frequency of postural adjustments and more efficient muscular activity (Wulf, 2007). Additionally, recent studies have demonstrated that performing continuous and challenging cognitive tasks while standing improve postural control even more

than an external focus (Polskaia, Richer, Dionne, & Lajoie, 2015; Richer, Saunders, Polskaia, & Lajoie, 2017b). Presumably, distracting the participant from postural control allows the emergence of automatic postural behaviours. Alternatively, improvements may be due to a co-contraction of muscles around the ankle joint to allow cognitive resources to be allocated to the challenging cognitive task (Dault, Frank, & Allard, 2001; Dault, Yardley, & Frank, 2003; McNevin & Wulf 2002; Melzer, Benjuya, & Kaplanski, 2001; Weeks, Forget, Mouchnino, Gravel, & Bourbonnais, 2003). The aim of the present thesis is therefore to verify if there are two types of postural control in young and older adults and, if so, to provide evidence of these two types of control. Specifically, there will be three objectives. Firstly, the effect of attentional focus and cognitive tasks will be examined in older adults to see if this population is capable, like young adults, of benefiting from automatic postural control. Secondly, the electromyographical signal from leg muscles will be analysed to provide evidence that the stiffening strategy is not used in older adults, as has already been done in young adults. Finally, dynamic measures of sway will be used to exhibit changes in the structure and composition of sway to reveal automatic components in both young and older adults.

Chapter 2 – Review of literature

Control of Posture

Postural control is a complex mechanism which is essential in our everyday lives. It is needed for most of our daily activities, such as standing, walking or any task requiring balance such as rising from a chair (Shumway-Cook & Horak, 1990). Postural control has two general goals: postural orientation and postural equilibrium (Horak, 2006). Postural orientation is the active control of body alignment and tone with respect to gravity, support surface, visual environment and internal references. Postural equilibrium represents the coordination of sensorimotor strategies to stabilise the body's centre of mass during self-initiated and externally triggered disturbances in postural stability (Horak, 2006). To maintain postural orientation, we resort to the sensory systems (vestibular, visual and proprioceptive system), the central nervous system and the musculoskeletal system (Downton, 1990). The proprioceptive system consists of joint and cutaneous receptors that give us information about the state of the effector system and about the environment (Winter, Patla, & Frank, 1990). The vestibular system gives us information about our body orientation in the inertial frame of reference and the accelerations of the body (Winter *et al.*, 1990). The visual system provides information about the environment and the orientation and movement of our body (Winter *et al.*, 1990). These sensory systems monitor mismatches between the intended and actual position of the body. A postural body scheme provides an internal representation of the body geometry, dynamics and orientation with respect to verticality (Massion, 1994). This internal representation is the basis on which all our anticipatory postural adjustments associated with voluntary movements are organized (Massion, 1994). When standing on a stable surface and surrounded by fixed visible objects, information from the three sensory sources is accurate and sufficient to maintain balance (Nashner, 2001). When one source

of information is distorted however, balance can be affected. For example, an experiment by Pyykkö, Jääntti and Aalto (1990) evaluated perturbation of sensory information in young and older individuals. They found that when older individuals closed their eyes, their sway velocity increased significantly. The effect of sensory distortion or deprivation is more apparent in older individuals due to the declines that come with age, as will be explained in the *Aging effects on postural control and attention* section.

Measuring Postural Control

Force platforms have been commonly used since the 1970s to measure balance performance (Palmieri, Ingersoll, Stone, & Krause, 2002). They provide indirect assessments of postural sway changes by recording the body's projections of ground-reaction forces (Browne & O'Hare, 2000; Palmieri *et al.*, 2002). From these forces, the centre of pressure (COP) is calculated, which reflects the trajectory of the centre of mass and the amount of torque applied at the support surface in order to control body-mass acceleration (Winter *et al.*, 1990; Palmieri *et al.*, 2002). Several parameters derived from the COP signal are used to quantify changes in balance (Palmieri *et al.*, 2002). The sway amplitude and velocity and the root mean square amplitude and velocity are examples of these parameters.

Firstly, there are one-dimensional measures of postural control. These measures evaluate postural control in the anterior-posterior (AP) and medial-lateral (ML) directions (Palmieri *et al.*, 2002). Sway amplitude represents the displacement of the COP. It can be represented by the maximum amplitude (maximum absolute displacement of the COP from its mean), minimum amplitude (minimum absolute displacement of the COP from its mean), peak-to-peak amplitude (difference between the maximum and minimum amplitudes of COP), or mean amplitude (Palmieri *et al.*, 2002). Minimum, maximum and peak-to-peak amplitude use 2 data points which

do not effectively represent the changes that occur during a trial. It is therefore important to not base analysis solely on these measures (Palmieri *et al.*, 2002). Mean amplitude of COP is a more representative measure of postural control than the minimum, maximum and peak-to-peak amplitude since it is an average value over all data points in a trial (Palmieri *et al.*, 2002). An increase in value of mean COP amplitude would suggest a decreased ability to maintain postural control, while a decrease is believed to represent an increase in postural stability (Baloh, Jacobson, Beykirch, & Honrubia, 1998; Murray, Seireg, & Sepic, 1975). Another one-dimensional measure that is frequently used is the standard deviation (SD) of the COP. Typically, an increase in SD of the COP is viewed as an indication of reduced postural stability (Riley, Baker, Schmidt, & Weaver, 2005).

Secondly, there are two-dimensional measures of postural control. These measures are a combination of the AP and ML COP movement (Palmieri *et al.*, 2002). The COP velocity is the total distance traveled by the COP over time (Palmieri *et al.*, 2002). It has been demonstrated as having a good reliability between sessions in two-legged stance ($R = .84$; Le Clair & Riach, 1996). An increase in COP velocity is believed to represent a decrease in ability to control posture, while a decrease in velocity would represent an increased ability to control posture (i.e. Baloh *et al.*, 1998; Baloh, Jacobson, Enrietto, Corona, & Honrubia, 1998). Another measure is the total excursion, also referred to as sway path. It represents the total distance traveled by the COP (Palmieri *et al.*, 2002). As these measures are two-dimensional, they are insufficient as lone measures and cannot adequately demonstrate changes that occur in postural sway. For example, it is possible to miss important directional information, such as a change in sway that occurs in only one direction (Palmieri *et al.*, 2002). For this reason, additional methods of measure are needed

for a complete analysis of posture, such as root mean square amplitude and velocity, area of 95% confidence ellipse, and time-frequency measures.

Root mean square amplitude is defined as the standard deviation of the displacement of the COP. It measures the average absolute displacements around the mean COP (Palmieri *et al.*, 2002). Root mean square velocity represents the distribution of COP displacements over time (i.e. Baloh *et al.*, 1998; Geurts, Nienhuis, & Mulder, 1993). A decrease in both these values represents an increase in postural control ability, while an increase would suggest a decreased ability to maintain an upright stance (Geurts *et al.*, 1993). These values are reliable to evaluate stability (Geurts *et al.*, 1993; LeClair & Riach, 1996). Le Clair and Riach (1996) found intersession reliability was high in AP ($R = .86$) and ML ($R = .81$) directions. Root mean square amplitude and velocity are useful to observe changes in postural control, however additional measures are needed to complete understanding of what happens during postural control (Palmieri *et al.*, 2002). Another measure is the area of 95% confidence ellipse. This is the measure of the area over which the COP travels. It is determined by taking the radius of the major and minor axes and fitting an ellipse that includes 95% of the points (Doyle, Hsiao-Wecksler, Ragan, & Rosengren, 2007). This measure was evaluated as being reasonably reliable in trials of at least 60 seconds ($G = 0.70$) according to Doyle and colleagues' experiment in 2007.

Finally, mean power frequency is a measure that is often used to evaluate postural control. Mean power frequency is calculated with the fast Fourier transformation. Higher frequency values have been attributed to more efficient and automatic postural control (Wulf *et al.*, 2001a), although they have also been attributed to stiffening of the ankle joint (Carpenter, Frank, Silcher, & Peysar, 2001). According to Ferdjallah, Harris and Wertsch (1997), the frequency content of postural sway has over 90% of its total energy below 2 Hz. An experiment by Cherng, Lee and Su (2003)

demonstrated that in young adults, median frequencies were between 0.74 and 1.02 Hz in the AP direction and between 0.85 and 1.05 Hz in the ML direction. Two experiments by the same research group were conducted to evaluate mean and median frequencies in young and older adults (McClenaghan *et al.*, 1995; Williams, McClenaghan, & Dickerson, 1997). McClenaghan and colleagues (1995) suggested that spectral power distribution is mostly concentrated at lower frequencies in older adults compared to young adults in both ML and AP directions. In the AP direction, young adults had a mean frequency of 1.15 Hz and older adults had a mean frequency of 1.10 Hz. In the ML direction, young adults had a mean frequency of 1.00 Hz and older adults had a mean frequency of 0.90 Hz. The researchers also found that ML mean sway frequency was significantly lower in the elderly participants who reported having fallen during a 1-year period. Williams and colleagues (1997) separated older adults into low- and high-risk groups. In the AP direction, mean frequencies were significantly higher for both elderly groups compared to young adults (young adults: 0.81 Hz; low-risk elderly: 1.12 Hz; high-risk elderly: 1.05 Hz). In the ML direction, young adults and low-risk elderly presented similar mean sway frequencies and high-risk elderly had significantly lower mean frequencies than low-risk elderly (young adults: 1.00 Hz; low-risk elderly: 0.95 Hz; high-risk elderly: 0.85 Hz). Results of these two experiments reveal that frequency values are not consistent between studies. Certain findings reveal higher frequency values in older adults, others report higher values in young adults. This may be due to differences in methodology or participants. However, Williams *et al.* (1997) and McClenaghan *et al.* (1995) have used the same protocol, analysis method and have very similar participant groups. The reason for the different frequency results may therefore be the different types of postural control that were used by participants. It is believed there are two types of frequency in individuals: a higher frequency which is used for automatic postural control and a lower frequency for posture that is

controlled consciously. The previous studies did not attempt to separate frequencies into high and low bands, instead the presented frequencies are average values that could be hiding these two types of control. As will be highlighted in the next few sections, mean power frequency might not be the best measure to evidence the two types of postural control. Instead, other types of measures allow a better representation of the structure of postural control.

Limitations of traditional COP measures

Traditional COP measures, such as sway area, SD of sway and velocity of sway, quantify the magnitude of variation of sway. This can provide an indication of changes in postural control, however may hide certain changes in sway that are imperceptible by simply examining one static value (i.e. Cavanaugh, 2005; Cavanaugh, Mercer, & Stergiou, 2007; Vaillancourt & Newell, 2000). The traditional COP measures can also be misleading. For example, patients with Parkinson's disease may present reductions in sway area compared to their healthy counterparts, however this does not represent an improvement in their postural control (Schieppati, Hugon, Grasso, Nardone, & Galante, 1994). It is therefore important to examine dynamic measures of postural control which examine the structure of variation in a sequence as well as indicate which systems are contributing to sway, to properly interpret what is happening during postural control.

Dynamic measures

To further understand the impact of attentional focus and dual-tasks on the structure and composition of sway, three dynamic measures were chosen. Firstly, the wavelet transform will provide an indication of how sensory systems are involved in postural control and how this involvement changes in dual-tasking. Secondly, sample entropy will indicate changes in regularity of a signal, with higher values representing a more complex signal thought to be indicative of increased automaticity (Potvin-Desrochers, Richer, & Lajoie, 2017; Donker, Roerdink, Greven, &

Beek, 2007). Finally, the rambling-trembling decomposition will be used to decompose sway in supraspinal and reflexive components, in order to examine how the systems' contributions change across conditions.

Wavelet

The frequency of sway can indicate important information about postural control and is typically calculated using the Fourier transform. For example, studies by Wulf and colleagues have proposed that higher mean power frequency values observed in external focus conditions are indicative of more automatic postural control (see Wulf, 2007 for review). Although the Fourier transform allows you to find a range of frequencies that appear over a certain amount of time, it cannot isolate the exact frequency of a signal in an exact moment of time. It therefore is impossible to isolate events that may occur in postural sway (Dallas, 2014; Chun-Lin, 2010). The Fourier transform is a reversible transformation that allows data to be processed in the time domain or in the frequency domain, but not both. This is appropriate for a stationary signal, in which the statistical properties of a signal are constant throughout a trial (Schumann, Redfern, Furman, El-Jaroudi, & Chaparro, 1995). However, studies have demonstrated that the COP signal is in fact non-stationary (Carroll & Freedman, 1993) and therefore the use of non-stationary measures that provide both time and frequency information at the same time is important to understand the time varying aspect of postural control (Schumann *et al.*, 1995; Polikar, 1996).

In the wavelet transform, small wavelike functions (known as wavelets) are manipulated over the COP signal (Addison, 2017). These wavelets are limited in both time and frequency, allowing the signal to be analyzed in both time and frequency domains simultaneously (Polikar, 1996). Furthermore, unlike the Fourier transform which works with infinite sine and cosine waves, the wavelets are limited in time and therefore allow higher resolution in the time domain (Dallas,

2014). These wavelets are slid across the signal in the time domain. At the same time, the scale of the wavelet is changed. It gets squeezed for high frequencies and stretched for low frequencies (Dallas, 2014). There are several different wavelet shapes that can be used, which will reflect the type of signal that is analyzed. Figure 1 is an example of four different wavelets, adapted from the book by Addison (2017). For the present thesis, the Symlet-8 wavelet will be used following methods by Quek, Brauer, Clark, and Treleaven (2014) and because it is thought to be a good fit for the COP signal. It is represented in Figure 2, an image from Hunter and colleagues (2010).

If the wavelet matches the shape of the signal at a specific location, a large transform value is obtained, and when it does not match well, the transform value is small. This computation is made in different locations along the signal and with different wavelet scales, therefore a correlation is made between the wavelet and the signal (Addison, 2017). As the wavelet scale is modified, the resolution of time and frequency changes. As time resolution decreases, frequency resolution increases and vice versa (Shensa, 1992).

The wavelet transform can be used in several different ways to investigate the content of a signal. In the present experiment, the COP will be decomposed into different frequency bands. Specifically, the signal will be decomposed into two parts using a high pass and low pass filter. Then, this step will be repeated with the low pass portion of the signal. This decomposition will continue for a predetermined number of levels to provide a decomposition of one signal into multiple bands each representing a specific frequency range (Polikar, 1996). The COP data which will be sampled at 500 Hz will be desampled to 100 Hz to allow decomposition to small frequency ranges that adequately represent sway. Twelve levels of decomposition will be performed. Table 1 represents the frequency content of each of these 12 levels.

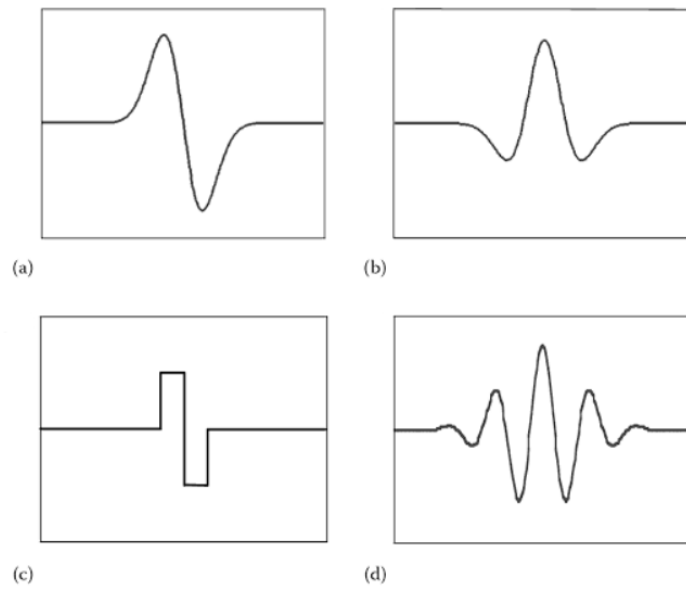


Figure 1. Example of four different wavelets: a) Gaussian wave; b) Mexican hat; c) Harr; d) Morlet
(Adapted from Addison, 2017).

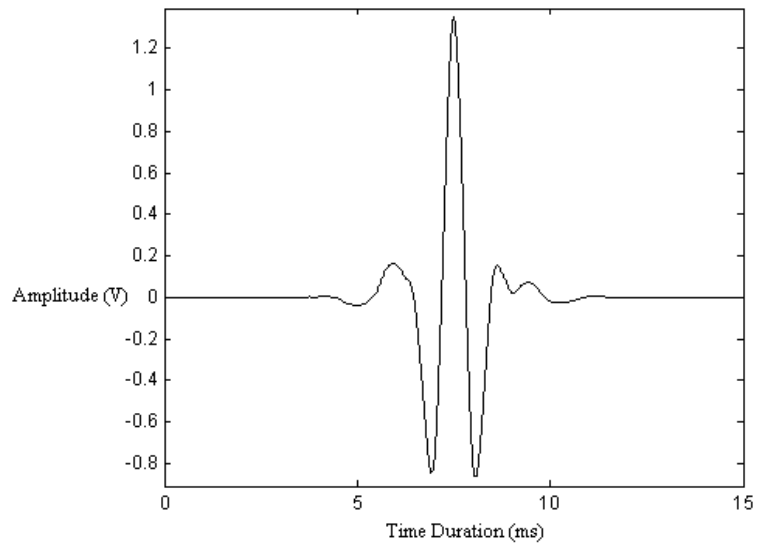


Figure 2. Example of a Symlet-8 wavelet (From Hunter *et al.*, 2010).

Table 1. *Frequency content of each level of decomposition of the discrete wavelet transform.*

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

Following the 12-level wavelet decomposition of sway, these frequency ranges can be combined into different frequency bands. Certain frequency bands are thought to capture postural movements associated with different systems (Quek *et al.*, 2014). By examining how these contributions change across conditions, it might be possible to provide support for automaticity of sway. Quek and colleagues (2014) propose that the moderate band (1.56 and 6.25 Hz) represents contributions from muscular proprioceptive components; the low band (0.39 and 1.56 Hz) represents cerebellar contributions; the very-low band (0.10 and 0.39 Hz) represents contributions from the vestibular system; and the ultralow band (under 0.10 Hz) represents contributions from the visual system. There is support for this separation of frequency bands, although certain bands are more established than others.

Firstly, many experiments were done to evaluate vestibular contributions to postural control. Kapteyn and de Wit (1972) report that the low frequency of about 0.20 Hz is associated with the vestibular system since it is absent in people without vestibular functions, and is present in people with vestibular dysfunction and when the vestibular system is stimulated. Similarly, Taguchi (1978) found that in patients with peripheral vestibular lesions that had their eyes closed, there was a peak from 0.20 to 0.30 Hz. Soames and Atha (1982) report the contribution of the vestibular system in the frequency range of 0.30 to 0.40 Hz as suggested by various authors (Gantchev & Popov, 1973; Cernacek, Jagr, Harman, & Vyskocil, 1973; Partridge & Kim, 1969; Mano *et al.*, 1976). Therefore, the range of 0.10 to 0.39 Hz seems to adequately represent vestibular contributions.

The visual contributions are also well established. According to a review by Berthoz and colleagues (1979), vision contributes to postural control in frequency ranges of around 0 to 0.10 – 0.20 Hz. Cernacek and colleagues (1973) found that when participants closed their eyes, sway

decreased in the 0 to 0.125 Hz band. Since it has previously been highlighted that frequencies of 0.20 Hz are attributed to vestibular contributions, it was decided that frequencies under 0.10 Hz would adequately represent visual contributions.

The muscular proprioceptive and cerebellar bands are less well established. Kapteyn and de Wit (1972) note that individuals without labyrinths and with eyes closed (who are therefore relying on proprioception) sway at higher frequencies, while healthy individuals who are administered diazepam, which slows postural reflexes, present lower frequencies. This suggests that higher frequencies are associated to the proprioceptive contributions. Taguchi (1978) found that individuals with proprioceptive hyperactivity presented sway frequencies of 2.0 to 2.5 Hz. For the cerebellar contributions, evidence is lacking. An experiment by Diener and colleagues (1984) was done on several types of cerebellar dysfunction. Participants with Friedrich's Ataxia swayed at frequencies of 0.10 to 1.0 Hz, both with eyes opened and closed. Authors report that this group has a loss of vibration sense and position sense, which indicates they are likely not relying on their proprioception. These frequencies were evidenced both with eyes opened and closed, which rules out the possibility that these frequencies were influenced by vision. Authors report that the cerebellar structures were intact in this group. Evidence suggests that frequencies of 0.10 to 0.39 Hz are attributable to vestibular contributions, which leaves the range of 0.39 to 1.0 Hz to cerebellar contributions (although the cerebellar function is not optimal, the fact that the structure is intact suggests it is still functional but relying on incorrect proprioceptive information). In the same experiment (Diener *et al.* 1984), patients with late cortical atrophy of the anterior lobe swayed at frequencies of 2.0 to 4.0 Hz when their eyes were closed. Authors report that these patients had dysfunctional and atrophied cerebellar structures, suggesting they relied on their proprioception when their eyes were closed. Considering this limited evidence, it was decided that

the frequency band of 0.39 to 1.56 Hz would represent cerebellar contributions, while the frequency band of 1.56 to 6.25 Hz would represent muscular proprioceptive contributions.

Automatic components of sway may therefore be revealed by a change in strategy used to control sway, more particularly by examining how the contributions of each system change. A shift toward the use of the cerebellum, for example, could reflect an increase in automaticity. In fact, the cerebellum is thought to be important for the acquisition and execution of automatic movements (Lang, & Bastian, 2002; Thach, 1998). A change in sensory contribution has been exposed previously by Chagdes and colleagues (2009), where closing the eyes led to a reduction in the lower frequency bands that are associated to visual contributions. If contributions were to change in dual-task conditions, it could therefore reveal a change in postural control strategy.

As previously mentioned, the separation of frequency content into bands that are thought to represent contributions from different systems is still not perfectly established, particularly for the higher bands. However, it has been proposed that higher frequencies of postural adjustments are representative of automatic control since they enable the motor system to quickly react to perturbations. An automatic control would therefore be characterized by frequent adjustments due to reflex-loops as opposed to slower, conscious feedback loops (Wulf, 2007). Therefore, an increased reliance on higher frequency bands instead of the lower bands, regardless of the systems contributions, would suggest more automatic postural control. In the present thesis, the wavelet transform will therefore be used in an attempt to highlight a shift in contribution from the different bands.

Sample entropy

Sample entropy represents the complexity of postural sway. It quantifies the temporal structure of sway by calculating the probability that two sequences similar for m points remain similar when one data point is added, while self matches are not included in calculating the probability (Richman & Moorman, 2000; Potvin-Desrochers *et al.*, 2017). In other words, it quantifies the probability a particular sequence of COP values has to repeat itself in time (Degani, Leonard, & Danna-dos-Santos, 2017). Sample entropy values range from zero to two: Zero represents a perfectly regular and predictable sequence and two represents a sequence that is repeated only by chance (Pincus, 1991). Therefore, a smaller sample entropy value represents more regular sway while higher values represent irregular and unpredictable sway (Potvin-Desrochers *et al.*, 2017). Sample entropy is calculated using the following formula:

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

where m represents the number of data points to compare in a sequence, N represents the length of the data sequence, and $A(r)$ and $B(r)$ the total number of concordant sequences according to the level of tolerance r in the appropriate dimensional space (i.e. m for $B(r)$ and $m + 1$ for $A(r)$; Richman & Moorman, 2000).

A healthy postural system will randomly fluctuate under normal sensory conditions and therefore yield higher sample entropy, which reflects the ability of the postural system to quickly respond to a perturbation (Stergiou & Decker, 2011). Conversely, smaller sample entropy values are typically indicative of a more constrained system (Newell & Molenaar, 2014). Research demonstrates lower entropy values in unhealthy, diseased or aging populations (Newell & Molenaar, 2014; Cavanaugh *et al.*, 2006; Pincus, Gladstone, & Ehrenkranz, 1991). A recent

experiment conducted by Potvin-Desrochers and colleagues (2017) has investigated the sample entropy of postural sway in young and older adults in dual-task conditions. They found that performing a cognitive task that requires continuous monitoring yielded higher sample entropy values in both groups compared to baseline standing and tasks that only required intermittent attention. They suggested that by continuously distracting from postural control, the continuous tasks led to more automatic behaviour, which was indicated by the higher sample entropy values. Similarly, Donker and colleagues (2007) compared the effect of two tasks on sample entropy in postural control: standing with eyes closed, which was proposed to create an internal focus by increasing task difficulty, and performing a cognitive task, which created an external focus of attention since it withdrew attention from postural control. They found that standing with eyes closed led to increased regularity of sway, higher variability, as well as decreased stability. Conversely, the cognitive task led to decreased regularity and reduced variability, which they suggest is indicative of more efficient and automatic postural control.

In the present experiment, sample entropy will be compared in attentional focus and cognitive task conditions to see if findings from Potvin-Desrochers *et al.* (2017) and Donker *et al.* (2007) can be reinforced and to provide further evidence of automaticity of sway.

Rambling and trembling

Zatsiorsky and Duarte (1999) have developed a method to decompose COP trajectories in two separate components; rambling and trembling. When the body deviates from its equilibrium point (where all forces acting on it are zero), forces act to restore equilibrium. The position by which the equilibrium is maintained is called the reference position and it is characterized by a reference point (or attracting point) on the supporting surface (Zatsiorsky & Duarte, 1999). The rambling component of sway represents the migration of the reference point (Figure 3). This

movement reflects an exploratory behaviour which does not induce substantial restoring forces. It reflects supraspinal components of sway (Zatsiorsky & Duarte, 2000; Paillard & Noé, 2015; Shin, Motl, & Sosnoff, 2011). The trembling, pendular-like component represents the oscillation of the COP around the reference point (Figure 4). This system aims to maintain equilibrium around the reference point using restoring forces. It reflects spinal reflexes and changes in the mechanical properties of the muscles and joints (Zatsiorsky & Duarte, 2000; Paillard & Noé, 2015; Shin *et al.*, 2011).

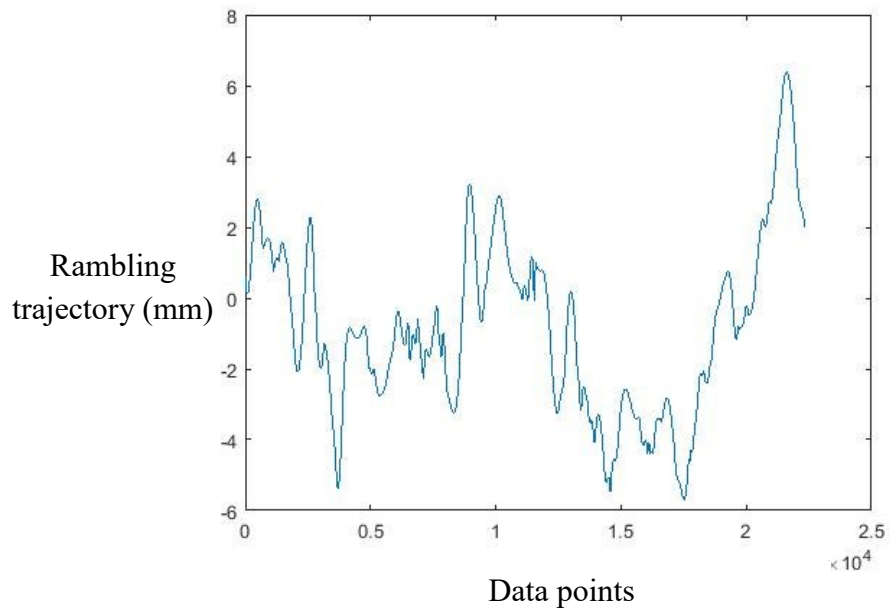


Figure 3. Example of the rambling trajectory in a single-task standing trial of a young adult participant.

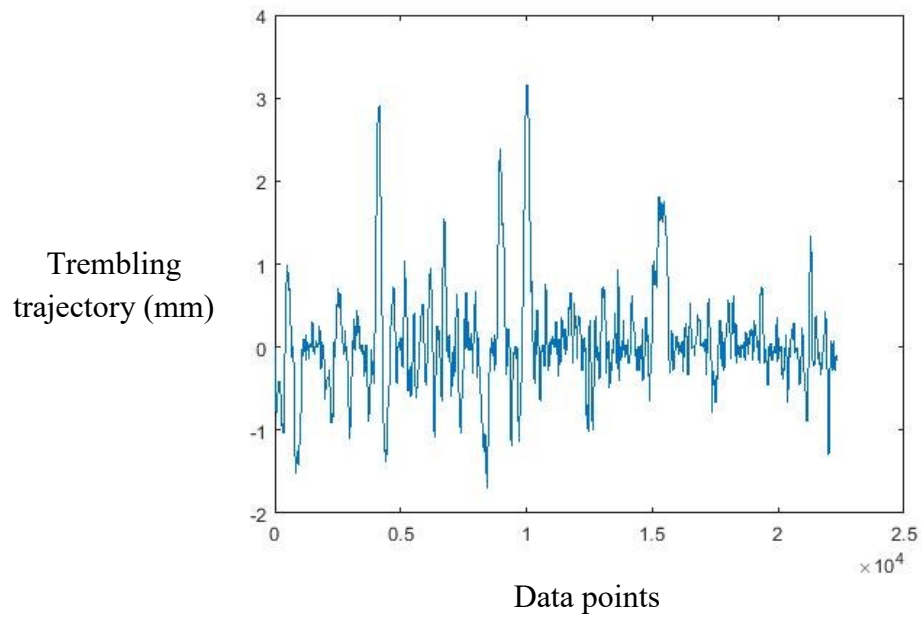


Figure 4. Example of the trembling trajectory in a single-task standing trial of a young adult participant.

According to the rambling-trembling hypothesis, the following chain of events occurs while maintaining balance: the central nervous system specifies an intended position of the body by a reference point on the supporting surface, in respect to which equilibrium is maintained. This reference point is considered a moving attracting point as it migrates. The body sways because of the migration of the reference point and the deviation away from the reference point. When a deflection is minimal, the restoring force is due to the apparent intrinsic stiffness of the muscles (Zatsiorsky & Duarte, 2000).

Rambling and trembling may help elucidate automaticity in postural sway. Specifically, the trembling component is suggested to reflect reflexive contributions to sway. A recent experiment has examined the validity of this fact (Shin *et al.*, 2011). According to the rambling-trembling hypothesis, trembling is due to spinal reflexes. Therefore, individuals with exaggerated spinal reflexes, such as multiple sclerosis patients with lower limb spasticity, should have a greater trembling component in their COP compared to healthy individuals. Indeed, authors report a higher trembling to COP ratio in multiple sclerosis patients compared to healthy controls, but no difference was found in rambling to COP ratios. Therefore, in a healthy population, an increase in trembling might indicate a higher reliance on spinal reflexes rather than supraspinal components, suggesting that sway is controlled more automatically. Alternatively, increased trembling has also been associated to stiffness of lower limbs (Freitas, Freitas, Duarte, Latash, & Zatsiorsky, 2009). To clarify if an increase in trembling is attributed to automaticity or stiffening, other measures must be evaluated such as muscle activity or regularity of sway, as will be done in the present thesis. For example, if increases in trembling components of sway were observed in cognitive task conditions and these conditions would also present increases in sample entropy, then the changes would more likely reflect automaticity than stiffening.

Rambling and trembling has been seldom examined during quiet standing in young adults. Zatsiorsky and Duarte (2000) reported that in healthy young adults the amplitude of rambling was about three times larger than the amplitude of trembling, while frequencies of trembling were about four times larger than those of rambling. A few studies have investigated the impact of aging on this measure. Degani *et al.* (2017) found that the rambling trajectory in older adults had a larger area, variability, velocity, and jerkiness in the AP direction compared to young adults, while no age effect was found in the ML direction. Also, the trembling component had a larger amplitude, variability, velocity, and jerkiness in the AP direction as well as an increased jerkiness in the ML direction in older adults compared to their younger counterparts. They suggest the increased rambling may reflect impaired sensory reweighting, sensorimotor integration, and corrective motor actions, while the increased trembling could reflect age-related changes in sensory receptors, muscle mass and properties, and spinal reflex gain modulation.

Few studies have examined rambling and trembling in young and older adults in quiet standing and dual-task conditions, yet this measure may reveal important information about the systems involved in postural control. For this reason, this measure will be applied to quiet standing, attentional focus and cognitive dual-task conditions in both health young and healthy older adults to try to reveal indications of automaticity in sway.

Complementarity between the three dynamic measures

Although the three dynamic measures that will be used in the present thesis measure distinct features of the COP signal, they will altogether provide an indication of a change in postural control. Figure 5 represents a 12-level decomposition of a single-task standing trial in a young adult participant (Richer & Lajoie, 2018a). This figure reveals that in higher decomposition levels there are large loops reflecting low frequency and large amplitude oscillations which may

be attributed to closed-loop control (Chagdes *et al.*, 2009). Similarly, lower levels of decomposition show high frequency and short amplitude oscillations indicative of an open-loop control. This relates to the decomposition of trembling and rambling, in which high frequency, low amplitude component represents the reflexive spinal components of sway, while the lower frequency, high amplitude component represents the supraspinal contributions (Zatsiorsky & Duarte, 1999; 2000; Chagdes *et al.*, 2009). Figure 6 represents how the dynamic measures might change if postural control were more conscious or automatic. Specifically, if postural control were more automatic, the wavelet transform should reflect an increased contribution in higher frequency bands, sample entropy would be higher and trembling might increase, as it represents spinal reflex contributions to sway. On the other hand, if sway were more conscious, it might be reflected by an increased reliance on the lower frequency bands, lower values of sample entropy, and possibly an increase in the rambling component of sway, as it represents supraspinal contributions to sway.

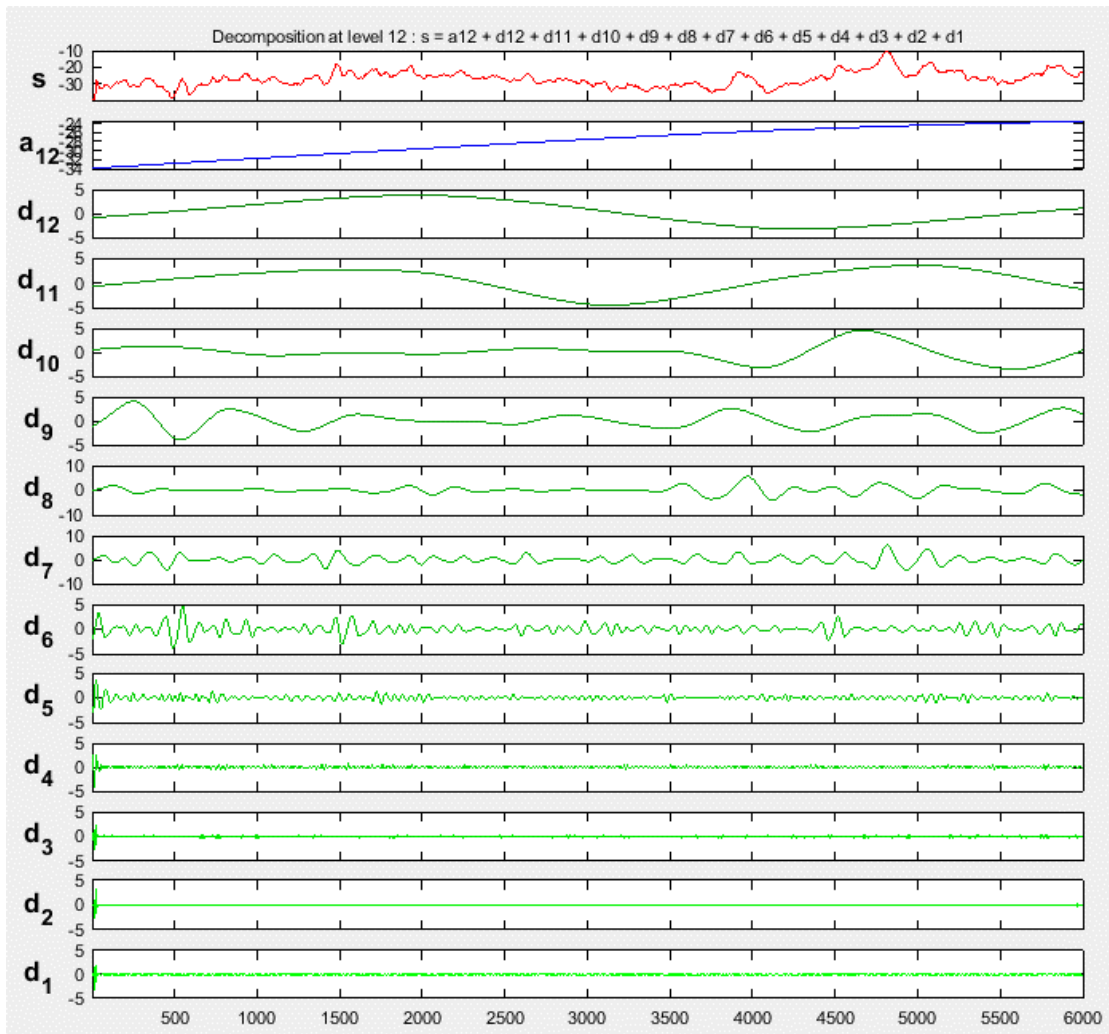


Figure 5. Example of a 12-level decomposition of a COP signal in quiet standing for a young adult participant. s represents the original COP signal and d_1 - d_{12} , the details of decomposition at each level. Figure taken from Richer & Lajoie (2018a).

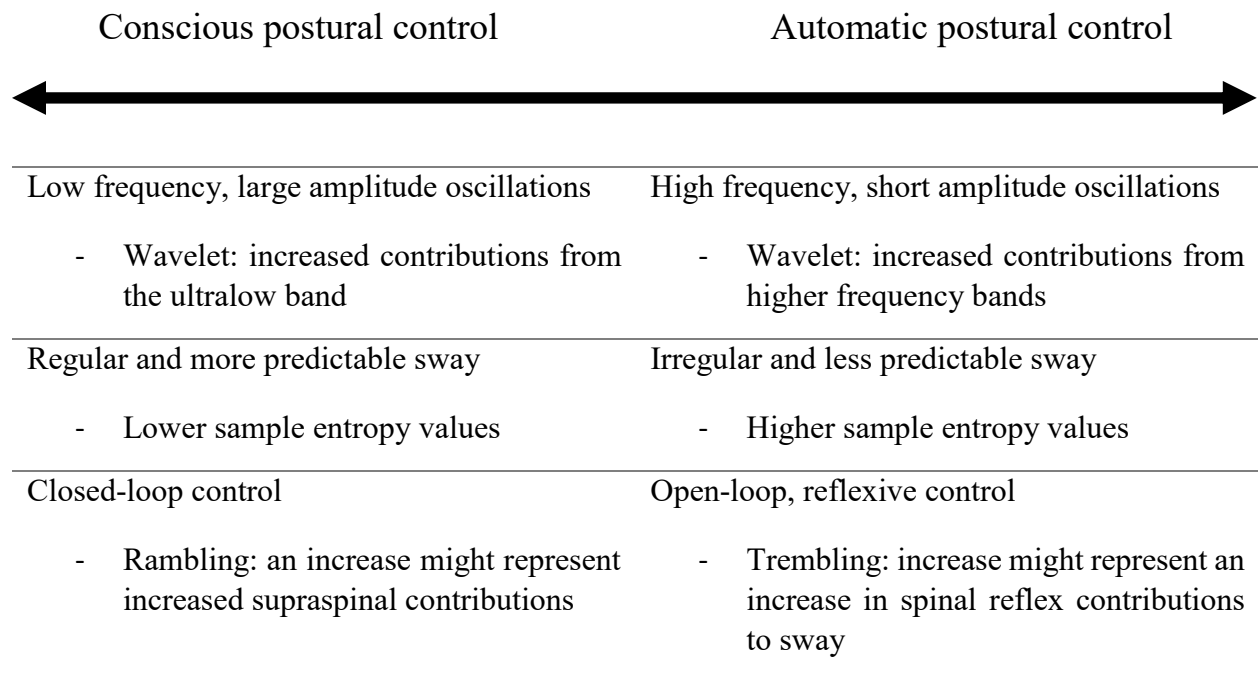


Figure 6. Representation of changes in the wavelet transform, sample entropy, and rambling and trembling that could represent a shift towards more conscious or more automatic postural control.

Attention in Postural Control

Attention is defined as the information processing capacity of an individual (Woollacott & Shumway-Cook, 2002). Evaluation of attention is usually done with the dual-task methodology, which is based on three assumptions: 1) there is a limited central processing capacity within the central nervous system; 2) performing a task requires part of that limited processing capacity; and 3) if two tasks share the processing capacity, and the capacity is exceeded, performance on one or both tasks can be affected (Kahneman, 1973; Parasuraman, 1981). The study of the attention required for postural control is done with the dual-task methodology, where postural control and a concurrent cognitive or motor task are performed simultaneously. The extent to which performance declines in either task demonstrates the competition between processes controlling each task and the extent to which the two tasks share attentional resources (Kerr *et al.*, 1985; Woollacott & Shumway-Cook, 2002).

Different models of attention attempt to explain changes that occur in dual-task conditions (Schmidt & Lee, 2011). The fixed capacity theory, or bottleneck theory, proposes that human information processing executes its functions in serial order, and some functions can only process one element at a time. The central-resource capacity theory stipulates that there is one central source of attention for which all activities requiring attention compete. The multiple-resource theory suggests there are several attention resource mechanisms that relate to a specific information-processing mechanism. When tasks compete for the same resources, they will be performed less well than if different resources are required. The present thesis will use the central-resource capacity theory since, as will be evidenced throughout, it has been suggested that performance of a cognitive task requires the majority of the attention capacity, leaving limited resources for postural control, hence provoking automatic mechanisms to regulate sway.

The dual-task methodology was used by Kerr and colleagues (1985) to demonstrate that postural control was attentionally demanding in healthy young adults. They asked young adults to stand in a tandem Romberg position (heel of the front foot directly in front of the toes of the back foot) while simultaneously performing cognitive tasks. There was a spatial (visual) memory and a non-spatial (verbal) memory task. They found no difference in postural sway, but found that performing the memory task concurrently with the postural task caused an increase in errors in the spatial but not the non-spatial memory task, as opposed to a sitting condition. This may be due to competition for attentional resources from the visual system for both postural control and the cognitive task. They concluded that postural control is attentionally demanding in younger adults, however not all cognitive tasks will have the same effect. Further studies have demonstrated that the attentional requirements of static balance increase with the difficulty of the balance requirements (e.g. Lajoie *et al.*, 1993; Remaud *et al.*, 2012). Lajoie *et al.* (1993) evaluated the dual-task of responding to an auditory reaction time stimulus while sitting, standing with a normal and reduced base of support, and walking. They demonstrated an increase in reaction time as the difficulty of the postural task increased. An experiment by Remaud *et al.* (2012) compared various standing positions (feet together, tandem and single-leg stances) in eyes open and eyes closed conditions, combined with a concurrent auditory reaction time task. Their results suggest that the addition of a concurrent reaction time task did not significantly alter postural control, but they did find that reaction time increased between the control and standing positions in the eyes-open conditions, and found significant differences in reaction time between the control, feet together, tandem stance and single-leg stance conditions but only in the eyes-closed conditions. Reaction time was not affected in trials performed with vision, suggesting that vision provides necessary

compensation for the increased attentional demands of the task in healthy young adults (Remaud *et al.*, 2012).

Attentional requirements of postural control change with the complexity of the postural or concurrent task (Kerr *et al.*, 1985; Lajoie *et al.*, 1993; Remaud *et al.*, 2012). Recent studies have also suggested that the type of postural control can change with attentional focus instructions (McNevin & Wulf, 2002; Wulf *et al.*, 2001a; Wulf, Mercer, McNevin, & Guadagnoli, 2004). These studies compare an internal focus of attention (directing attention to body movements, such as focusing on keeping one's feet horizontal while standing on a stabilometer) and an external focus of attention (directing attention to the effects of a movement, such as focusing on keeping markers on a stabilometer horizontal). Findings consistently demonstrate that an external focus of attention is beneficial for learning and performance (see Wulf, 2007 for review). Researchers have hypothesised that the reason why an external focus of attention is so beneficial is that it promotes a more automatic control of movement (McNevin *et al.*, 2003; Wulf *et al.*, 2001a; Wulf & Prinz, 2001; Wulf *et al.*, 2001b). Wulf and colleagues (McNevin *et al.*, 2003; Wulf *et al.*, 2001a; Wulf & Prinz, 2001; Wulf *et al.*, 2001b) have elaborated the constrained action hypothesis which suggests that by focusing on one's body movements, the individual actively intervenes in movement control, interfering with normal automatic processes that would regulate the movement. If the individual were to focus instead on external cues, he would then allow the motor system to self-organize and produce movement or maintain posture in a more automatic, efficient way (McNevin *et al.*, 2003; Wulf *et al.*, 2001a; Wulf & Prinz, 2001; Wulf *et al.*, 2001b). There is strong support for this hypothesis, as research has demonstrated that faster reaction times, higher frequency of adjustments, and more efficient muscular activity can be observed in external focus as opposed to internal focus conditions (Wulf, 2007). Wulf *et al.* (2001a) compared effects of

attentional focus on the dual-task of balancing on a stabilometer while responding to a concurrent reaction time task. They found that the external focus improved postural performance and promoted faster reaction times as opposed to the internal focus group. This suggests that by focusing on factors that are unrelated to movement control, the individual is allowing a more automatic control process to produce the movement, which allows for more attentional resources to be available for other tasks. Similar studies have used the measure of frequency to evaluate the effect of attentional focus of postural control (McNevin *et al.*, 2003; Wulf *et al.*, 2001a; Wulf *et al.*, 2001b). They have found that an external focus of attention promotes a higher frequency of postural adjustments as opposed to an internal focus (McNevin *et al.*, 2003; Wulf *et al.*, 2001a; Wulf *et al.*, 2001b). A high frequency of postural adjustments enables the motor system to quickly react to perturbations (Wulf, 2007). External focus seems to promote the use of more, and faster, reflex-loops that operate at an automatic level, as opposed to an internal focus which promotes the use of conscious, and slower, feedback loops (Wulf, 2007). Finally, studies have demonstrated more efficient muscular activity in external focus conditions (Wulf, 2007). Recent studies have used electromyography to examine what happens at a neuromuscular level that could explain differences between an external and an internal focus (Vance, Wulf, Töllner, McNevin, & Mercer, 2004; Zachry, Wulf, Mercer, & Bezodis, 2005; Marchant, Greig, & Scott, 2009). Studies have shown faster movements and higher levels of produced force, with less muscular activity required in external focus conditions versus internal focus conditions, suggesting more efficient muscular activity (likely due to a more effective recruitment of muscle fibers and improved coordination between muscles; Vance *et al.*, 2004; Zachry *et al.*, 2005; Marchant *et al.*, 2009; Wulf, 2007). Altogether, these findings support the constrained action hypothesis and strongly suggest that an external focus promotes automaticity compared to an internal focus, allowing attention to be

allocated to other tasks (Wulf, 2007). There are, however, conflicting results regarding the effect of attentional focus on quiet standing. Some studies show no effect of attentional focus (Polskaia *et al.*, 2015) while others show an effect (Richer *et al.*, 2017b). This may be a result of the proximity of the external focus cue. An experiment by McNevin and colleagues (2003) demonstrated more important benefits of an external focus when the cue is distanced from the body. This may be because distance makes the cue easier to distinguish from body movements (McNevin *et al.*, 2003).

According to the constrained action hypothesis, directing attention away from control of movement is beneficial, and increasing the distance of the external focus cue seems to be more beneficial (McNevin *et al.*, 2003). Therefore, perhaps removing attention completely from the postural task would yield even further improvements. This was investigated by Polskaia and colleagues in 2015. They asked participants to stand while either focusing internally on minimizing movements of their hips, externally on reducing movement of markers placed on their hips, or on a cognitive task. The task was challenging and required constant monitoring of the answer, therefore participants unlikely had sufficient attention remaining to allocate to the postural task. Results revealed improved postural control in the cognitive task condition compared to both internal and external focus of attention. Results support the constrained action hypothesis, since attention was removed from postural control altogether, which seems to have allowed automatic processes to control sway. Similar findings are outlined in various studies (Dault *et al.*, 2001; Andersson, Hagman, Talianzaded, Svedberg, & Larsen, 2002; Riley, Baker, & Schmit, 2003; Stins, Roerdink, & Beek, 2011; Donker *et al.*, 2007).

As noted previously, improvements in postural control while performing a cognitive task could be due to attention being withdrawn from postural control, allowing automatic mechanisms

to operate. Of course, there are alternative explanations for this effect. It might be that task switching is occurring, and that the cognitive task requires a greater proportion of attention in each trial than postural control, causing this change in stability. Whether attention is being prioritized towards the cognitive task, task switching is occurring, or an alternative process is creating this change, it is proposed that the cognitive task serves as a distraction from postural control. For the present thesis, this theory will be prioritized, but it is important to note that it is not possible to know what exactly is happening cognitively during a trial to create this change in postural control.

These previously mentioned studies lead us to believe it is possible to change from one type of postural control to another by varying instructions or task difficulty. Ideally, to improve equilibrium, we should find ways to encourage the use of this more automatic type of postural control. Studies on attentional focus have suggested that it is possible in healthy younger adults, by varying focus instructions. However, it remains to be determined if the mechanism and advantages are similar in healthy older adults.

Aging effects on postural control and attention

It is well known that postural control is affected in older adults; aging is associated with a loss of sensitivity of the sensory systems, a slowing of nerve conduction velocity and a reduction in muscle size (Woollacott, Shumway-Cook, & Nashner, 1982). Aging is also associated with a slower processing capacity (Welford, 1988) and a decrease in the ability to divide attention to properly distribute resources between tasks (Craik & Byrd, 1982; Teasdale *et al.*, 1992). Furthermore, aging requires a greater proportion of attentional resources to be allocated to postural stability and balance (Lajoie *et al.*, 1996). Studies have shown significant attentional demands related to postural control in older adults, even under relatively simple conditions (Woollacott & Shumway-Cook, 2002), and these attentional requirements increase with difficulty of the task

(Teasdale *et al.*, 1993; Maylor & Wing, 1996; Shumway-Cook, Woollacott, Kerns, & Baldwin, 1997; Shumway-Cook & Woollacott, 2000; Lajoie *et al.*, 1996). For example, an experiment by Shumway-Cook and Woollacott (2000) compared the effect of an auditory choice reaction time task on the control of posture in different conditions: firm or sway-referenced surface each performed with eyes open, eyes closed, or with visual motion. In the sway-referenced condition, the platform under the participant's feet tilts forward and back in accordance with his AP sway (Shumway-Cook & Woollacott, 2000). These conditions were performed by healthy young, healthy older and older individuals with a history of falls. They found that in healthy young adults, the modification of sensory conditions did not increase reaction time. In the older adults, when they were standing on a firm surface, a change in visual condition did not significantly increase reaction time, but in the three sway-referenced conditions, reaction time was significantly increased. This suggests that changing the sensory context of the task, in this case by changing the surface conditions, influenced attentional demands of postural control. As for the older adults with a history of falls, any change in the availability of sensory information caused a significant increase in reaction time, suggesting higher attentional demands. Since maintaining upright posture requires greater attention in older adults, it needs to be determined if this population can demonstrate a more automatic type of postural control. They may be unable to attain this automatic type of control due to the age-related decrease in quality of sensory information that affects postural stability (Woollacott *et al.*, 1982) or possibly due to fear of falling (e.g. Adkin, Frank, Carpenter, & Peysar, 2000; Carpenter, Frank, & Silcher, 1999; Carpenter *et al.*, 2001).

Studies that have been done on attentional focus in older adults are limited. In a recent experiment by McNevin, Weir, & Quinn (2013), researchers asked young and older participants to stand upright while performing a tracking task under internal (focusing on the hand) or external

(focusing on the stylus) focus conditions. The tracking task was performed at slower and faster speeds to modify difficulty of the task. Results demonstrated that an external focus yielded greater accuracy of the tracking task than an internal focus, but this benefit was not more pronounced with the increased speed. Effects of attentional focus on postural control were modest, with an external focus yielding less ML postural sway in the slower tracking speed only. Furthermore, older adults failed to reach the same level of tracking performance as the young adults for the more difficult task. These findings therefore support the benefits of an external focus of attention on mildly challenging tracking tasks. Huxhold, Li, Schmiedek, and Lindenberger (2006) support these findings by demonstrating that a simple concurrent cognitive task reduced postural sway in young and older individuals but as difficulty of the cognitive task increased, postural control performance diminished in the older adults only. Therefore, further research needs to be done in healthy older adults to reinforce the findings of these studies.

In summary, attentional demands are greater in older adults and that this has an impact on postural control. It is important to determine if external focus and cognitive task conditions can yield improvements in stability in older individuals, as it does in health young adults. If improvements are possible, it must be determined if they are due to automaticity of sway. If automaticity is possible in this population, it could lead to improvements in the interventions that aim to improve stability and reduce the risk of falls in the aging population.

Stiffening strategy

One hypothesis that attempts to explain the postural changes that are observed in dual-task conditions is that participants adopt a stiffening strategy to stabilize the body while attention is placed on the concurrent task (Dault *et al.*, 2001; Dault *et al.*, 2003; McNevin & Wulf, 2002; Melzer *et al.*, 2001; Weeks *et al.*, 2003). The stiffening of the ankle joint was initially proposed

by Winter and colleagues (1998). According to this view, the agonist and antagonist muscles around the ankle joint are co-contracted to increase stability. This strategy is often evidenced by a reduction in the variability of the COP, an increase in sway frequency (Dault *et al.*, 2003; McNevin & Wulf, 2002), and an increase in sway velocity (Roerdink *et al.*, 2006). This co-contraction can be apparent in older adults due to the lack of ability to fine-tune postural adjustments (Woollacott, Inglin, & Manchester, 1988) and is also observed in young and older populations in situations of postural threat (e.g. Adkin *et al.*, 2000; Carpenter *et al.*, 1999; Carpenter *et al.*, 2001).

Fear of falling has been evaluated in studies comparing postural control in healthy young and healthy older participants on platforms of different heights. Perception of threat to stability was found to have an impact on strategies used for postural control (e.g. Adkin *et al.*, 2000; Carpenter *et al.*, 1999; Carpenter *et al.*, 2001). Studies on this topic typically involve standing on the edge of a raised platform to induce fear and restrict movement. In fearful young participants, the typical strategy is a backward shift in the mean AP position of the COP. In addition, there is a decrease in the COP amplitude variability and an increase in the mean frequency of the COP displacement (Adkin *et al.*, 2000; Carpenter *et al.*, 1999; Carpenter *et al.*, 2001; Davis, Campbell, Adkin, & Carpenter, 2009), which suggests a stiffening strategy used in threatening conditions (Laufer, Barak, & Chemel, 2006). This has also been demonstrated in older individuals (Maki, Holliday, & Fernie, 1990; Brown, Sleik, Polych, & Gage, 2002). In fact, an experiment by Laufer *et al.* (2006) compared postural control in young and older adults while they faced a postural threat. They found that postural threat significantly increased AP frequency in older participants only, suggesting they used a stiffening strategy in threatening conditions. Furthermore, Huffman, Horslen, Carpenter, and Adkin (2009) suggested that the increase in threat is associated with a shift to a more conscious control of posture.

Although older adults are more likely to experience anxiety in postural control than young adults, and therefore have a higher chance of displaying stiffening, the older participants that will be examined in the present thesis will be healthy, community dwelling older adults who will not have a reported history of falls. For this reason, postural control might not yet cause anxiety. Furthermore, the postural task will be done in unperturbed and safe standing conditions. It is important to confirm if stiffening is present in older adults in attentional focus or cognitive task conditions to either confirm or deny the theory that changes are attributed to the stiffening strategy.

If the stiffening strategy were used in a dual-task situation, it would be present in multiple muscles responsible for stabilising the body, such as in the legs and torso. Since during quiet, unperturbed standing, participants would likely adopt an ankle strategy and stiffness would likely not be isolated to only one side of the body, it was decided that examining the muscle activity of the dominant lower leg would be sufficient for the present thesis.

Chapter 3 – Rationale, Purpose, Objectives and Hypotheses

The general purpose of this thesis is to provide evidence of two types of postural control in young and healthy older adults. This will be done in three parts. Firstly, the effect of attentional focus and cognitive tasks on postural control must be confirmed in older adults. Secondly, the stiffening strategy hypothesis must be invalidated in older adults, as it has been in young adults. Finally, dynamic measures of sway must be used to exhibit changes in the structure and composition of sway and reveal automatic components in both young and older adults.

Part 1: Effect of attentional focus and cognitive tasks in older adults

A few experiments have already investigated the effect of attentional focus and cognitive tasks in young adults. While certain experiments show improvements in postural control when focusing on an external cue (Richer *et al.*, 2017b), others do not (Polskaia *et al.*, 2015). However, there seems to be important postural benefits when performing a continuous, attention-demanding cognitive task while standing (Polskaia *et al.*, 2015; Richer *et al.*, 2017b). Since the external focus of attention and the performance of a cognitive task have been suggested to elicit automatic postural behaviours, it is important to examine if older adults present postural control improvements in these conditions. If they do, it might suggest they could display automatic postural behaviours and further investigations in the structure and composition of their sway would be warranted.

Therefore, the first objective is to examine the effects of an internal focus on the hips, an external focus on markers placed on the hips, and a continuous cognitive task on postural control in healthy older adults. In young adults, the same external focus did not present any improvements compared to the internal focus, while the cognitive task led to reductions in sway area and

variability compared to both focus conditions (Polskaia *et al.*, 2015). For this reason, the proposed hypothesis is that there will be no difference between internal and external focus conditions and that cognitive tasks will reduce sway area and sway variability compared to both focus conditions.

Part 2: Examining the use of the stiffening strategy in older adults while standing

One theory that could explain improvements in postural control particularly in cognitive task conditions is the use of a stiffening strategy, in which there is co-contraction of muscles around the ankle joint to stabilize the body to allow attention to be placed on the challenging cognitive task (Dault *et al.*, 2001). A recent investigation in young adults revealed no change in muscle activity of the tibialis anterior and the medial gastrocnemius between baseline, attentional focus and cognitive task conditions while standing (Richer *et al.*, 2017b). This suggests that in this population, improvements in postural control in external focus and cognitive task conditions may not be due to stiffening in the ankle joint. However, stiffening is more likely to be observed in older adults than in young individuals since it is typically associated to fear of falling (Stins *et al.*, 2011); since older adults typically demonstrate decrements in postural control, it is more likely they would experience anxiety while standing. However, in a healthy older population and during bipedal stance on a stable surface, fear of falling is unlikely. To examine if automatic postural behaviours can be observed in an older adult population, it is firstly important to investigate if changes to postural control that may occur in external focus or cognitive task conditions in older adults are can be attributed to the use of a stiffening strategy.

The second objective is to examine muscle activity in the tibialis anterior and medial gastrocnemius in older adults while they focus internally on the ankles, externally on markers extending from the ankle joint, and on easy and difficult cognitive tasks. In young adults, sway area decreased in the external focus condition compared to baseline standing and the internal focus

condition, and decreased further in both cognitive task conditions. Furthermore, sway variability in the ML direction was reduced in cognitive task conditions compared to the rest, while in the AP direction it was lower in external focus than internal focus, and lowest in the more difficult cognitive task condition. Finally, as previously mentioned, no difference was observed in muscle activity of the tibialis anterior and medial gastrocnemius across conditions (Richer *et al.*, 2017b). The external focus led to improvements in young adults compared to the internal focus conditions, compared to Polskaia and colleagues (2015) where no difference was present between internal and external focus of attention. This is probably because the focus apparatus was more distanced from the body than in the previous experiment. This suggests that the distance of the external focus is important for quiet standing, as if it is too close the effect will not be visible (McNevin *et al.*, 2003). For this reason, it is hypothesized that sway area and variability will decrease in the external focus condition compared to baseline standing and internal focus conditions, and will decrease further in both cognitive task conditions in the older adult participants. More importantly, these changes in sway will not be attributed to modifications in muscle activity around the ankle joint.

Part 3: The use of dynamic measures of sway to elucidate changes in postural strategies during attentional focus and cognitive task conditions in young and older adults

If it results from experiment 2 demonstrate no change in muscle activity across focus and cognitive task conditions, it will suggest that changes are not attributed to the use of the stiffening strategy. It will then be important to investigate the structure and composition of sway to attempt to explain why these changes are occurring in young and healthy older adults. If the stiffening strategy is not in play during these conditions, it is quite probable that automaticity of sway can explain the changes that are observed. It would suggest that by distracting individuals from postural control, it allows automatic processes to function in an unhindered way. Unfortunately,

the traditional measures of sway do not reveal much about the structure and composition of sway as they provide a single, average value representing the magnitude of variation of sway. For this reason, it is important to use dynamic measures of sway to attempt to explain the changes that are observed in postural control between various dual-task conditions. Notably, three measures were chosen to represent the postural strategies that are used in postural control: the wavelet transform, sample entropy, and rambling and trembling. By examining these measures, it will reveal important information about the structure of sway and suggest which systems and postural components are involved in the control of sway across conditions.

The third objective is therefore to apply dynamic measures of sway to attentional focus and cognitive task conditions to provide evidence that different postural strategies are used in these conditions. Theoretically, continuous cognitive task conditions should demonstrate automaticity compared to baseline standing and focus conditions since they withdraw attention completely from postural control, hence allowing automatic mechanisms to work in an unconstrained manner. For this reason, it is hypothesized that in both populations, cognitive task conditions will present increased contribution from higher frequency bands and decreased contribution from lower frequency bands, will elicit higher sample entropy values, and will provoke increased trembling compared to baseline standing and focus conditions. It is also predicted that the external focus condition will not provoke similar postural strategies as the cognitive task conditions. Although the external focus condition has led to improvements in postural control in young adults compared to baseline standing and internal focus conditions, these improvements are limited and inconsistent (Polskaia *et al.*, 2015; Richer *et al.*, 2017b). Furthermore, focus is still placed on an aspect of postural control and may therefore create interference with truly automatic processes.

Chapter 4 – Effect of attentional focus and cognitive tasks in older adults

Continuous Cognitive Task Promotes Greater Postural Stability than an Internal or External Focus of Attention in Older Adults.

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Background/Study Context: Recent evidence suggests that removing attention from postural control using either an external focus or a cognitive task will improve stability in healthy young adults. Due to increases in attentional requirements of upright stance in older adults, it is unclear if similar benefits would be observed in this population. The aim of the present study was to examine the effect of attentional focus and of a continuous cognitive task on postural control in older adults.

Methods: Sixteen healthy older adults (71.9 ± 4.32 years) were asked to stand quietly on a force platform with feet together in three different conditions: internal focus (minimizing movement of the hips), external focus (minimizing movement of markers placed on the hips), and cognitive task (silently counting the occurrence of a single digit in a 3-digit number sequence). A one-way analysis of variance with repeated measures on condition was performed for each postural control measure.

Results: Hypotheses were partially supported because the cognitive task led to greater stability than both focus conditions, as evidenced by a smaller sway area ($p < .01$, $\eta_p^2 = .41$), reduced sway variability (anterior-posterior: $p = .001$, $\eta_p^2 = .37$; medial-lateral: $p < .0001$, $\eta_p^2 = .49$), and higher mean power frequency in the anterior-posterior direction ($p = .01$, $\eta_p^2 = .78$). However, no difference was observed between internal and external focus conditions.

Conclusions: A continuous, attention-demanding cognitive task significantly improved stability in older adults compared with an internal or external focus of attention. This suggests that older adults were able to effectively allocate their attention away from postural control, allowing a more automatic type of control to operate. Future studies should investigate a variety of cognitive tasks to determine the degree of postural improvement that can be observed in older adults.

1. Introduction

Research has consistently demonstrated performance and learning benefits when directing attention toward movement effects (external focus of attention) as opposed to movement production (internal focus of attention) in healthy young adults, notably in postural control (Wulf, 2007 for review). According to the constrained action hypothesis (Wulf, McNevin & Shea, 2001), an external focus of attention promotes superior control of movement by allowing automatic control processes to emerge, as opposed to an internal focus of attention which promotes conscious interference in movement control.

Few studies have examined the effect of attentional focus on postural control in older adults. McNevin and colleagues (2013) asked young and older participants to stand upright while performing a supra-postural tracking task under internal or external focus conditions. The tracking task was performed at slow and fast speeds to alter the difficulty level of the task. Relative to the

internal focus condition, the external focus promoted greater accuracy but only in the less challenging tracking task condition. Few improvements were observed in postural control and seemed to be driven by tracking difficulty rather than attentional focus. Similarly, Chiviacowsky and colleagues (2010) observed learning benefits of using an external focus of attention in a stabilometer task as opposed to an internal focus of attention in older adults. The aforementioned studies demonstrate that learning benefits and supra-postural task improvements can be observed in older adults when using an external focus, however, it should be noted that the observed improvements appear to be limited to less challenging tasks (McNevin *et al.*, 2013). Further research is required to better ascertain the effect of attentional focus on postural control in older adults.

Recently, the effect of cognitive tasks on postural control has been extensively studied in both young and older adults. In young adults, the impact of cognition on postural control has produced inconsistent findings; cognitive task performance has led to both decreases (Dault, Yardley & Frank, 2003; Pellecchia, 2003; Ceyte, Lion, Caudron, Kriem, Perrin & Gauchard, 2014; Maylor, Allison & Wing, 2001) and improvements (Weeks, Forget, Mouchnino, Gravel & Bourbonnais, 2003; Dault, Geurts, Mulder & Duysens, 2001; Andersson, Hagman, Talianzadeh, Svedberg & Larsen, 2002; Riley, Baker, Schmit & Weaver, 2005; Swan, Otani & Loubert, 2007; Stins, Roerdink & Beek, 2011; Polskaia, Richer, Dionne & Lajoie, 2015) in postural control. Pellecchia (2003) compared the impact of various cognitive tasks on postural control and found that more challenging tasks increased postural sway. Conversely, Polskaia and colleagues (2015) compared the effect of internal and external foci of attention to a continuous, attention-demanding cognitive task on postural control. They found that performing a concurrent cognitive task while standing led to a more stable posture than both focus conditions. There are several factors that

could explain this discrepancy in results, such as the difficulty of the postural task (e.g. Teasdale, Bard, La Rue & Fleury, 1993; Lajoie, Teasdale, Bard & Fleury, 1993; Barra, Bray, Sahni, Golding & Gresty, 2006), the difficulty and the type of cognitive task (e.g. Huxhold, Li, Schmiedek & Lindenberger, 2006; Pellecchia, 2003) or the use of a stiffening strategy (McNevin & Wulf, 2002; Stins *et al.*, 2011).

Cognitive task influence on postural control has also been examined in older adults (e.g. Weeks, Forget, Mouchnino, Gravel & Bourbonnais, 2003; Swan, Otani, Loubert, Sheffer & Dunbar, 2004; Jamet, Deviterne, Gauchard, Vançon & Perrin, 2007; Maylor *et al.*, 2001; Huxhold *et al.*, 2006; Shumway-Cook, Woollacott, Kerns & Baldwin, 1997). As in young adults, cognitive task performance has led to contradictory results with some studies demonstrating improvements in postural control (Weeks *et al.*, 2003; Swan *et al.*, 2004) and others decrements (Jamet *et al.*, 2007; Shumway-Cook *et al.*, 1997). For instance, in a study by Shumway-Cook and colleagues (1997), the concurrent performance of a language processing task while standing led to decreases in postural control, while performance of a perceptual matching visual task did not alter stability. In contrast, Weeks and colleagues (2003) compared quiet standing to standing while either focusing on a cognitive or a motor task in young and older adults. In both groups they observed decreased medial-lateral (ML) sway in the cognitive dual-task condition, while the motor dual-task condition increased ML sway. Similarly, Swan and colleagues (2004) investigated the effect of performing spatial and non-spatial cognitive tasks on postural control in young and older adults. They found balance improvements in older adults in the difficult eyes-closed, sway-referenced force plate condition when performing both the spatial and non-spatial cognitive tasks (Swan *et al.*, 2004). In line with the constrained action hypothesis (Wulf *et al.*, 2001), the authors suggest the observed improvement may be a result of the secondary task which could have distracted

participants from actively intervening in postural control. As no differences were found in young adults, Swan and colleagues (2004) suggest that the postural task must not have been challenging enough to evoke improvement. Alternatively, in a study by Huxhold and colleagues (2006), an easy cognitive task (viewing a series of digits on a computer screen) led to improvements in the postural performance of older adults while a more cognitively demanding task (digit 2-back working memory conditions) led to a decline in stability.

Natural effects of aging may be one of the factors causing conflicting results in stability and certainly can account for the declines in postural control in this group of individuals. Aging leads to a reduction in the attentional capacity of individuals which diminishes their ability to flexibly allocate resources between tasks (Teasdale, Bard, Dadouchi, Fleury, LaRue & Stelmach, 1992). Additionally, older adults require that a greater proportion of attentional resources be allocated to postural control to ensure stability (Lajoie, Teasdale, Bard & Fleury, 1996). According to the posture first principle, older adults prioritize stability at the expense of cognitive performance in a dual-task situation to avoid losing stability (Lacour, Bernard-Demanze & Dumitrescu, 2008). Therefore, it remains unclear if they would demonstrate similar benefits to young adults if attention were shifted away from postural control. Furthermore, it is unclear if a continuous cognitively demanding task would be too difficult to elicit benefits in postural performance in an older population. Therefore, the objectives of the present study were two-fold; to examine attentional focus effects on postural control in older adults and to extend the findings of Polskaia and colleagues (2015) to the older adult population in order to determine if they are able to flexibly allocate attention to a cognitive task to promote the emergence of a more stable postural control. The first hypothesis was that an external focus would improve postural stability in comparison to an internal focus (McNevin *et al.*, 2013; Chiviakcowsky *et al.*, 2010). The second

hypothesis was that older adults would be able to allocate their attention to the cognitive task and consequently demonstrate improvements in stability. Additionally, the cognitive task was proposed to yield greater stability than both the internal and external focus of attention conditions (Polskaia *et al.*, 2015).

2. Methods

2.1. Participants

Sixteen healthy, community-dwelling older adults (71.9 ± 4.32 years; 13 female, 3 male) were recruited. Health status data are reported in Table 1. A health questionnaire was used to ensure participants had no injury or condition that could impair their balance and no history of falls. Additionally, the mini-mental state evaluation (MMSE) (Folstein, Folstein & McHugh, 1975) was administered as a screening tool for any neurological condition that could impair performance in the study. A cut point for the MMSE was established at 24 which allows the assumption of a certain degree of cognitive function within the limitations of a cognitive screening measure. Each participant signed an informed consent form approved by the Research Ethics Board at the University of Ottawa prior to their participation in the study.

Table 1. *Health status data of participants.*

Participant	Height (cm)	Weight (lbs)	Recent injury or fall (affecting postural control)	Vestibular problem	MMSE
1	158	127	N/A	N/A	24
2	180	195	N/A	N/A	30
3	158	176	N/A	N/A	30
4	165	190	N/A	N/A	30
5	158	175	N/A	N/A	30
6	152	156	N/A	N/A	27
7	152	142	N/A	N/A	28
8	158	150	N/A	N/A	29
9	145	145	N/A	N/A	28
10	160	109	N/A	N/A	30
11	158	164	N/A	N/A	30
12	170	165	N/A	N/A	30
13	163	110	Injury, resolved	N/A	30
14	158	129	N/A	N/A	30
15	155	108	N/A	N/A	30
16	168	190	N/A	N/A	30
17	180	170	N/A	N/A	29
Average (SD)	161 (9.3)	153 (28.9)	---	---	29 (1.6)

2.2. Apparatus

To evaluate postural control, an AMTI force platform (ORG-6-1000, Don Mills, ON, Canada) was used to record center of pressure (COP) data at a sampling frequency of 500 Hz. Audio recordings for the cognitive task were presented using a digital media player and two speakers placed behind the participants. An elastic belt with two markers on the ventral side and two markers on the dorsal side was used for the external focus condition (Figure 1). This lightweight belt was comfortably tied around participants' hips, aligned with the anterior and posterior superior iliac spines, and was removed when participants were not engaging in an external focus.

2.3. Procedure

Participants were asked to stand quietly on the force platform with feet together and arms at their sides while looking at an eye-level target placed on a wall 3 meters ahead. Three experimental conditions were performed in this stance: an internal focus of attention condition, an external focus of attention condition and a cognitive task condition. No baseline standing was recorded since it has previously been demonstrated that performance in a balance task was similar between a control condition and the internal focus condition (Wulf & McNevin, 2003). Each condition was comprised of two blocks of three 60-s trials. The blocks were counterbalanced to prevent an order effect. Two different testing protocols were used interchangeably to vary the order of conditions across participants. Instructions regarding attentional focus were specific to condition. In the internal focus of attention condition, participants were instructed to concentrate on minimizing movements of their hips. In the external focus of attention condition, participants were instructed to concentrate on minimizing movements of the markers placed around their hips. No visual feedback of the markers was provided as this was purely a mental task. As in the other

conditions, the participants were asked to look at the eye-level target placed in front of them. Following each trial of the internal and external focus conditions, manipulation checks were performed to ensure attention was properly allocated to the instructed task. Participants provided a subjective percentage rating indicating how dedicated they were to the attentional focus instructions. If a value of 60% or lower was reported, the trial was redone immediately. During data collection, only two scores lower than 60% were reported in the external focus condition for which trials were redone. In the cognitive task condition, participants were asked to silently count and sum the total occurrence of a pre-selected digit in a sequence of 3-digit numbers. The sequence contained 30 numbers administered at two-second intervals for the entire duration of the 60-second trial. After each trial, participants provided their total count to the investigator. Verbalization was prohibited during the task to eliminate the impact of articulation on postural sway (Dault *et al.*, 2003). Using fingers as a counting aid was proscribed to ensure body sway was not affected and to maximize cognitive effort. Two different number sequences were used interchangeably and the number to count was changed every trial to reduce the chances of memorization. Trials were discarded if a participant's answer was off by three or more. The error score was established to match the difficulty of the cognitive task and was not based on previous literature. All participants made at least one mistake, but only 6 trials were discarded due to an error of three or more.



Figure 1. Belt used for the external focus condition. The lightweight elastic belt is outfitted with two markers on the ventral side and two on the dorsal side, which are aligned with the anterior and posterior superior iliac spines, respectively.

2.4. Data Analyses

The COP was obtained using the ground-reaction forces collected by the force platform. MatLab software (MathWorks Inc., Natick, MA, USA) was used to derive the following dependent variables that were used to characterize postural control: area of 95% confidence ellipse, standard deviation (SD) of the COP in the anterior-posterior (AP) and ML directions, and mean velocity in the AP and ML directions. BioProc3 software (D.G.E. Robertson, Ottawa, Canada) was also used to perform a Fast Fourier Transform (FFT) on the COP data to determine mean power frequency (MPF).

2.5. Statistical Analyses

For each dependent variable, one average value per condition was calculated for each participant and subsequently used for analysis. A one-way analysis of variance (ANOVA) with repeated measures on condition (internal, external and cognitive) was performed for each of the dependant variables. Furthermore, data was compared to previously published data in young adults (Polskaia *et al.*, 2015), to examine the effect of age. For this, a two-way ANOVA on age (young and older) and condition (internal, external and cognitive), with repeated measures on condition, was performed for each of the dependent variables. Statistical significance was set at $p < 0.05$. If Mauchly's Test of Sphericity was violated, Greenhouse-Geisser corrections were performed. When necessary, Newman-Keuls post-hoc analysis was performed to determine the location of significance. Partial eta squared (η_p^2) values were calculated to determine effect size. A small effect size is represented by values ≥ 0.01 , a medium effect size is represented by values ≥ 0.06 , and a large effect size is represented by values ≥ 0.14 (Sink and Stroh, 2006).

3. Results

3.1. Area of 95% confidence ellipse

The ANOVA yielded a significant main effect of condition for area ($F_{2, 30} = 10.39, p < 0.01, \eta_p^2 = 0.41$; Figure 2). Post-hoc analyses revealed that the cognitive task produced a significantly smaller sway area (3.44 cm^2) compared to the internal (4.85 cm^2) and external (5.10 cm^2) focus conditions. Sample COP displacements for internal, external and cognitive conditions are depicted in Figure 3. No statistical difference was found between internal and external focus conditions.

3.2. SD of COP

A significant main effect of condition was found for SD of COP in the AP and ML directions (AP: $F_{2,30} = 8.51, p = 0.001, \eta_p^2 = 0.37$; ML: $F_{2,30} = 14.28, p < 0.0001, \eta_p^2 = 0.49$; Figure 4). The cognitive task yielded a significantly smaller SD of COP in both AP (0.46 cm) and ML (0.39 cm) directions than the internal (AP: 0.57 cm; ML: 0.47 cm) and external (AP: 0.57 cm; ML: 0.49 cm) focus conditions. There was no statistical difference between internal and external focus conditions in either direction.

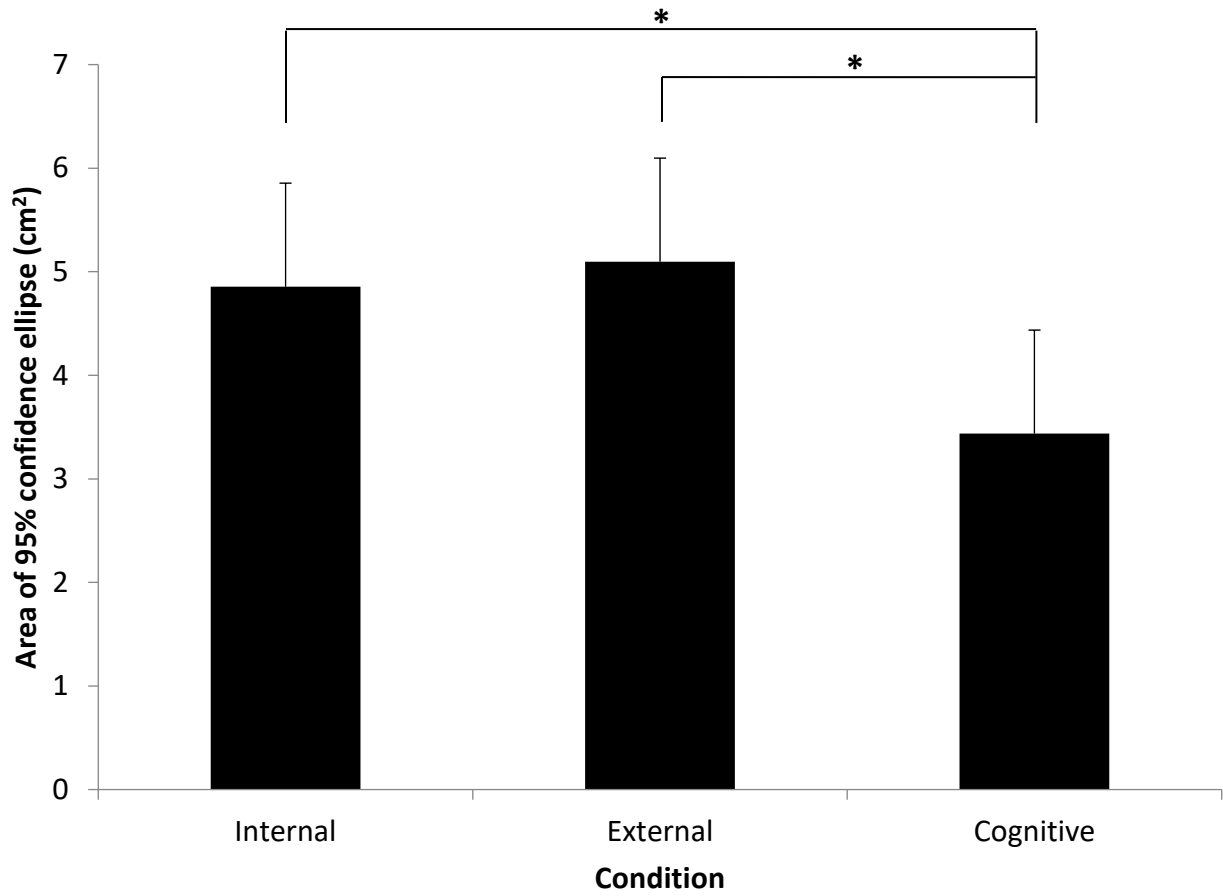


Figure 2. Average (+ 1 SD) area of 95% confidence ellipse (cm²) for the internal, external and cognitive conditions (* $p < 0.01$).

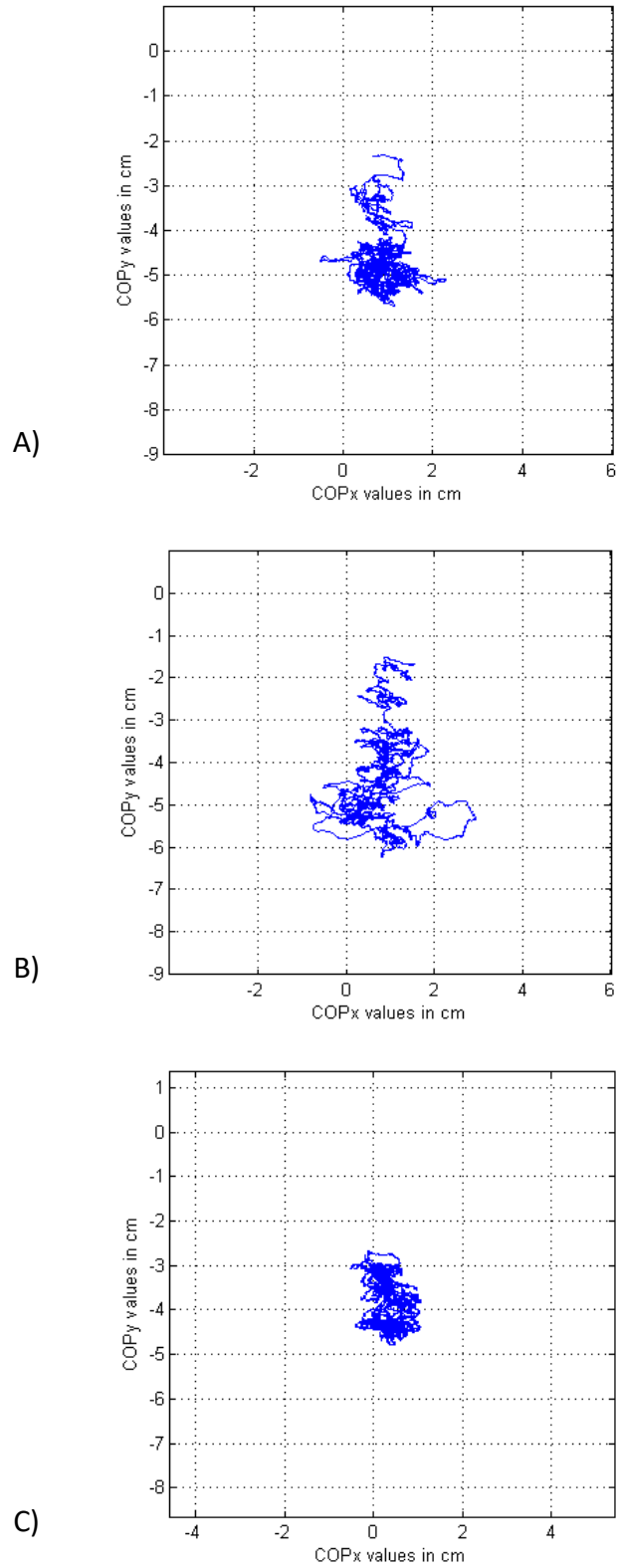


Figure 3. Sample COP displacement in AP (COPy) and ML (COPx) directions (cm) for A) internal focus, B) external focus and C) cognitive task conditions.

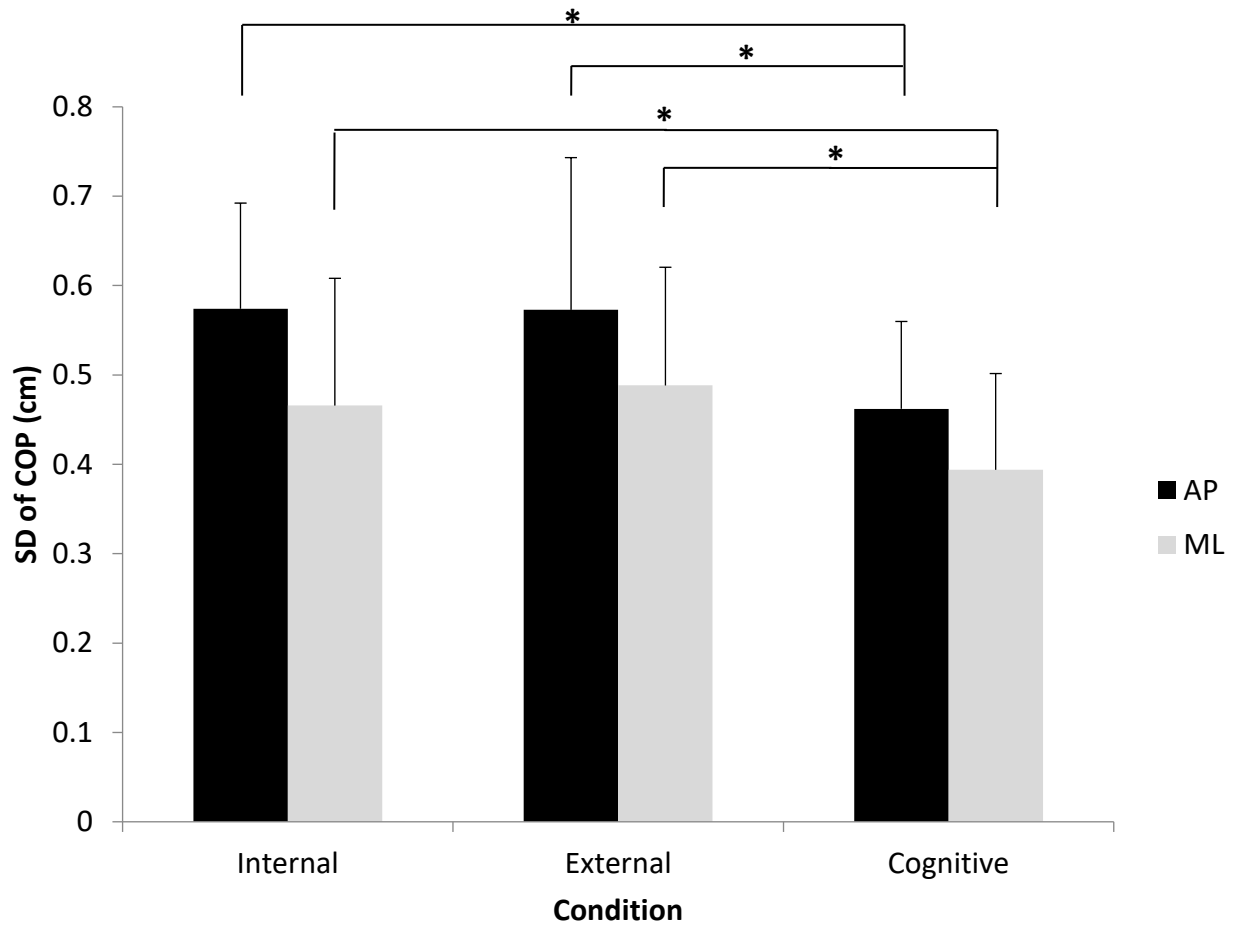


Figure 4. Average (+ 1 SD) SD of COP displacements (cm) in the AP and ML directions for the internal, external and cognitive conditions (* $p < 0.01$).

3.3. Mean Velocity

The ANOVA did not yield a main effect of condition for mean velocity in either AP or ML directions (AP: $F_{2, 30} = 1.71, p > 0.05, \eta_p^2 = 0.10$; ML: $F_{2, 30} = 1.18, p > 0.05, \eta_p^2 = 0.07$). In both the AP and ML directions, the internal, external and cognitive conditions yielded relatively comparable mean velocity values (AP: 2.86 cm/s; ML: 2.63 cm/s; AP: 2.94 cm/s; ML: 2.73 cm/s; AP: 2.99 cm/s; ML: 2.70 cm/s, respectively).

3.4. MPF

A significant main effect of condition was found for MPF in the AP direction ($F_{2, 30} = 5.23, p = 0.01, \eta_p^2 = 0.78$). The cognitive task yielded a significantly higher MPF (1.65 Hz) than the internal (1.59 Hz) and external (1.61 Hz) focus conditions. There was no statistical difference between internal and external focus conditions. No difference was found in the ML direction ($F_{2, 30} = 0.38, p > 0.05, \eta_p^2 = 0.03$). The internal, external and cognitive conditions produced similar values (1.59 Hz; 1.58 Hz; 1.60 Hz, respectively).

3.5. Cognitive task performance

The percentage of cognitive task trials containing errors is reported in Table 2. Trials with errors of 3 or more have been excluded. Every participant made at least one error in the cognitive task. Overall, 59.69% of trials contained an error.

Table 2. *Percentage of cognitive tasks containing errors (%) for each participant, with average error across participants (% \pm SD).*

Participant	Percentage of cognitive task trials with error (%)
1	60.00
2	50.00
3	83.33
4	66.67
5	66.67
6	50.00
7	50.00
8	100.00
9	83.33
10	75.00
11	33.33
12	50.00
13	66.67
14	20.00
15	33.33
16	66.67
Average error	59.69 \pm 20.84

3.6. Age comparison

Average values for each measure and condition in young and older adults are reported in Table 3.

3.6.1. Area of 95% confidence ellipse

There was no main effect of age on sway area ($F_{1, 34} = 0.03$, $p > 0.05$). There was a main effect of condition ($F_{2, 68} = 18.76$, $p < 0.0001$, $\eta_p^2 = 0.36$), where the cognitive task led to significantly smaller sway area than both focus conditions.

3.6.2. SD of COP

In both AP and ML directions, there was no main effect of age on SD of COP (AP: $F_{1, 34} = 0.49$, $p > 0.05$; ML: $F_{1, 34} = 0.33$, $p > 0.05$). There was, however, a main effect of condition (AP: $F_{2, 68} = 19.85$, $p < 0.0001$, $\eta_p^2 = 0.37$; ML: $F_{2, 68} = 23.93$, $p < 0.0001$, $\eta_p^2 = 0.41$), where the cognitive task led to smaller SD of COP than both focus conditions.

3.6.3. Mean Velocity

In both AP and ML directions, there was no main effect of age (AP: $F_{1, 34} = 0.26$, $p > 0.05$; ML: $F_{1, 34} = 2.90$, $p > 0.05$) and no main effect of condition (AP: $F_{2, 68} = 1.82$, $p > 0.05$; ML: $F_{2, 68} = 1.29$, $p > 0.05$) on mean velocity.

3.6.4. MPF

In the AP direction, there was no main effect of age on MPF ($F_{1, 34} = 0.11$, $p > 0.05$). There was, however, a main effect of condition ($F_{2, 68} = 4.78$, $p < 0.05$, $\eta_p^2 = 0.12$). The cognitive task led to higher MPF than both focus conditions.

In the ML direction, there was a main effect of age on MPF ($F_{1, 34} = 5.66, p < 0.05, \eta_p^2 = 0.14$). Older adults presented significantly higher MPF than young adults. There was no main effect of condition ($F_{2, 68} = 0.42, p > 0.05$).

Table 3. Average values (SD) for each measure and condition in young and older adults (* significant difference between groups).

	Internal focus		External focus		Cognitive task	
	Young adults	Older adults	Young adults	Older adults	Young adults	Older adults
Average (SD) Area of 95% confidence ellipse (cm²)	5.13 (3.09)	4.86 (1.80)	4.96 (2.52)	5.10 (2.40)	3.66 (1.98)	3.44 (1.41)
Average (SD) SD of COP in AP direction (cm)	0.56 (0.16)	0.57 (0.12)	0.53 (0.12)	0.57 (0.17)	0.44 (0.11)	0.46 (0.10)
Average (SD) SD of COP in ML direction (cm)	0.49 (0.15)	0.47 (0.14)	0.50 (0.17)	0.49 (0.13)	0.43 (0.13)	0.39 (0.11)
Average (SD) Mean velocity in AP direction (cm/s)	2.85 (0.48)	2.86 (0.44)	2.86 (0.49)	2.94 (0.56)	2.84 (0.50)	2.99 (0.48)
Average (SD) Mean velocity in ML direction (cm/s)	2.42 (0.45)	2.63 (0.48)	2.42 (0.46)	2.73 (0.63)	2.39 (0.45)	2.70 (0.54)
Average (SD) MPF in AP direction (Hz)	0.22 (0.07)	0.19 (0.05)	0.22 (0.06)	0.21 (0.06)	0.23 (0.06)	0.25 (0.09)
Average (SD) MPF in ML direction (Hz)*	0.22 (0.05)	0.25 (0.08)	0.22 (0.05)	0.25 (0.06)	0.22 (0.04)	0.26 (0.06)

4. Discussion

The objectives of the present experiment were to examine attentional focus effects on postural control in older adults and to determine if a continuous, attention-demanding cognitive task could improve postural stability in older adults relative to an internal and external focus of attention. Contrary to the first hypothesis, no significant differences were observed between the internal and external focus of attention conditions. However, the second hypothesis was confirmed since the results demonstrated that the cognitive task increased stability as opposed to the internal and external focus conditions as evidenced by a reduction in sway area and sway variability in AP and ML directions and an increase in MPF in the AP direction.

Contrary to previous findings (McNevin *et al.*, 2013; Chiviakcowsky *et al.*, 2010), no significant difference between internal and external focus was found (Figures 2 and 4). This finding may be attributed to the distance of the external focus. A study by McNevin and colleagues (2003) demonstrated that the beneficial effects of an external focus of attention are greater when the distance of the external cue is increased. They postulate that increasing the distance of the external cue enhances the ability to distinguish a movement effect from the movement itself. In the present study, markers were placed directly on the hips, which may have made it challenging for participants to distinguish the movement of the markers from the movements of the hips. A comparable effect was found in the study by Polskaia and colleagues (2015) where an identical setup was used.

Six cognitive task trials containing an error of 3 or more were discarded to eliminate trials where cognitive effort was not sufficiently maintained. As observed in Table 2, 59.69% of remaining cognitive task trials contained an error under 3 which demonstrates that the cognitive task was highly challenging and difficult enough to require participants' attention during the length

of the trial. Due to the nature of the cognitive task, it was not possible to ensure participants' attention was placed on the task at all times. However, the difference in postural control measures between focus conditions and the cognitive task condition (Figures 2, 3 and 4) suggest participants were allocating their attention to the task as requested. Slightly less trials contained errors in previously unreported data in young adults (Polskaia *et al.*, 2015), with an average of $50.00 \pm 25.13\%$ of trials containing errors.

The cognitive task prompted a more stable posture than both internal and external foci of attention (Figures 2 and 4). This suggests that, despite their reduced attentional capacities (Teasdale *et al.*, 1992), older adults were able to effectively allocate attention away from postural control. According to the posture first principle, older adults prioritize stability at the expense of cognitive performance in a dual-task situation to avoid losing stability (Lacour *et al.*, 2008). However, participants in the present study were self-reported healthy non-fallers. Presumably, since they had no apparent issues with their stability, they may have been less inclined to prioritize posture over cognitive performance to avoid the possibility of a fall. A review by Boisgontier and colleagues (2013) notes that the ability to stand in stable conditions is not affected by age, however when the complexity of the postural task is increased, performance of the postural, concurrent or both tasks becomes more affected than young adults. According to this view and the results of the present study, the postural task used in this study would not have been challenging enough to elicit changes due to age. Results from the present study compare to findings from Swan and colleagues (2004) who also found a cognitive task to improve postural control in older adults. The authors suggested that the highly demanding cognitive task distracted participants from focusing on their postural control. This is in line with the constrained action hypothesis (Wulf *et al.*, 2001) which suggests that removing focus from movement control will allow automatic processes to control

the movement more efficiently than an active control. Results of the present study suggest that the continuous, attention-demanding task was sufficiently challenging to require the greater part of participants' attention, potentially leaving limited opportunities for conscious control of posture. This may have allowed a more automatic mode of postural control to emerge. In support of this assumption, the cognitive task led to higher MPF than both focus conditions. According to previous findings, a higher sway frequency is indicative of a more automatic control (Wulf, 2007; Wulf *et al.*, 2001). Alternatively, the internal focus condition provoked participants to consciously control their sway, leading to a less stable posture than the cognitive task condition. Since the external and internal focus conditions led to similar results, it can be suggested that the lack of distance between the internal and external focus conditions (McNevin *et al.*, 2003) provoked the same type of conscious control.

Certain researchers propose that a higher frequency is indicative of a more automatic type of postural control when it is coupled with smaller sway amplitude (Wulf *et al.*, 2001). Alternatively, other studies suggest that a higher frequency of sway in combination with reduced sway variability (Carpenter, Frank, Silcher & Peysar, 2001) and increased COP velocity (Roerdink, Haart, Daffertshofer, Donker, Geurts & Beek, 2006) is indicative of the use of a stiffening strategy. In the present study, the increased frequency observed in the AP direction during performance of the cognitive task was coupled with a reduced area and reduced sway variability, suggesting improvements could be attributed to either option. However, the cognitive task provoked no change in mean velocity in either AP or ML directions, which suggests that the higher frequencies observed in the cognitive task condition were not due to the use of a stiffening strategy. The discordant findings in the literature make it difficult to ascertain if participants in the present study engaged in a stiffening strategy. However, results suggest that the continuous nature

of the cognitive task limited opportunities for participants to consciously engage in the postural control process therefore promoting the use of more automatic control processes.

The auditory nature of the cognitive task may provide another explanation for the observed improvements in postural stability. Since the auditory stimulus was always presented directly behind participants, this could have provided the participants with an external spatial reference. However, there is conflicting evidence on the effect of auditory stimulation location on postural control. Raper and Soames (1991) found that auditory conditions in all directions led to increased postural sway as opposed to a silent condition. Conversely, Easton and colleagues (1998) found a decrease in sway when speakers were placed adjacent to each ear. Therefore, it remains unclear whether the location of the speakers would have led to an increase or decrease in postural sway. Regardless, there is a clear contrast between the internal and external focus conditions and the cognitive task condition, and this effect has been repeated in similar studies using auditory conditions (i.e. Swan *et al.*, 2004, where the sound source was behind and to the right of the participant), which leads us to suggest the effect is due to more than just location of sound.

Results from the present study were compared to those from the study by Polskaia and colleagues (2015) to examine age differences in postural control. No group differences were found for area, SD of COP in the AP or ML directions, or MPF in the AP direction, suggesting there were minimal differences in postural control between young and older adults (Table 3). Although contradictory to many findings (e.g. Maylor *et al.*, 2001; Shumway-Cook *et al.*, 1997), authors suggest that the excellent health status of participants in the present study may have contributed to their stability. A significant difference was found for MPF in the ML direction. MPF was higher in the older adult group (0.25 Hz) compared to the young adult group (0.22 Hz). As previously mentioned, an increase in MPF coupled with a reduced sway amplitude is indicative of a more

automatic postural control (Wulf *et al.*, 2001), and a higher MPF coupled with an increase in sway velocity or a reduction in SD could be indicative of the use of a stiffening strategy (Roerdink *et al.*, 2006; Carpenter *et al.*, 2001). Since the difference in frequency is not accompanied by any other age effects, we cannot attribute the increased MPF to either option. It could simply be that older participants made more frequent postural corrections in the ML axis than younger adults. This could be due to the fact that participants were standing with feet together, leading to a reduced ML stability, and that the postural control of older adults is more easily affected in this position. However, even though the variables might not suggest a purely automatic postural control, the cognitive task was found to improve postural control in the older adults similarly to the young individuals. Authors believe this is due to the fact that the cognitive task promotes the use of a less voluntary postural control.

5. Conclusion

Results of the present study demonstrate that performing a cognitive task while standing upright improves postural control in older adults compared to an internal and external focus of attention. This suggests that healthy older adults are able to allocate attention away from postural control in order to allow a more automatic type of control to emerge. Future research should examine the effect of a cognitive task in individuals with fear of falling or frail older adults, who may not be able to flexibly remove attention from postural control.

Conflict of interest

The researchers have no conflict of interest to declare.

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Chapter 5 – Examining the use of the stiffening strategy in older adults while standing

Improvements in postural control in external focus and cognitive task conditions are unlikely due to stiffening in healthy older adults

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Background: Research suggests that focusing externally while standing may improve postural control, and that performing a cognitive task while standing is also beneficial. This could be because removing attention from movement production promotes automaticity, or may be due to the use of a stiffening strategy.

Research question: Will changes in postural control in attentional focus and cognitive task conditions be attributed to modifications in muscle activity around the ankle joint in healthy older adults?

Methods: Twenty older adults (69.2 ± 3.47 years) stood with feet together on a force platform while performing 5 tasks: baseline standing, internally focusing on reducing movements of their ankles, externally focusing on reducing movements of markers attached to their ankle joints, and two cognitive tasks consisting of counting the occurrence of digits in a sequence. A one-way

analysis of variance with repeated measures on condition was performed for sway area, standard deviation of the centre of pressure, mean velocity of the centre of pressure, and integrated muscle activity of the tibialis anterior and medial gastrocnemius

Results: Results reveal improvements in stability in external focus and cognitive task conditions compared to baseline standing and internal focus conditions, and increased velocity in cognitive task conditions, while no change occurred in integrated muscle activity of the tibialis anterior and medial gastrocnemius.

Significance: Results prove that focusing externally and performing a cognitive task during quiet standing can improve postural control in older adults. Furthermore, since no change occurred in muscle activity across conditions, this suggests that stiffening cannot explain these changes, and therefore lends support to the theory that improvements are due to automaticity of sway. Specifically, by removing attention from movement production, the external focus and cognitive tasks may have allowed automatic processes to regulate sway more efficiently.

1. Introduction

A myriad of investigations reveal benefits of using an external focus of attention on motor learning and performance [1 for review]. An external focus encourages an individual to allocate attention to the effect their movement has on an external cue or apparatus such as the movement of a golf club, while an internal focus directs attention to the production of movement such as the swing of the arm [1]. The constrained action hypothesis [2-4] suggests these improvements are because the external focus removes attention from movement production, allowing automatic processes to regulate the movement in a more efficient way. It is of interest to investigate if the attentional focus effects can be replicated in quiet standing conditions, more particularly in older

adults since it might reveal strategies to improve stability in a population who experiences declining postural control and increased risks of falls.

The effect of attentional focus on quiet standing is not well established. Experiments in young adults report conflicting effects, either demonstrating a beneficial effect of using an external focus [5] or no effect at all [6]. Similarly in older adults, a recent experiment revealed no effect of attentional focus on quiet standing [7] while another demonstrates modest effects of an external focus on postural control [8]. Although the effect of attentional focus on quiet standing seems to be limited, many experiments have taken the constrained action hypothesis one step further by attempting to remove attention from postural control altogether with the use of a challenging cognitive task [6,7,9-11]. These studies demonstrate that in both young and older adults, performing a cognitive task while standing leads to improvements in stability [6,7,9-11].

The reason cognitive tasks improve stability is thought to be the automaticity of sway. As described previously, removing attention from the control of movement allows automatic processes to function in an unconstrained manner. Focusing on an aspect of movement production would interfere with these automatic processes, leading to less efficient movement control [2-4]. However, another hypothesis states that improvements in postural control in challenging dual-task conditions might reflect the use of a stiffening strategy. According to this view, individuals co-contract the muscles surrounding the ankle joint to maximize stability to allow cognitive resources to be allocated to the challenging concurrent task [9,11,12].

A recent experiment examined the effect of attentional focus and cognitive tasks on quiet standing while examining the muscle activity of the tibialis anterior (TA) and medial gastrocnemius (MG) in young adults [5]. They found improvements in stability in the external focus condition compared to baseline standing and internal focus conditions, and further

improvements in the cognitive task conditions. No effect was observed in muscle activity across conditions, suggesting that these improvements were not due to stiffening but to automaticity of sway. This is to be expected in young adults since stiffening is usually only observed while standing at the edge of an elevated surface [13] and is energetically inefficient [14].

Results may differ in an older adult population. Aging inevitably leads to declines in postural stability. Furthermore, aging leads to reductions in the attentional capacity of the individual, which decreases the ability to flexibly allocate resources between tasks [15]. Since older adults require that a greater proportion of attention be placed on the postural task to ensure their stability [16], they might use a different strategy than young adults to stabilize in a dual-task situation. Specifically, they might use a co-contraction strategy to freeze the ankle joint to allow the attentional resources to be placed on the cognitive task. However, since the present experiment is conducted on healthy and active older adults, the consequences of aging might not yet be important enough to provoke this type of strategy. It is important to investigate if improvements in stability that are observed in cognitive task conditions are due to automaticity or to the use of a stiffening strategy in older adults.

The aim of the present experiment is to extend findings of Richer et al. [5] to an older adult population. Specifically, the objectives are firstly to reinforce the effect of attentional focus and cognitive tasks on postural control in healthy older adults and secondly to test that no change occurs in the muscle activity of the lower leg in these conditions. It is hypothesized that, similarly to young adults [5], the external focus condition will improve stability compared to baseline standing and internal focus conditions, and that cognitive tasks will improve stability compared to all other conditions. It is also hypothesized that no change in muscle activity will be observed

across conditions, supporting the theory that changes in sway are due to automaticity and not to stiffening.

2. Methods

2.1. Participants

Twenty healthy older adults (69.2 ± 3.47 years, 15 male) were recruited. Health status data of participants are reported in Table 1. Participants signed a consent form approved by the Research Ethics Board at the University of Ottawa. They completed a health questionnaire to verify they had no injury or condition that could impair their motor performance in the study. The Mini-Mental State Examination [17] was administered to screen for neurological impairments, with a cut-off set at 24.

Table 1. *Health status data of participants.*

Participant	Height (cm)	Weight (lbs)	Recent injury or fall (affecting postural control)	Vestibular problem	MMSE score
1	155	148	No	N/A	30
2	152	158	No	N/A	28
3	163	138	No	N/A	29
4	163	140	Yes, tripped on obstacle	N/A	30
5	152	153	No	N/A	30
6	183	212	No	N/A	30
7	173	145	No	N/A	29
8	160	105	No	N/A	30
9	175	185	No	N/A	30
10	168	185	No	N/A	30
11	173	175	No	N/A	29
12	175	180	No	Vertigo (No concern during testing)	30
13	188	210	Yes, slippery surface	N/A	30
14	185	200	No	N/A	28
15	178	190	No	N/A	29
16	173	151	No	N/A	30
17	175	155	No	N/A	30
18	170	265	No	N/A	30
19	175	183	No	N/A	27
20	183	190	No	N/A	29
Average (SD)	171 (10.6)	173 (34.7)	---	---	29 (0.9)

2.2. Apparatus

An AMTI force platform (OR6-6- 1000, Watertown, MA, USA) was used to record centre of pressure (COP) data at a sampling rate of 500 Hz. Electromyography (EMG) data was recorded at a sampling rate of 1000 Hz using two wireless electrodes (Delsys Inc., Natick, MA, USA) placed on the muscle bellies of the right TA and the right MG [18].

For the external focus condition, two L-shaped devices were attached to participants' ankles [5]. Each device consisted of one metal strip placed horizontally along the lateral length of the foot and another placed vertically along the lateral side of the lower leg. These strips were loosely linked at the ankle joint to allow a pivoting movement in the AP direction without impeding movement in the ML direction. Three markers extended laterally by 9 cm from these strips, one near the toe, the second resting on the lateral malleolus, and the third in the middle of the lower leg. One such apparatus was attached to each lower leg using elastic Velcro straps.

Cognitive tasks were pre-recorded to ensure consistency and the audio recordings were presented using a digital media player with two speakers placed on either side of the participant.

2.3. Postural task

Participants stood on the force platform with feet together, arms hanging loosely at the sides, and eyes fixed on an eye-level target 3 meters ahead. Foot placement was standardized across trials.

2.4. Attentional focus

In the internal focus condition, participants were instructed to concentrate on minimizing movements of their ankles. In the external focus condition, they were outfitted with the apparatus described in section 2.2 [5] which moved proportionally to their postural sway. Prior to an external focus trial, participants could look down at the position of the markers to ensure they had an

accurate mental representation of the apparatus. When they swayed, the position of the top marker relative to the bottom two markers would change, in both AP and ML directions. They were asked to concentrate on keeping the same initial position of the top marker relative to the bottom two, in other words to minimize movements of the markers. This was exclusively a mental task, in which focus was placed on the effect their sway had on the apparatus. For this reason, no visual feedback of the apparatus was provided during the trials and participants were asked to fixate the target in front of them as in all other conditions.

2.5. Cognitive tasks

The single-number (SNS) and double-number (DNS) sequence conditions both consisted of the same task but differed in the level of difficulty. For both tasks, an auditory sequence consisting of 30 three-digit numbers was presented (e.g., 257, 586, 390, etc.). Numbers were presented every two seconds for the entire duration of the trial. In the SNS condition, participants were asked to count the number of times a target digit was presented in the sequence (e.g., count the total number of 3s.) and provide the total at the end of the trial. In the DNS condition, participants were asked to count the number of times two target digits were presented in the sequence (e.g., count the number of 3s and 5s.) and provide two separate totals at the end of the trial. Both, the SNS and DNS tasks required participants to search for the target digit(s) in each 3-digit number, while simultaneously maintaining a running total.

2.6. Procedure

The study consisted of five experimental conditions: baseline standing, internal focus, external focus, SNS, and DNS. In the baseline condition, participants were asked only to perform the postural task outlined in section 2.3. The remaining conditions were dual-tasks, in which a focus or cognitive task was performed concurrently with the postural task. Four 60-second trials

were collected for each condition, for a total of 20 trials. The trials were counterbalanced to eliminate an order effect. One familiarization trial was performed for each condition prior to data collection, to ensure participants fully understood the requirements of each task.

For attentional focus conditions, manipulation checks were performed after each trial to ensure participants allocated attention to the requested cue. They were asked to rate the percentage of attention they had placed on minimizing the movements of their ankles in the internal focus task, and on maintaining the position of the markers in the external focus task. If a score of 50% or lower was reported, the trial was redone, unbeknownst to the participant.

For both SNS and DNS conditions, six different sequences were used interchangeably and target digits were alternated to reduce chance of memorization. To ensure participants were performing the cognitive tasks and not resorting to guessing, trials containing errors exceeding a predetermined range were discarded and repeated, unbeknownst to the participant [19]. For the SNS condition, if the participant's error was greater than 3, the trial was redone. For the DNS condition, if the participant's error was greater than six, the trial was redone. Use of fingers as a counting aid during the cognitive tasks was prohibited. All conditions were performed silently to eliminate impact of verbalization on postural sway [20].

2.7. Data analyses

To evaluate postural control, several dependant variables were derived from the COP data using MatLab software (MathWorks Inc., MA, USA). These measures were area of 95% confidence ellipse (area), standard deviation (SD) of COP in anterior-posterior (AP) and medial-lateral (ML) directions, and mean velocity of COP in AP and ML directions. BioProc3 software was used to perform a 4th order Butterworth band-stop filter on EMG data to remove data between 59.5 and 60.5 Hz, eliminating any possible noise caused by alternating current used to power equipment. A full wave rectification of EMG data was also performed to acquire the integral of muscle activity for TA and MG over the entire 60-sec trial. Data from three participants was excluded from EMG analyses due to a technical error with the EMG electrodes.

2.8. Statistical analyses

For each dependent variable, one average value per condition was calculated for each participant and subsequently used for analysis. A one-way analysis of variance with repeated measures on condition was performed for each of the dependant variables. Furthermore, data was compared to previously published data in young adults [5] to examine the effect of age. For this, a two-way ANOVA on group and condition, with repeated measures on condition, was performed for each of the dependent variables. If Mauchly's Test of Sphericity was violated, Greenhouse-Geisser corrections were performed. Newman-Keuls post-hoc analyses were performed to determine location of significance when necessary. Statistical significance was set at $p < 0.05$.

3. Results

3.1. Area of 95% confidence ellipse

Results reveal a significant main effect of condition on area, $F(4,76) = 5.72, p < 0.05, \eta_p^2 = 0.23$ (Fig. 1). Area was significantly smaller in external, SNS, and DNS than in baseline and internal focus conditions.

3.2. Standard Deviation of Center of Pressure

A significant main effect of condition was found for SD of COP in the AP direction, $F(4,76) = 6.09, p < 0.05, \eta_p^2 = 0.24$ (Fig. 2). SD of COP in SNS and DNS was significantly smaller than in the baseline and internal focus conditions.

A significant main effect of condition was also found for SD of COP in the ML direction, $F(4,76) = 6.01, p < 0.05, \eta_p^2 = 0.24$ (Fig. 2). SD of COP was significantly smaller in external focus, SNS and DNS than in baseline standing. SD of COP was also significantly smaller in external focus and SNS compared to the internal focus condition.

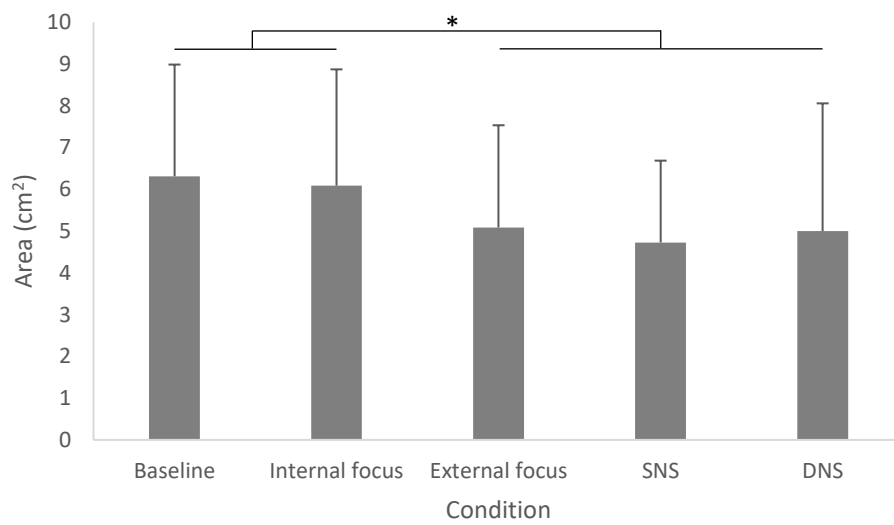


Fig. 1. Average +1 SD area (cm²) for baseline standing, internal focus, external focus, SNS, and DNS conditions (* $p < 0.05$).

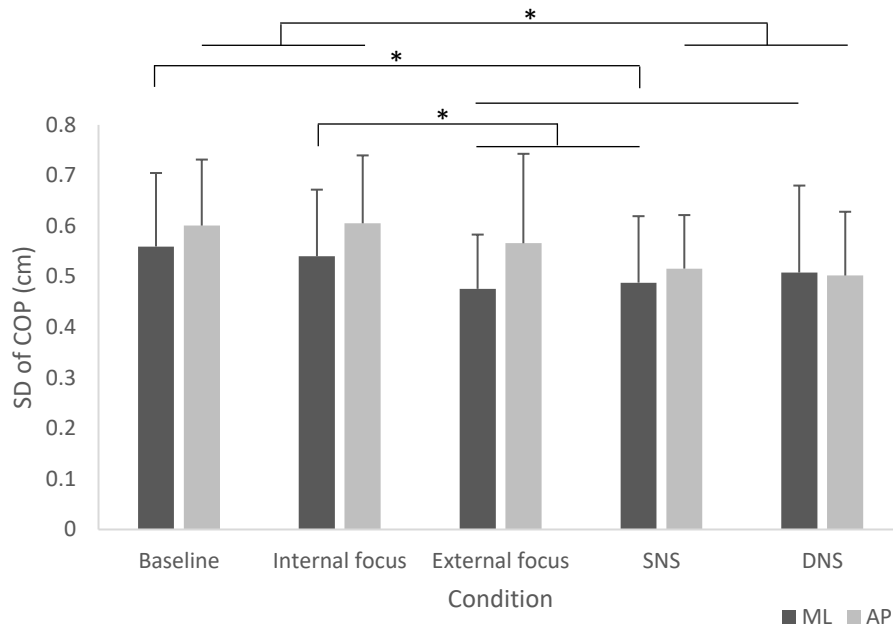


Fig. 2. Average +1 SD SD of COP (cm) in ML and AP directions for baseline standing, internal focus, external focus, SNS, and DNS conditions (* $p < 0.05$).

3.3. Mean Velocity of Center of Pressure

Results reveal a significant main effect of condition on mean velocity in the AP direction, $F(1.25, 23.7) = 28.2, p < 0.05, \eta_p^2 = 0.60$ (Fig. 3). Mean velocity was significantly higher in SNS and DNS than in baseline, internal focus, and external focus conditions.

A significant main effect of condition was also found for mean velocity in the ML direction, $F(2.62, 49.7) = 32.3, p < 0.05, \eta_p^2 = 0.63$ (Fig. 3). Mean velocity was significantly higher in SNS and DNS than in baseline, internal focus, and external focus conditions. Mean velocity was significantly lower in EF than in the internal focus condition.

3.4. Muscle Activity

No significant main effect was found for integrated muscle activity in the TA, $F(4, 64) = 0.62, p > 0.05$, or MG muscles, $F(4, 64) = 1.05, p > 0.05$ (Fig. 4).

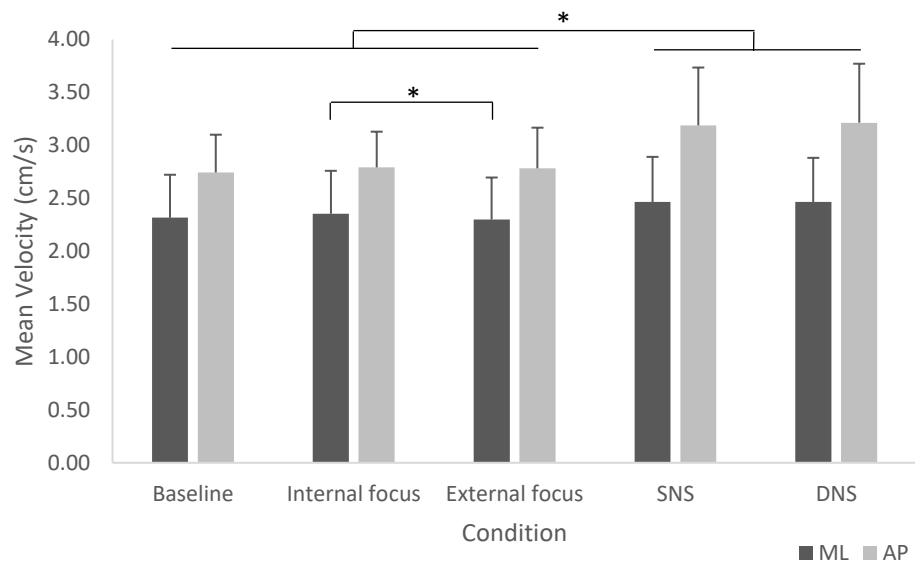


Fig. 3. Average +1 SD mean velocity (cm/s) in ML and AP directions for baseline standing, internal focus, external focus, SNS, and DNS conditions ($*p < 0.05$).

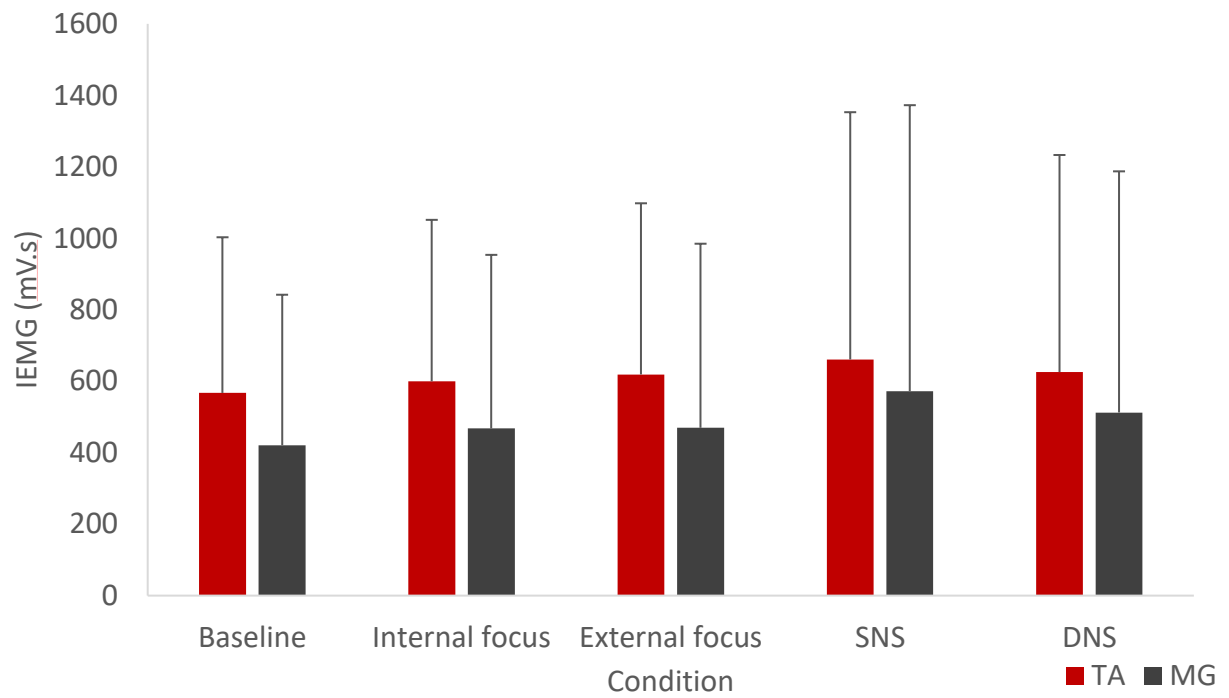


Fig. 4. Average (+ 1 SD) IEMG (mV.s) for baseline standing, internal focus, external focus, SNS, and DNS conditions.

3.5. Age comparison

Average values for each condition in young and older adults are reported for COP variables in Table 2 and for integrated muscle activity in Table 3.

3.5.1. Area of 95% confidence ellipse

There was no main effect of group on sway area, $F(1,43) = 2.86, p > 0.05$. There was, however, a main effect of condition, $F(3.23,138.81) = 20.95, p < 0.05, \eta_p^2 = 0.33$. External focus and both cognitive task conditions produced significantly smaller sway area than baseline and internal focus conditions.

3.5.2. Standard Deviation of Center of Pressure

For both directions, there was no main effect of group on SD of COP, AP: $F(1,43) = 3.07, p > 0.05$, ML: $F(1,43) = 2.04, p > 0.05$. In the AP direction, there was a main effect of condition, $F(4,172) = 17.20, p < 0.05, \eta_p^2 = 0.29$. SD of COP was smaller in external focus, SNS and DNS than in baseline and internal focus conditions, and was smaller in both cognitive tasks than in the external focus condition. In the ML direction, there was a main effect of condition, $F(3.06,131.59) = 17.88, p < 0.05, \eta_p^2 = 0.29$. All dual-task conditions presented significantly smaller SD of COP than baseline. External focus and both cognitive task conditions also presented significantly smaller SD of COP than in the internal focus condition. Finally, in the ML direction, there was an interaction between group and condition, $F(3.06,131.59) = 3.09, p < 0.05, \eta_p^2 = 0.07$. In young adults, all dual-task conditions presented significantly smaller SD of COP than baseline, and the DNS condition also presented smaller SD of COP than internal focus and SNS conditions. In older adults, external focus and both cognitive task conditions led to significantly smaller SD of COP than baseline, and the external focus and SNS also led to significantly smaller SD of COP than the

internal focus. There was no difference between groups in baseline, external focus and SNS conditions, while in internal focus and DNS conditions older adults had significantly higher SD of COP than young adults.

3.5.3. Mean Velocity of Center of Pressure

In the AP direction, there was no main effect of group on mean velocity, $F(1,43) = 0.73$, $p > 0.05$. There was a main effect of condition, $F(1.47,63.25) = 49.53$, $p < 0.05$, $\eta_p^2 = 0.54$. The cognitive tasks presented significantly higher mean velocity than the other conditions. There was also a significant interaction between group and condition, $F(1.47,63.25) = 7.75$, $p < 0.05$, $\eta_p^2 = 0.15$. For both groups, both cognitive tasks led to higher mean velocity than the other conditions. Older adults had significantly lower mean velocity than young adults in baseline, internal focus and external focus conditions, however in the cognitive task conditions there was no difference between groups.

In the ML direction, there was a main effect of group on mean velocity, $F(1,43) = 6.41$, $p < 0.05$, $\eta_p^2 = 0.13$. Mean velocity was significantly lower in older adults compared to young adults. There was also a main effect of condition, $F(1.30,56.07) = 27.23$, $p < 0.05$, $\eta_p^2 = 0.39$. Mean velocity was significantly higher in cognitive task conditions than in other conditions.

3.5.4. Muscle Activity

There was a main effect of group on muscle activity for both the TA, $F(1,39) = 12.79$, $p < 0.05$, $\eta_p^2 = 0.25$, and MG, $F(1,39) = 7.00$, $p < 0.05$, $\eta_p^2 = 0.15$. For both muscles, integrated muscle activity was significantly higher in older adults than in young adults. There was no main effect of condition in the TA, $F(1.74,67.93) = 0.65$, $p > 0.05$, or the MG, $F(1.76,68.77) = 1.63$, $p > 0.05$.

Table 2. Average (SD) area (cm²), SD of COP (cm) and mean velocity (cm/s) for each condition in young and older adults (* significant difference between groups; † smaller than baseline and internal focus; ‡ smaller than external focus; # smaller than baseline; × higher than baseline, internal focus and external focus; ± smaller than internal focus and SNS; % higher than baseline, internal focus and external focus).

Condition	Group	Average (SD) Area (cm ²)	Average (SD) SD of COP in AP direction (cm)	Average (SD) SD of COP in ML direction (cm)	Average (SD) Mean velocity in AP direction (cm/s)	Average (SD) Mean velocity in ML direction (cm/s)
Baseline standing	Young adults	5.53 (2.36)	0.57 (0.15)	0.53 (0.13)	2.98 (0.56)*	2.65 (0.53)*
	Older adults	6.31 (2.68)	0.60 (0.13)	0.56 (0.15)	2.74 (0.36)*	2.32 (0.41)*
Internal focus	Young adults	5.00 (1.81)	0.54 (0.14)	0.48 (0.08)* #	2.99 (0.58)*	2.64 (0.53)*
	Older adults	6.09 (2.78)	0.61 (0.13)	0.54 (0.13)*	2.79 (0.34)*	2.35 (0.41)*
External focus	Young adults	4.19 (1.66)†	0.51 (0.13)†	0.45 (0.09)#	3.03 (0.58)*	2.63 (0.54)*
	Older adults	5.09 (2.45)†	0.57 (0.18)†	0.48 (0.11)# †	2.78 (0.38)*	2.30 (0.40)*
SNS	Young adults	4.03 (2.12)†	0.45 (0.14)† ‡	0.47 (0.11)#	3.20 (0.63)%	2.89 (0.55)* ×
	Older adults	4.73 (1.96)†	0.52 (0.11)† ‡	0.49 (0.13)# †	3.19 (0.55)%	2.46 (0.43)* ×
DNS	Young adults	3.36 (1.42)†	0.43 (0.11)† ‡	0.41 (0.08)* # ±	3.18 (0.62)%	2.87 (0.54)* ×
	Older adults	5.00 (3.06)†	0.50 (0.13)† ‡	0.51 (0.17)* #	3.21 (0.56)%	2.47 (0.42)* ×

Table 3. Average (SD) integrated muscle activity of the TA and MG muscles (mV.s) for each condition (* significant difference between groups).

Condition	Group	Average (SD) integrated muscle activity of TA (mV.s)*	Average (SD) integrated muscle activity of MG (mV.s)*
Baseline standing	Young adults	184.12 (280.85)	163.06 (173.35)
	Older adults	567.15 (435.65)	420.70 (421.28)
Internal focus	Young adults	198.36 (259.61)	156.83 (138.35)
	Older adults	599.55 (451.94)	467.62 (485.88)
External focus	Young adults	172.32 (216.84)	165.64 (234.74)
	Older adults	618.85 (479.01)	469.55 (515.13)
SNS	Young adults	178.18 (259.26)	179.23 (235.92)
	Older adults	660.76 (691.98)	572.03 (800.36)
DNS	Young adults	173.75 (232.49)	162.30 (171.48)
	Older adults	625.53 (607.45)	512.34 (674.91)

3.6. Cognitive task performance

The percentage of cognitive task trials containing errors is reported in Table 4. Trials with errors of 4 or more have been excluded for the SNS condition, and of 7 or more for the DNS condition. Every participant made at least one error in the cognitive tasks. All participants always made at least one error in the DNS condition. Overall, 77.97% of trials contained an error.

Table 4. *Percentage of cognitive tasks containing errors (%) for each participant, with average error across participants (% ± SD).*

Participant	Percentage of error in SNS condition (%)	Percentage of error in DNS condition (%)	Percentage of error in all cognitive task conditions (%)
1	75.00	100.00	87.50
2	100.00	100.00	100.00
3	50.00	100.00	75.00
4	80.00	100.00	88.89
5	50.00	100.00	75.00
6	50.00	100.00	75.00
7	75.00	100.00	85.71
8	66.67	100.00	83.33
9	20.00	100.00	55.56
10	75.00	100.00	87.50
11	75.00	100.00	87.50
12	50.00	100.00	75.00
13	75.00	100.00	83.33
14	75.00	100.00	87.50
15	25.00	100.00	62.50
16	50.00	100.00	75.00
17	25.00	100.00	62.50
18	50.00	100.00	75.00
19	25.00	100.00	62.50
20	50.00	100.00	75.00
Average (SD)	57.08 (22.00)	100.00 (0.00)	77.97 (11.16)

4. Discussion

The objectives of the present study were to reinforce the effect of attentional focus and cognitive tasks on postural control in healthy older adults and to verify that no change occurred in the muscle activity of the lower leg in these conditions. Results mostly support the proposed hypotheses. The external focus and both cognitive task conditions yielded improvements in postural control compared to baseline standing and internal focus conditions. Changes in velocity were only observed in the cognitive task conditions. Finally, none of these changes were attributed to modification in muscle activity of the TA and MG.

Present results have revealed that the external focus led to reduced sway area and SD of the COP in the ML direction compared to both baseline standing and internal focus condition (Fig. 1 and 2). These results have demonstrated that it was possible to elicit improvements in quiet standing in older adults by using an external focus of attention. Results contradict previous findings that revealed no difference between internal and external focus conditions [7]. This could have been due to the distance of the external focus cue. It has been demonstrated that increasing the distance of the cue makes it easier to distinguish its movement from movements of the body [4]. In the present study, the markers were further away from the body than in the comparable study [7], making it easier to allocate attention to the requested cue [4]. These results have reinforced the findings of [8] which revealed modest improvements in postural control, only in the ML direction, while using an external focus on a suprapostural tracking task.

It was hypothesized that, as in young adults [5], the cognitive task conditions would improve postural control more than the external focus condition. This was not fully evidenced in the present study. In fact, there was no difference between the external focus and the cognitive task conditions in sway area (Fig. 1), however the external focus did not yield the same reductions

in SD of COP in the AP direction as the cognitive task conditions (Fig. 2). Additionally, mean velocity was higher in cognitive task conditions than in all other conditions (Fig. 3). This has indicated that both external focus and cognitive task conditions elicited benefits in postural control, however the cognitive tasks may have provoked a different strategy than the external focus, as evidenced by changes in mean velocity. Perhaps by removing attention from postural control altogether, cognitive task conditions have allowed a more automatic postural control to regulate sway, while in the external focus condition attention was still placed on an aspect of the movement, which might still have caused some interference with automatic processes [6].

As highlighted in Table 4, each participant made errors in the cognitive tasks. The DNS was very difficult, as evidenced by the fact that no participant every obtained the correct answer. However, in a silent cognitive task, is it difficult to examine cognitive task performance and to ensure that participants are performing the task as requested. Therefore, trials exceeding a predetermined error score were excluded to try to eliminate trials where participants may have guessed the answer. The high error rate suggests that both cognitive tasks were difficult enough to require a great proportion of participants' attention, and that the DNS task was more difficult than the SNS task. Previously unreported error scores in young adults [5] reveal they presented similar difficulties with the cognitive tasks, since 56.2 % of SNS trials contained errors (compared to 57.1% for older adults) and 98.3% of DNS trials contained errors (compared to 100% for older adults). On average, 77.3% of cognitive task trials contained errors in young adults, which is very similar to the 78.0% of trials containing errors in older adults.

The hypothesis that no change would occur in muscle activity of the TA and MG was fully supported by the present findings (Fig. 4). Participants were asked to quietly stand on a stable surface without perturbation, suggesting they would primarily be using an ankle strategy to

maintain postural control. For this reason, an increase in integrated muscle activity of the TA and MG might suggest stiffening of these muscles. Since no change occurred across conditions, it is possible to suggest that the modifications in postural control in external focus and cognitive task conditions were not due to stiffening of the muscles surrounding the ankle joint. Similar findings were evidenced in young adults [5]. The present postural task was not very challenging, in that participants were standing in a bipedal stance on a stable surface at ground level. Previous experiments examining stiffening have shown that it occurred in postural threat situations, such as standing at a height [21], although others have found indications of stiffening in dual-task conditions in both young and older adults [9,11,12]. Participants in this present study were healthy and fit, which likely contributed to the health of their postural system. It is therefore possible that the level of difficulty of the postural and cognitive tasks combined with the health of participants contributed to the apparent absence of stiffening. In fact, stiffening is considered to be energetically inefficient [14], which would indicate it is not the optimal strategy to use when there is no threat to stability. Instead, results suggest that by removing attention from postural control and placing it either on an external cue or a continuous cognitive task, participants have allowed automatic processes to regulate sway in a more efficient manner [2-4,6].

Data from the current experiment was compared to previously published data in young adults [5] to verify the effect of age. No main effect of group was found for sway area, SD of COP, and mean velocity in the AP direction although some interactions were revealed for SD of COP in the ML direction and mean velocity (Table 2). There was a main effect of group in mean velocity in the ML direction, where older adults presented significantly lower mean velocity than young adults. Therefore, although some differences were observed, young and older adults generally presented similar sway. Interestingly, there was a main effect of group on EMG activity, which

was significantly higher in the older adults compared to the young (Table 3). Nonetheless, no main effect of condition was found on EMG activity which suggests that a change in muscle activity between groups was not representative of the use of a stiffening strategy, but rather of changes in the mechanical properties of muscles that normally occur in aging.

5. Conclusion

Results of the present study have proven that an external focus of attention can lead to improvements in stability while standing quietly in healthy older adults. Furthermore, findings have reinforced the fact that continuous cognitive tasks can improve postural control in this population. Finally, the present experiment has provided support to the theory that improvements in postural control observed in external focus and cognitive task conditions were the result of automaticity, since no increase in lower leg muscle activity occurred in these conditions.

Conflict of interest statement

Authors have no conflict of interest to declare.

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Chapter 6 – The use of dynamic measures of sway to elucidate changes in postural strategies during attentional focus and cognitive task conditions in young and older adults

Automaticity of postural control while dual-tasking revealed in young and older adults

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Abstract

Many authors have suggested that improvements in postural control in cognitive task conditions occur because the cognitive tasks allow automatic postural control processes to regulate sway more efficiently. To provide evidence for this theory, dynamic measures of sway (wavelet, sample entropy, rambling and trembling) were used to analyse postural control in attentional focus and cognitive task conditions to reveal changes in the structure and composition of sway. The centre of pressure data from twenty-two young adults (20.8 ± 2.82 years, 9 male) and twenty older adults (69.2 ± 3.47 years, 15 male) was used. Participants stood with feet together in 5 conditions: baseline standing, internal focus, external focus, easy cognitive task, and difficult cognitive task.

Results reveal a change in strategy in both cognitive task conditions, which was more pronounced for the more difficult condition. Specifically, both cognitive task yielded higher contributions from higher frequency bands, and less contributions from the lowest frequency band, compared to other conditions. They also presented higher complexity and irregularity of sway, which reflected a more efficient postural control. Finally, the external focus and more difficult cognitive task presented increased trembling, which suggests increased contributions from spinal reflex components, however this was only evidenced in young adults. These results provide support to the theory that stability improvements in cognitive task conditions were due to automatization of postural control, in both young and older adults. They have also suggested that more difficult tasks yielded further automaticity than tasks that required less cognitive involvement.

Keywords: Automaticity, postural control, young and older adults, wavelet, sample entropy

Introduction

Recent investigations into dual-tasking reveal improvements in postural control when using an external focus and when performing a challenging cognitive task in both young and older adults (Polskaia, Richer, Dionne, & Lajoie, 2015; Richer, Saunders, Polskaia, & Lajoie, 2017b; Richer, Ly, Fortier, & Lajoie, 2018). An external focus is used to direct attention away from movement production and onto the effects sway has on an external apparatus, while an internal focus requires attention to be placed on the production of movement itself. Wulf and colleagues have proposed the constrained action hypothesis (Wulf, McNevin, & Shea, 2001a; Wulf, Shea, & Park 2001b; McNevin, Shea, & Wulf, 2003) which states that by allocating attention away from movement production, an individual allows automatic mechanisms to control the movement more efficiently. Conversely, consciously attending to movement production interferes with these

mechanisms. Therefore, an external focus can lead to improvements in stability compared to an internal focus as well as baseline standing (i.e. Richer *et al.*, 2017b; Richer *et al.*, 2018).

Since the constrained action hypothesis was proposed, a few authors have expanded the idea to cognitive tasks. Since a challenging cognitive task distracts individuals from postural control altogether, it might allow an even more automatized control of sway than when using an external focus of attention, in which attention is still placed on an aspect related to movement control. In fact, performing a cognitive task while standing has led to improvements in postural stability compared to both an internal and external focus in young and older adults (Polskaia *et al.*, 2015; Richer, Polskaia, & Lajoie, 2017a; Richer *et al.*, 2017b). Several other experiments have similarly demonstrated the benefit of performing a cognitive task while standing in both young and older adults (i.e. Dault, Frank, & Allard, 2001; Swan, Otani, & Loubert, 2007; Weeks, Forget, Mouchnino, Gravel, & Bourbonnais, 2003).

The constrained action hypothesis has been supported by more than just improvements in postural sway in external focus or cognitive task conditions. Experiments have revealed that external focus conditions also led to faster reaction times (Wulf *et al.*, 2001a), higher frequencies of adjustments (McNevin *et al.*, 2003; Wulf *et al.*, 2001a; Wulf *et al.*, 2001b), and more efficient muscular activity (Vance, Wulf, Töllner, McNevin & Mercer, 2004; Zachry, Wulf, Mercer & Bezodis, 2005; Marchant, Greig & Scott, 2009) compared to internal focus conditions (Wulf, 2007 for review). However, the application of the constrained action hypothesis to quiet standing needs to be further supported. Many authors attribute improvements in postural control in cognitive task conditions to automaticity (Polskaia *et al.*, 2015; Bernard-Demanze, Dumitrescu, Jimeno, & Borel, 2009; Riley, Baker, & Schmit, 2003; Donker, Roerdink, Greven, & Beek, 2007), however this has yet to be proven. Traditional postural measures quantify the magnitude of variation of sway. This

may hide events that occur in the structure or composition of postural control. Dynamic measures (wavelet, sample entropy, rambling and trembling) offer the possibility of decomposing sway or looking at the structure of sway over a trial. These measures can therefore tell us a lot about what is happening during a trial, and might provide important evidence of automatic behaviour.

The discrete wavelet transform decomposes the centre of pressure signal into multiple frequency ranges, which can then be combined into predetermined frequency bands. Certain frequency bands are thought to capture postural movements associated with different systems. Quek and colleagues (2014) propose that the moderate band (1.56 and 6.25 Hz) represents contributions from muscular proprioceptive components (Kapteyn & de Wit, 1972; Taguchi, 1978); the low band (0.39 and 1.56 Hz) represents cerebellar contributions (Diener *et al.*, 1984); the very-low band (0.10 and 0.39 Hz) represents contributions from the vestibular system (Kapteyn & de Wit, 1972; Taguchi, 1978; Soames & Atha, 1982; Gantchev & Popov, 1973; Cernacek, JAGR, Harman, & Vyskocil, 1973; Partridge & Kim, 1969; Mano *et al.*, 1976); and the ultralow band (under 0.10 Hz) represents contributions from the visual system (Berthoz *et al.*, 1979). By examining how these contributions change across conditions, it might be possible to reveal a change in strategy demonstrating automaticity. For example, a higher reliance on higher frequency bands could suggest automaticity. Specifically, the low and very-low bands are thought to represent contributions from the cerebellum and the vestibular system, respectively. The cerebellum has been recognized as important for the acquisition and execution of automatic movements (Lang, & Bastian, 2002; Thach, 1998). As for the vestibular system, there is recent evidence that vestibular inputs are attenuated during active motion (movements that are a consequence of our own actions) as opposed to passive or unexpected motion (movements that result from changes in the external world) to eliminate self-generated vestibular information from

orientation and postural control computations (Cullen, Brooks, Jamali, Carriot, & Massot, 2011). This suggests that movements that are more conscious would display less involvement from the vestibular system.

Sample entropy is a measure that can be used to characterize the complexity of sway. It has been shown that higher values are representative of irregular and unpredictable sway (Potvin-Desrochers, Richer, & Lajoie, 2017). A healthy postural system will randomly fluctuate under normal sensory conditions (Stergiou & Decker, 2011). Smaller values normally reflect a system that is more constrained and controlled, such as in aging or disease (Newell & Molenaar, 2014; Pincus, Gladstone, & Ehrenkranz, 1991). Since higher sample entropy values indicate a more random, less predictable signal, it is believed that higher sample entropy values will reflect a more automatic type of postural control (Donker *et al.*, 2007). A recent experiment examined the effect of various cognitive tasks on sample entropy of quiet standing and found that tasks that required continuous attention yielded higher values of sample entropy than tasks that only intermittently required attention in both young and older adults (Potvin-Desrochers *et al.*, 2017). Presumably, the tasks that only intermittently required attention allowed lapses of time where participants could attend to their postural control, thus interfering with automatic processes. Similarly, another experiment reveals higher sample entropy values while performing a cognitive task compared to standing with eyes closed (Donker *et al.*, 2007).

The rambling-trembling decomposition separates sway into a rambling component (the migration of the of the reference point about which equilibrium is maintained) which is thought to represent supraspinal contributions to sway, and a trembling component (the oscillation around the reference point) which is thought to represent contributions from spinal reflexes and changes in mechanical properties of muscles and joints (Zatsiorsky & Duarte, 1999; Shin, Motl, & Sosnoff,

2011). By examining how contributions change across conditions, it might reveal evidence of automaticity. For instance, if trembling components were to increase in cognitive task conditions, it could indicate a higher reliance on spinal reflexes, which would be more automatized. Alternatively, trembling also indicates changes in mechanical properties of muscles and joints and is therefore an indication of stiffness of lower limbs (Freitas, Freitas, Duarte, Latash, & Zatsiorsky, 2009). Thus, it is important to examine other measures to reveal if changes in trembling are due to stiffening or reflexive components. For instance, if higher trembling were observed with higher sample entropy values, it would unlikely be due to stiffening since increased sample entropy is indicative of higher automaticity (Donker *et al.*, 2007).

The main objective of the present study was to lend support to the automaticity hypothesis with the use of dynamic measures of sway. Specifically, the effect of attentional focus and cognitive tasks on the structure and composition of postural sway as well as on the sensory contributions to postural control will be examined in both young and older adults using the discrete wavelet transform, sample entropy, and the rambling-trembling decomposition. It is hypothesized that cognitive task conditions will yield higher contributions from higher frequency bands and less contributions from the lower frequency bands compared to baseline and focus conditions. Since higher sample entropy values represent a more efficient and automatic postural control, it is hypothesized that sample entropy will be higher in cognitive task conditions compared to baseline standing and focus conditions. It is also hypothesized that cognitive task conditions will lead to higher amounts of trembling than other conditions, representing increased reflexive components of sway. Finally, it is believed that these effects will be evidenced in both young and older adults similarly, since previous experiments demonstrate the benefits of performing a cognitive task in

both young and older adults (Polskaia *et al.*, 2015; Richer *et al.*, 2017a; Richer *et al.*, 2017b; Richer *et al.*, 2018).

Although the external focus has on occasion improved postural stability compared to baseline standing and internal focus conditions (e.g. Richer *et al.*, 2017b; Richer *et al.*, 2018), it is believed that these improvements will not be reflected in the three dynamic measures. Specifically, in the external focus condition, participants still focus on an aspect of postural control. Even if it has provoked improvements in previous studies, it might not be due to a fully automatic movement strategy. Therefore, even if improvements are present in the traditional measures of stability, this will not be reflected by a change in the dynamic measures of sway, which could have indicated a change of postural strategy.

It is believed that examining the effect of attentional focus and cognitive tasks on postural control using dynamic measures will help clarify which processes are responsible for changes observed in these dual-task conditions. This will hopefully reveal evidence of automatic components of sway.

Methods

Participants

The centre of pressure (COP) data from twenty-two young adult participants from Richer *et al.* (2017b; 20.8 ± 2.82 years, 9 male) and from twenty older adults from Richer *et al.* (2018; 69.2 ± 3.47 years, 15 male) was selected to take part in this secondary analysis. Health status data are reported in Table 1 for young adults and in Table 2 for older adults. The methods are the same as Richer *et al.* (2017b) and Richer *et al.* (2018), as described below. Participants signed a consent form approved by the University of Ottawa Research Ethics Board and filled out a health

questionnaire to verify they had no injury or condition that could impair postural control. Older adult participants were administered the Mini-Mental State Examination (Folstein, Folstein, & McHugh, 1975) to screen for neurological impairments which could impair participation in the study, with a cut-off set at 24.

Sample size was calculated using the following formula (Rigby, & Vail, 1998):

$$n = \frac{2 \times (\text{standard deviation})^2}{(\text{clinically worthwhile difference})^2} \times 7.8$$

Where n = number of subjects per group and 7.8 = number representing .80 Power ($1 - \beta$) and 0.05 Significance level (α). To determine standard deviation and clinically worthwhile difference, a recent paper using similar conditions was used (Potvin-Desrochers *et al.*, 2017b). Clinically worthwhile difference was set to 1.124 and the standard deviation was set to 1.281. Sample size was set to 20 participants per group.

Table 1. *Health status data of young adult participants.*

Participant	Height (cm)	Weight (lbs)	Recent, unresolved injury to lower limb (affecting postural control)	Vestibular problem
1	165	125	No	No
2	182	150	No	No
3	175	128	No	No
4	168	130	No	No
5	185	202	No	No
6	165	120	No	No
7	163	115	No	No
8	165	120	No	No
9	175	145	No	No
10	188	225	No	No
11	170	163	No	No
12	160	130	No	No
4	155	110	No	No
5	173	120	No	No
6	152	115	No	No
7	150	114	No	No
8	173	200	No	No
9	163	120	No	No
10	168	150	No	No
12	196	260	No	No
13	183	260	No	No
14	165	120	No	No
Average (SD)	170 (11.7)	151 (47.3)	---	---

Table 2. *Health status data of older adult participants.*

Participant	Height (cm)	Weight (lbs)	Recent, unresolved injury to lower limb (affecting postural control)	Vestibular problem
1	155	148	No	No
2	152	158	No	No
3	163	138	No	No
4	163	140	No	No
5	152	153	No	No
6	183	212	No	No
7	173	145	No	No
8	160	105	No	No
9	175	185	No	No
10	168	185	No	No
11	173	175	No	No
12	175	180	No	Yes (no concern during testing)
13	188	210	No	No
14	185	200	No	No
15	178	190	No	No
16	173	151	No	No
17	175	155	No	No
18	170	265	No	No
19	175	183	No	No
20	183	190	No	No
Average (SD)	171 (10.6)	173 (34.7)	---	---

Apparatus

An AMTI force platform (OR6-6-1000, Watertown, MA, USA) was used to record centre of pressure (COP) data at a sampling rate of 500 Hz. For the external focus condition, two L-shaped devices were used (Richer et al., 2017b). Each device consisted of a horizontal flat metal strip placed along the lateral side of each foot, and a vertical flat metal strip placed along the lateral side of the lower leg. The two strips were loosely linked at the ankle joint and allowed a pivoting movement in the anterior-posterior direction without preventing any natural movement in the medial-lateral direction. The apparatus was attached to the lower limbs using elastic Velcro straps to allow natural movement. Three markers were attached to each device, one at the ankle joint resting on the lateral malleolus, one near the toe, and one at the middle of the lower leg. These markers extended laterally by 9 cm. Pre-recorded cognitive tasks were presented using a digital media player and two speakers placed on either side of the participant.

Postural task

Participants stood on the force platform with feet together, arms hanging loosely at the sides and eyes fixed on an eye-level target 3 m ahead. Foot position on the force platform was standardized across conditions and participants.

Attentional focus

In the internal focus condition, participants were asked to concentrate on minimizing movements of the ankles. In the external focus condition, they were outfitted with the external focus apparatus described in the apparatus section (Richer et al., 2017b). The markers on the apparatus moved in relation to the participant's body sway. Participants were asked to look down before every external focus trial to ensure they had an accurate mental representation of all six

markers. They were then asked to concentrate on keeping the same initial position of the top markers relative to the bottom two, in other words to minimize movements of the markers. This was exclusively a mental focus task, therefore no visual feedback of the markers was provided during trials. Similarly to all other conditions, participants maintained their eyes fixed on the target ahead.

Cognitive tasks

For both cognitive tasks, participants were presented with an auditory recording containing a string of 30 three-digit numbers, presented at 2-s intervals (e.g., 123, 746, 702, 485, etc.). In the single-number sequence (SNS) condition, participants were asked to count the occurrence of a single digit within these numbers (e.g., count the number of 2s). At the end of each trial, the total was provided by the participant. In the more difficult double-number sequence (DNS) condition, participants were asked to simultaneously count the occurrence of two separate single digits within these numbers (e.g., count the number of 2s and 7s). At the end of the DNS trial, two totals were provided.

Procedure

The study consisted of five conditions: one single-task standing condition (baseline standing) and four dual-task conditions performed while standing (internal focus, external focus, SNS, and DNS). For young adults, five 60-s trials were performed for each condition, in a randomized order. For older adults, four 60-s trials were performed for each condition, in a randomized order. One 20-s familiarization trial was performed for each condition prior to data collection.

For both focus conditions, manipulation checks were performed to ensure attention was allocated sufficiently to the task. Participants were asked to rate the percentage of attention they had allocated to the requested task, and if a percentage of 50% or lower was reported, the trial was redone unbeknownst to participants.

For both cognitive task conditions, six different auditory sequences were used interchangeably and target digits were alternated. These tasks were performed silently, and use of fingers as a counting aid was prohibited. To ensure participants were performing the cognitive task, acceptable error scores were implemented. For young adults, if participants' answers were off by 3 or more for the SNS condition, and by a combined value of 6 or more for the DNS condition, the trial was redone unbeknownst to them. For older adults, if participants' answers were off by 4 or more for the SNS condition, and by a combined value of 7 or more for the DNS condition, the trial was redone unbeknownst to them.

Data analyses

Wavelet

Matlab's wavelet toolbox (MathWorks Inc., MA, USA) was used to analyse the COP data recorded from the force platform. The analysis performed is based on the research of Quek and colleagues (2014). Since Quek *et al.* (2014) used a sampling frequency of 100 Hz, the 500 Hz signal obtained during data collection was desampled to 100 Hz. The data was processed using the discrete wavelet transform, which separates the COP data into multiple independent signals based on frequency content (Quek *et al.*, 2014). Specifically, the signal was separated using a 12-level Symlet-8 wavelet with one-dimension multisignal analysis. The independent signals were then

combined to create the following four frequency bands: (1) moderate (1.56–6.25 Hz), (2) low (0.39–1.56 Hz), (3) very-low (0.10–0.39 Hz), and (4) ultralow (<0.10 Hz; Quek *et al.*, 2014).

Matlab was used to calculate sample entropy values as in (Potvin-Desrochers *et al.*, 2017). Data was desampled to 100 Hz and processed with the following 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 represents the length of the data sequence, and $A(r)$ and $B(r)$ the total number of concordant sequences according to the level of tolerance r in the appropriate dimensional space (i.e. m for $B(r)$ and $m + 1$ for $A(r)$; Richard, & Moorman, 2000). Parameters were set to $m = 2$ and $r = 0.2 * \text{SD}$ (Potvin-Desrochers *et al.*, 2017).

Matlab was also used to determine rambling and trembling values, using the methods developed by Zatsiorsky and Duarte (1999). Then, BioProc 3 software (D.G.E. Robertson, Ottawa, Canada) was used to calculate mean power frequency values of rambling and trembling.

Statistical analyses

For each dependent variable, one average value per condition was calculated for each participant and subsequently used for analysis. For the wavelet analysis, a four-way analysis of variance on group (young and older adults), frequency band (moderate, low, very-low, and ultralow), condition (baseline, internal focus, external focus, SNS, and DNS), and direction (ML and AP) was performed with repeated measures on frequency band, condition, and direction. For sample entropy, a three-way analysis of variance on group (young and older adults), condition

(baseline, internal focus, external focus, SNS, and DNS), and direction (ML and AP) was performed, with repeated measures on condition and direction. For rambling trembling, a four-way analysis of variance on group (young and older adults), rambling-trembling (rambling and trembling), condition (baseline, internal focus, external focus, SNS, and DNS), and direction (ML and AP) was performed with repeated measures on rambling-trembling, condition, and direction. For all measures, a Newman-Keuls post-hoc analysis was performed when necessary to determine the location of significance, which was set at $p < 0.05$.

Results

Wavelet

There was no main effect of group on this variable ($F_{1,40} = 1.41, p > 0.05$). Results reveal a significant interaction between condition and frequency band ($F_{12,480} = 22.33, p < 0.05, \eta_p^2 = 0.36$; Figure 1). In the medium band, there was no change across conditions. In the low frequency band, there was no significant difference between baseline standing, internal focus and external focus. However, the low frequency band had a higher contribution in the SNS condition than baseline standing and focus conditions, and had a higher contribution in DNS than in all other conditions. In the very-low band, there was no difference between baseline standing and any of the other conditions. The very-low band had a significantly higher contribution to both cognitive task conditions compared to both focus conditions. In the ultralow band, there was no significant difference between baseline standing, internal focus and external focus. The ultralow band contributed significantly less to the SNS condition than baseline standing and focus conditions, and contributed significantly less to the DNS condition than all other conditions.

In summary, wavelet results indicate that performing a cognitive task provoked a shift towards increased contributions of the low and very-low bands and decreased contribution from the ultralow band. This shift was more pronounced in the DNS task than the SNS task.

Sample entropy

There was no significant main effect of group ($F_{1,40}=2.35, p > 0.05$) There was a main effect of condition ($F_{4,160}=18.54, p < 0.05, \eta_p^2 = 0.32$; Figure 2). All conditions presented higher sample entropy than baseline standing. Both cognitive tasks yielded higher sample entropy values than the other conditions. Results reveal a triple interaction between group, condition and direction ($F_{4,160}= 3.29, p < 0.05, \eta_p^2 = 0.08$; Figure 2). In the ML direction, sample entropy was significantly higher in external focus and DNS conditions than in baseline standing. There was no significant difference between young and older adults. In the AP direction, there was a significant difference between young and older adults, with older adults demonstrating higher sample entropy than young adults across conditions. For young adults, the SNS condition yielded higher sample entropy than baseline standing. In older adults, sample entropy was significantly higher in SNS and DNS than in baseline standing and focus conditions. There was no significant difference between SNS and DNS for older adults.

As for the effect of direction, in young adults, the external focus and DNS conditions yielded smaller sample entropy values in the AP direction than in the ML direction. In older adults, the SNS and DNS conditions yielded higher sample entropy values in the AP direction than in the ML direction.

Overall, the cognitive task conditions led to increased complexity of sway in both groups. This represents more irregular, unpredictable and therefore more efficient sway.

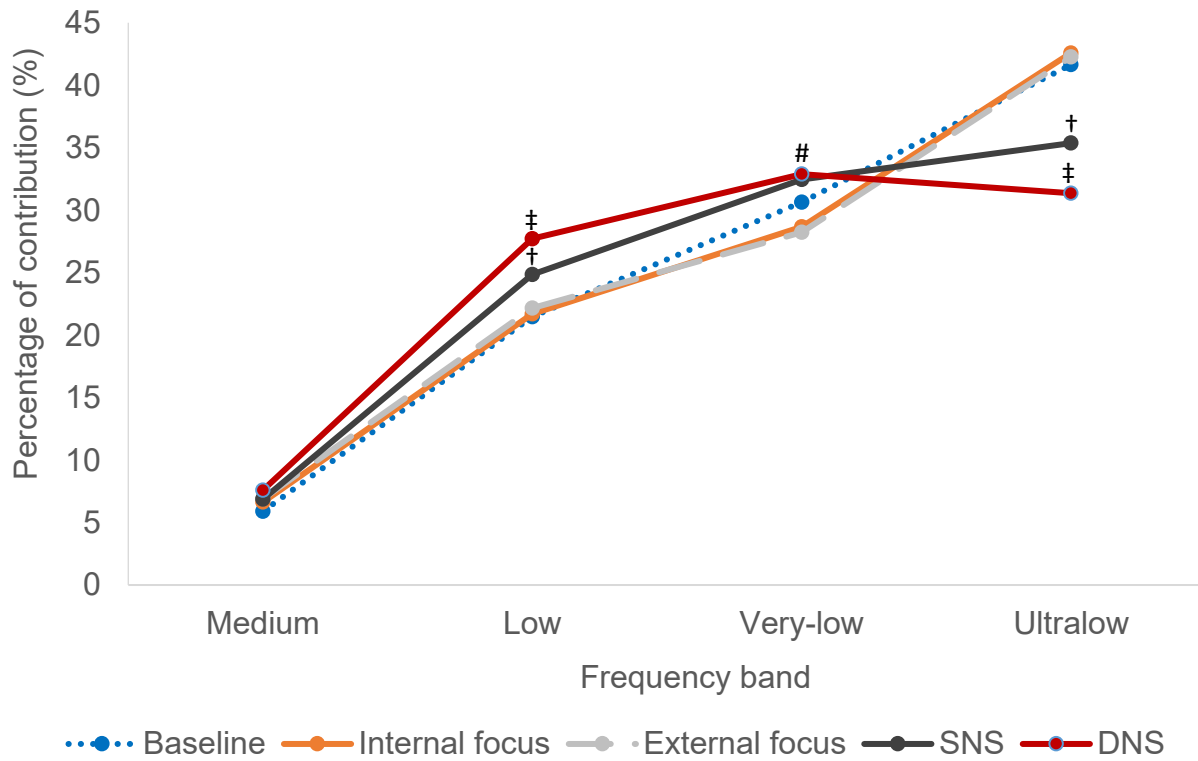


Figure 1. Representation of the wavelet decomposition into four frequency bands. Percentage of contribution (%) of each band (medium, low, very-low, and ultralow) for baseline, internal focus, external focus, single number sequence (SNS), and double number sequence (DNS) conditions. SD values not depicted to facilitate observation of results. Significant results are indicated as follows: † different contribution than in baseline and focus conditions; ‡ different contribution than in all other conditions; # difference between both cognitive task conditions and both focus conditions.

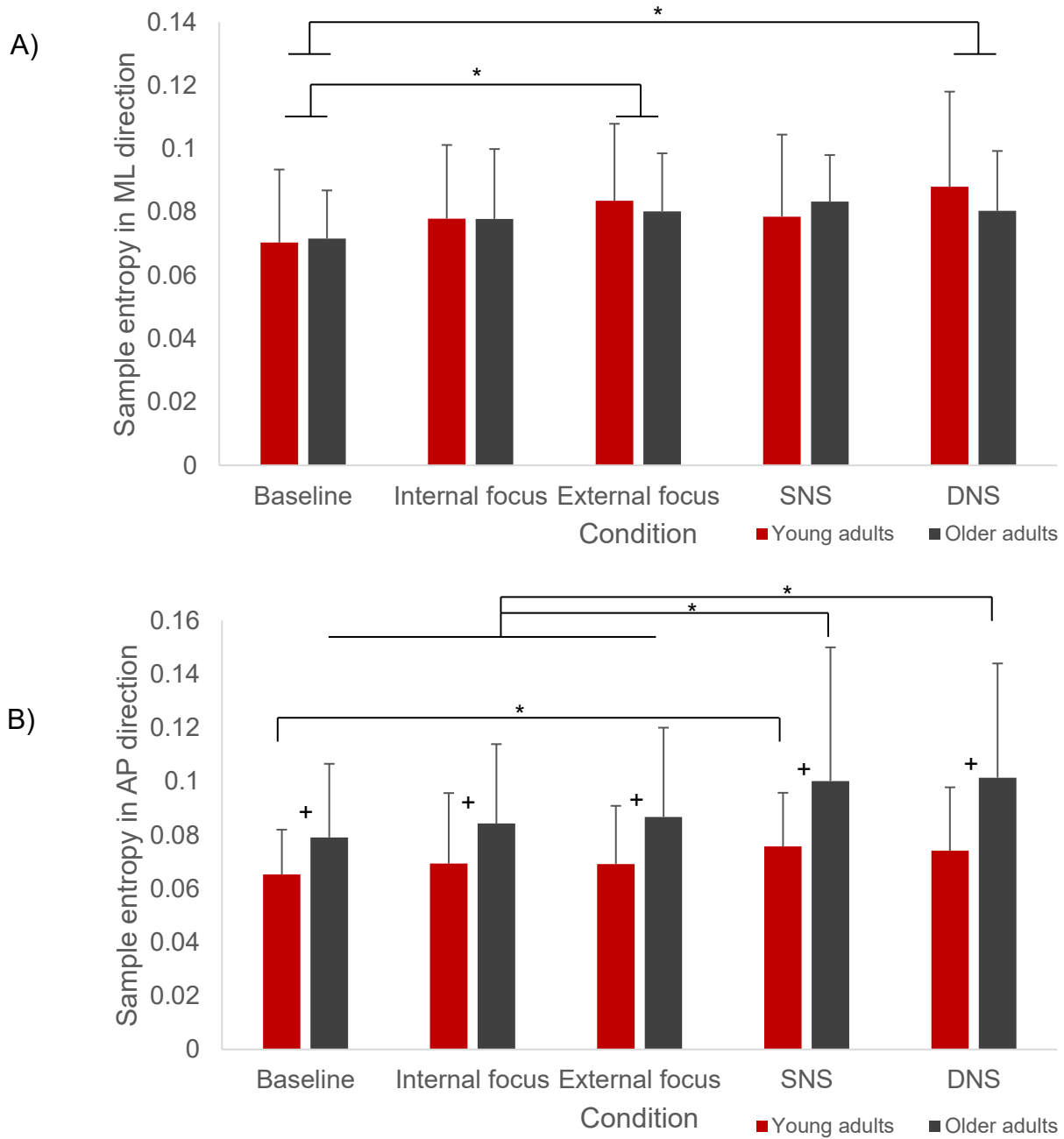


Figure 2. Sample entropy +1 SD for A) ML and B) AP directions in young and older adults for baseline, internal focus, external focus, single number sequence (SNS), and double number sequence (DNS) conditions. Significant main effects are indicated by significance bars and symbols (* $p < 0.05$; + difference between young and older adults).

Rambling and trembling

Results reveal a triple interaction between group, condition and rambling-trembling ($F_{4,160} = 2.65, p < 0.05, \eta_p^2 = 0.06$; Figure 3). There was no significant difference in rambling frequencies between conditions or groups. There were, however, changes in trembling. In young adults, the external focus yielded significantly higher trembling frequencies than baseline standing, the SNS condition yielded significantly lower trembling frequencies than focus conditions, and the DNS condition yielded significantly higher trembling frequencies than baseline standing, internal focus and SNS conditions. In older adults, there was no difference in trembling frequencies across conditions. Differences were also observed between groups for trembling frequencies. Higher trembling frequencies were observed in older adults compared to young adults in baseline standing and SNS conditions. Finally, trembling frequencies were significantly higher than rambling frequencies.

To summarize, no change occurred in rambling frequencies, however the trembling frequencies were higher in older adults. Furthermore, in young adults, focusing externally and on the DNS condition provoked an increase in trembling.

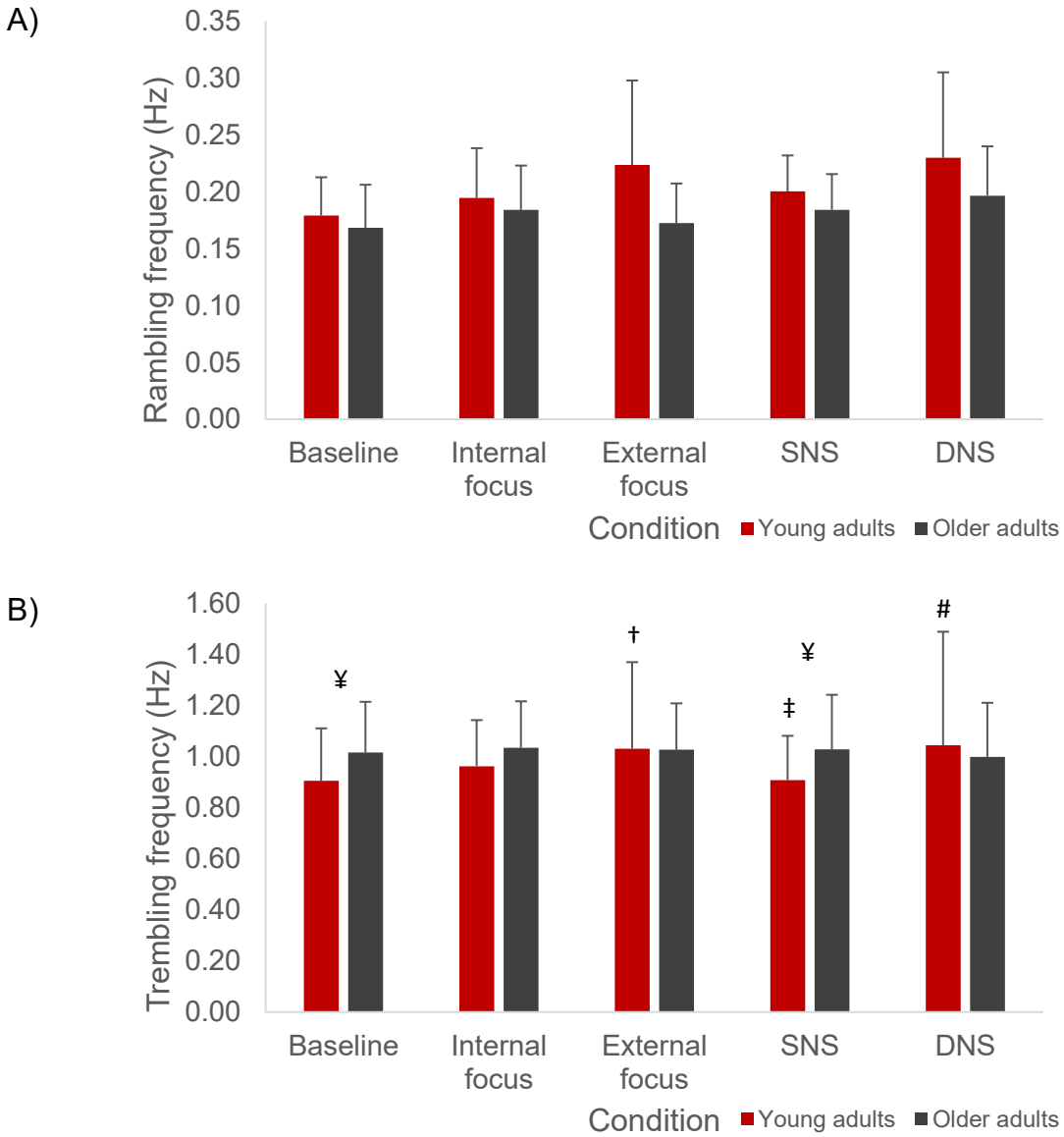


Figure 3. A) Rambling and B) trembling frequencies (Hz) +1 SD for baseline standing, internal focus, external focus, single number sequence (SNS), and double number sequence (DNS) conditions in young and older adults. Significant results are indicated as follows: † higher than baseline; ‡ lower than focus conditions; # higher than baseline, internal focus, and SNS; ¥ significant difference between groups.

Discussion

The objective of the present experiment was to evaluate the effect of attentional focus and cognitive tasks on the structure and composition of postural sway as well as on the sensory contributions to postural control by using three dynamic measures, in the overall aim to provide support to the automaticity hypothesis. It was hypothesized that, in both groups, 1) wavelet transform would reveal increased contributions from the cerebellum and vestibular system and reduced contributions from the visual system in cognitive task conditions compared to other conditions; 2) sample entropy values would be higher in cognitive task conditions compared to other conditions; and 3) rambling-trembling analysis would reveal increased trembling in cognitive task conditions compared to other conditions. Hypotheses have been mostly confirmed by the present findings.

Wavelet

Results from the wavelet transform reveal that both cognitive tasks yielded higher contributions from the low and very-low bands and less contributions from the ultralow band (Figure 1). A shift towards higher frequencies is thought to reflect automaticity since higher frequency adjustments allow the motor system to quickly respond to perturbations (Wulf, 2007). The low and very-low bands are thought to represent contributions from the cerebellum (Diener *et al.*, 1984) and vestibular system (Kapteyn & de Wit, 1972; Taguchi, 1978; Soames & Atha, 1982; Gantchev & Popov, 1973; Cernacek *et al.*, 1973; Partridge & Kim, 1969; Mano *et al.*, 1976), respectively, while the ultralow band is thought to reflect contributions from the visual system (Berthoz *et al.*, 1979). The cerebellum is important for the acquisition and execution of automatic movements (Lang, & Bastian, 2002; Thach, 1998). As for the vestibular system, there is evidence

that vestibular inputs in active movements are reduced (Cullen *et al.*, 2011), which could suggest that in more conscious control of movement there would be less vestibular contributions and vice versa. Therefore, a higher reliance on the cerebellum and vestibular system is an indication that in these conditions, participants relied more on automatic components. Furthermore, the more difficult DNS task yielded an even greater shift to these systems, compared to the easier SNS tasks (Figure 1), which suggests that the more difficult task provoked a shift to an even more automatic strategy. It is important to note that there was no difference between groups, therefore both young and older adults have presented automatic behaviours in the cognitive task conditions.

Sample entropy

The main effect of condition revealed increased sample entropy in cognitive task conditions compared to other conditions (Figure 2), which fully supported the proposed hypothesis. This was also observed in a recent experiment comparing discrete and continuous cognitive tasks, in which the continuous tasks both led to higher sample entropy values compared to the discrete tasks, in both young and older adults (Potvin-Desrochers *et al.*, 2017), and similarly in a cognitive task condition compared to standing with eyes closed (Donker *et al.*, 2007) When looking at the present interaction, however, the effect was different in the ML and AP direction. In the ML direction, sample entropy was higher in external focus and DNS compared to baseline standing and no difference was found between groups (Figure 2). Strangely, no effect was observed in the easier cognitive task. In the AP direction, the effect is reversed, with higher sample entropy in SNS direction compared to baseline but no effect in external focus and DNS conditions for young adults (Figure 2). In older adults in the AP direction, SNS and DNS both yielded more complex sway than baseline standing as well as focus conditions (Figure 2). Altogether, results

did demonstrate more complex sway in external focus condition (only young adults) and both cognitive task conditions.

Results in the AP direction revealed a very unexpected result, sample entropy was significantly higher in older adults than young adults (Figure 2). It must be noted that about half of the older adult participants were very active older adults, participating in group sports such as hockey a few times a week. If these participants were excluded from analysis, this difference between groups would have been minimized. Furthermore, the main effect of group revealed no overall difference between young and older adults.

Altogether, these results indicated more complex sway in SNS and DNS directions. However, the changes were sometimes limited to one direction of sway.

Rambling and trembling

Results indicated no changes occurred in the rambling frequencies, however there were some changes in trembling components of sway. Specifically, young adults presented increased trembling frequencies in the external focus condition compared to baseline standing, and increased trembling in DNS condition compared to baseline, internal focus and SNS (Figure 3). This suggests an increased reliance on spinal reflexive components of sway. The SNS condition provoked a decrease in trembling values, which was contrary to the proposed hypothesis. In older adults, no change was observed in trembling frequencies, although the frequencies they presented were already high – older adults had significantly higher trembling frequencies in baseline and SNS conditions than young adults, while no difference was found in the other conditions (Figure 3). This demonstrated that when young adults performed an external focus or cognitive task, their trembling frequencies increased to that of the older adults.

Overall

Altogether, results demonstrated that a change in strategy occurred in the cognitive task conditions. The wavelet results were clear in demonstrating automaticity of sway, with a change frequency band contributions in both SNS and DNS conditions compared to the other conditions (Figure 1). Specifically, the shift was towards the use of senses which have been attributed to automatic control. The main effect in sample entropy helped to reinforce this suggestion, since it revealed increased complexity of sway in cognitive task conditions (Figure 2). Finally, rambling and trembling values offered only a slight support to the automaticity theory. In fact, only the external focus condition and DNS condition demonstrated higher trembling, and only in younger adults (Figure 3).

As was outlined by Chagdes *et al.* (2009), higher wavelet decomposition levels revealed large loops that reflect low frequency and large amplitude oscillations (Figure 4). These can be attributed to a closed-loop control and relate to the rambling trajectories which represent supraspinal contributions (Zatsiorsky, & Duarte, 1999; 2000; Chagdes *et al.*, 2009). These frequency ranges are also associated to visual contributions, which could be considered as a more conscious sense. Lower levels of decomposition showed high frequency and short amplitude oscillations (Figure 4) which are indicative of an open-loop control (Chagdes *et al.*, 2009). This relates to the trembling component of sway which represents spinal reflex contributions as well as mechanical properties of muscles and joints (Zatsiorsky, & Duarte, 1999; 2000; Chagdes *et al.*, 2009). When considering this altogether, it would suggest that a higher contribution from lower frequency bands coupled with an increase in rambling components of sway would represent a more conscious, closed-loop and supraspinal control of sway, while a shift to higher frequency bands coupled with an increase in trembling would represent a more automatic, open-loop and reflexive

control of sway. The latter option was observed in the present study. Particularly, the DNS condition presented automatic components in all three measures: a shift to higher frequency bands, higher complexity, and increase in trembling (only observed in young adults). This provides the first evidence of the use of an automatic type of postural control in a challenging cognitive task condition. Changes were also observed in the external focus and SNS conditions, although were not always reflected in all three measures. This suggests that the external focus and easier cognitive task still encouraged a shift toward more automatic postural control, however might not have provoked fully automatized behaviour. This was reinforced by the previous centre of pressure findings that reveal improvements in postural stability in external focus condition, and further improvements in cognitive task conditions for young adults (Richer *et al.*, 2017b), while in older adults similar improvements were observed in the external and cognitive task conditions (Richer *et al.*, 2018).

Several authors have suggested that improvements in postural control while performing a cognitive task while standing were due to automaticity of sway (Polskaia *et al.*, 2015; Bernard-Demanze *et al.*, 2009; Riley *et al.*, 2003; Donker *et al.*, 2007). The present findings are the first that provide evidence to support this hypothesis. Furthermore, this evidence derives from multiple measures which complement each other, further reinforcing this important finding.

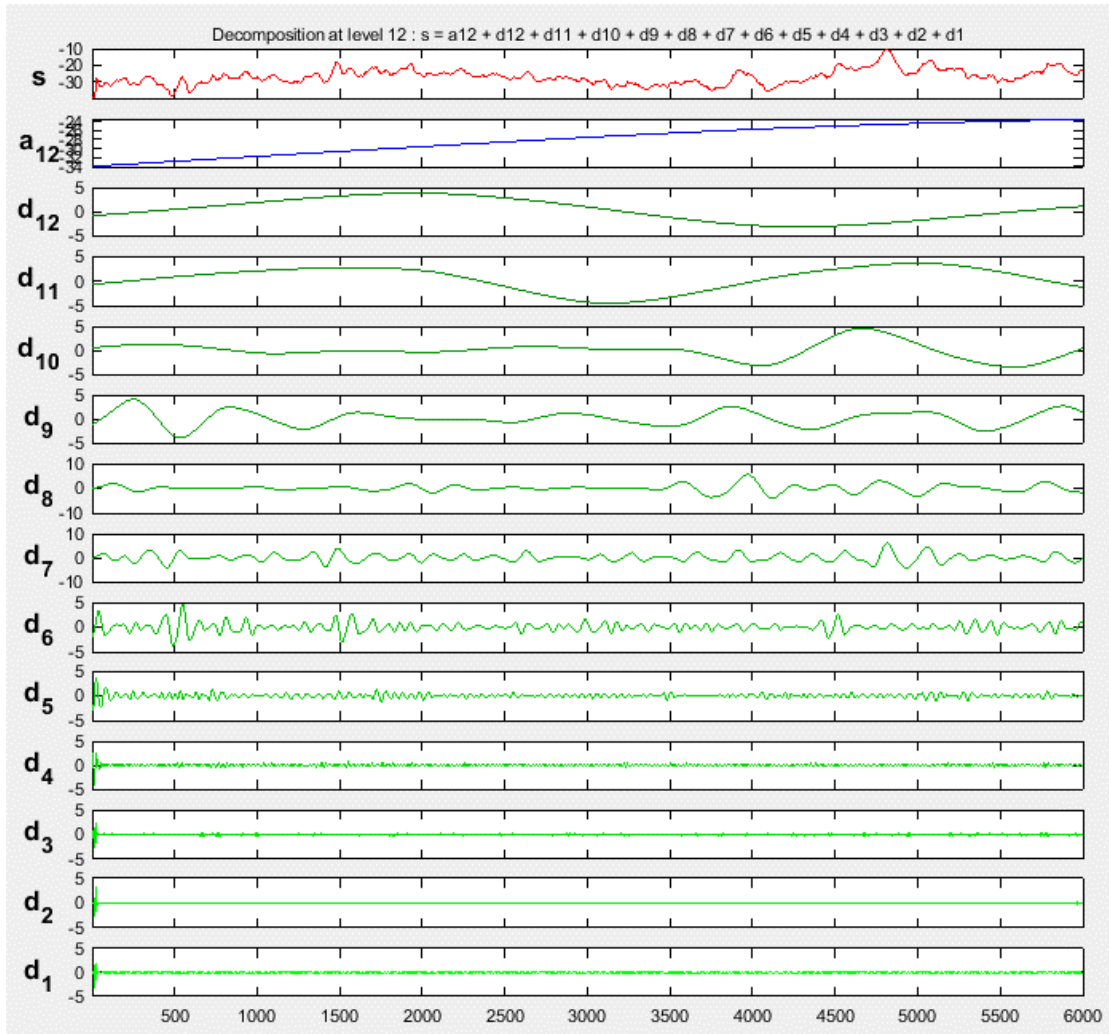


Figure 4. Example of a 12-level decomposition of a COP signal in quiet standing for a young adult participant. s represents the original COP signal and d_1 - d_{12} , the details of decomposition at each level.

Conclusion

The present experiment provides evidence that performing a continuous cognitive task while standing, in healthy young and older adults, provoked a shift toward a more automatic type of postural control. This was evidenced by increased contributions from higher frequency bands and decreased contributions from the lowest band, increased complexity of sway, and a higher frequency of trembling representing reflexive components of sway (only in young adults) in the more challenging condition. Although the only way to fully confirm if automatic behaviour is the cause of improvements in external focus and cognitive task conditions is to examine brain activity during standing, the present paper is the first to identify automatic processes involved in postural control in young and older adults.

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Chapter 7 – General Discussion

The general purpose of this thesis was to provide evidence of two types of postural control in young and healthy older adults.

The first objective was to examine the effects of attentional focus and a continuous cognitive task on postural control in healthy older adults to verify that they demonstrate improvements in cognitive task conditions similarly to young adults. It was hypothesized that there would be no difference between internal and external focus conditions and that cognitive tasks would reduce sway area and SD of COP compared to both focus conditions. This hypothesis was confirmed.

The second objective was to examine muscle activity in the lower leg in older adults during attentional focus and cognitive tasks to verify that stiffening of muscles surrounding the ankle joint was not responsible for changes in postural control observed in these conditions. It was hypothesized that sway area and SD of COP would decrease in the external focus condition compared to baseline standing and internal focus conditions, and would decrease further in both cognitive task conditions in the older adult participants. This was partially confirmed, since the external focus and cognitive task conditions all led to a similar decrease in sway area, while SD of COP in the AP direction was only decreased in single number sequence (SNS) and double number sequence (DNS) conditions compared to baseline and internal focus conditions, and SD of COP in the ML direction was smaller in external focus and SNS compared to baseline and internal focus, and smaller in DNS compared to baseline standing. Secondly, it was also hypothesized that no change would occur in muscle activity of the tibialis anterior and medial gastrocnemius and this hypothesis was confirmed.

The third objective was to apply dynamic measures of sway to attentional focus and cognitive task conditions to provide evidence that different postural strategies were used in these conditions in both young and older adults. The hypotheses were that in both populations, cognitive task conditions would present increased contribution from higher frequency bands and decreased contribution from the lower bands, would elicit higher sample entropy values, and would provoke increased trembling compared to baseline standing and focus conditions. Overall, the hypotheses were mostly confirmed with a few exceptions that will be discussed in the following section.

Evidence of two types of postural control

Altogether, the results of the present experiments provide evidence of two types of postural control. In older adults, it was demonstrated that they are capable of improvements in dual-task conditions (Richer, Polskaia, & Lajoie, 2017a; Richer, Ly, Fortier, & Lajoie, 2018b) and these changes were not attributed to stiffening of the ankle joint (Richer *et al.*, 2018b). When the external focus was far enough from the body, improvements were observed compared to internal focus conditions (Richer *et al.*, 2018b). However, when the external focus was too close, no changes were observed (Richer *et al.*, 2017a). The cognitive tasks consistently improved postural control compared to baseline and internal focus conditions (Richer *et al.*, 2017; 2018b). Young adults presented similar findings. In previous studies, it was determined that a close external focus did not have an effect (Polskaia *et al.*, 2015) but that a further external focus reduced sway area compared to baseline standing and internal focus conditions and reduced SD of COP compared to an internal focus (Richer *et al.*, 2017b). Similarly to older adults, cognitive tasks always elicited improvements compared to baseline, internal focus and external focus conditions (Polskaia *et al.*, 2015; Richer *et al.*, 2017b). The changes in COP variables observed in both groups were reflected in dynamic measures of sway and provide the first evidence of automatic components of sway.

The results from the wavelet transform suggest that in both groups there was a shift in strategy during cognitive task conditions. Both cognitive tasks led to increased contributions from the low and very-low bands, which are thought to reflect contributions from the cerebellum and vestibular system, and a decreased contribution from the ultralow band, thought to represent visual contributions to sway (Richer & Lajoie, 2018a). Higher frequencies have been suggested to represent more automatic behaviours (Wulf, 2007). Furthermore, the cerebellum is important for the acquisition and execution of automatic movements (Lang & Bastian, 2002; Thach, 1998). Experiments examining learning in individuals with cerebellar lesions reveal deficits in the later stages of motor learning during the automatization process (Doyon *et al.*, 1997; Doyon *et al.*, 1998). The role of the vestibular system in automaticity is much less established than the cerebellum. However, there is recent evidence that its contributions could reflect automaticity. It has been observed that vestibular inputs are attenuated during active movements, which are a consequence of our own actions, compared to when movements are passive or unexpected, such as those resulting from changes in the outside world (Cullen, Brooks, Jamali, Carriot, & Massot, 2011). This attenuation occurs to eliminate self-generated vestibular information from orientation and postural control computations (Cullen *et al.*, 2011). Therefore, in sway that is consciously controlled, there should be less reliance on the vestibular system. Altogether, a shift to an increased use of the cerebellum and vestibular system and a decreased use of the visual system clearly shows a change in postural control strategy between the cognitive task conditions and the baseline and focus conditions. Notably, the more difficult task yielded a more important shift than the easier task, suggesting that the DNS condition might have provoked a greater proportion of automatic contributions than the SNS condition.

Overall, sample entropy values also demonstrated a postural control change in cognitive task conditions. For both groups, an increase in sample entropy was observed in both cognitive task conditions compared to baseline standing and focus conditions. An increased sample entropy indicated sway was more complex, suggesting a more irregular and unpredictable sway (Potvin-Desrochers *et al.*, 2017). This increased complexity has been associated to an increase in automaticity of sway (Donker *et al.*, 2007). Other studies have found similar effects in dual-task conditions. Potvin-Desrochers and colleagues (2017) found increased sample entropy values in both young and older adults while they performed cognitive tasks that required continuous attention compared to baseline standing and to tasks that only required intermittent attention. They proposed that by continuously distracting participants from postural control, this allowed automatic mechanisms to emerge, while performing tasks that only intermittently distracted from sway allowed lapses of time where attention could be placed on postural control, hindering automaticity. Donker and colleagues (2007) similarly found increased sample entropy values in young adults while they performed a cognitive task while standing compared to standing with eyes closed and also attribute this change to automaticity of postural control. Therefore, present results support these previous findings and reinforce the idea that cognitive task conditions elicited more efficient and automatic postural control.

The rambling-trembling decomposition also yielded interesting results, although they are limited. As predicted, no change occurred in the rambling frequencies. However, the trembling frequencies changed across conditions for young adults only. Frequencies were higher in external focus than baseline standing, and higher in DNS than in baseline, internal focus, and SNS conditions. This suggests that the external focus and cognitive task conditions yielded an increase in the spinal reflex contributions to sway (Zatsiorsky & Duarte, 1999; Shin *et al.*, 2011). Increased

trembling has also been attributed to an increase in stiffness of lower limbs (Freitas *et al.*, 2009), however no stiffening was observed in the present data (Richer *et al.*, 2017b). An increase in spinal reflex contributions to sway could suggest a shift to the use of more automatic processes, which supports the findings in the other measures. Strangely, the SNS condition yielded lower trembling frequency values than focus and DNS conditions. It is difficult to explain why this effect occurred, as the SNS condition did elicit changes in sensory contributions similarly to the DNS condition and elicited increases in AP sample entropy in both groups. Perhaps the rambling-trembling decomposition is not the most accurate to represent automaticity of sway, as the wavelet transform and sample entropy analyses were clear in demonstrating a change between conditions. Another finding was that older adults presented higher trembling than young adults in baseline and SNS conditions. In fact, when young adults presented increased trembling values in the external focus and DNS condition, it brought the frequency values up to those of older adults. Higher trembling values in older adults might not reflect a change in postural strategy, but rather a change in the mechanical properties of muscles and joints. Notably, results from Richer *et al.* (2017b) and Richer *et al.* (2018b) indicate that older adults had significantly higher muscle activity in the TA and MG than young adults, which could explain the increase in trembling in this group. Degani and colleagues (2017) similarly demonstrated that the trembling component of sway presented larger amplitude, variability, velocity, and jerkiness in older adults compared to young adults, which they attributed to age-related changes in sensory receptors, muscles, and spinal reflex gain modulation. Degani *et al.* (2017) also found a difference between groups in rambling frequencies, which is contrary to the present findings. This could reflect the health of the participants in the present set of experiments. Altogether, the rambling and trembling results from the present experiment offered support, although limited, to the theory that improvements in cognitive task conditions are due to

automaticity. Only the external focus and more difficult cognitive task led to increased trembling, suggesting increased spinal reflex contribution to sway, and only in young adults. In fact, this might provide evidence that only the DNS condition provoked a fully automatic control in young adults, since it is the only condition to elicit changes in all three dynamic measures.

Is automaticity a continuum?

When taken altogether, results of the three experiments presented in this dissertation provide evidence that cognitive task conditions yielded more automatic sway components. It is interesting to note that the distinction between conscious and automatic control of sway does not seem as black and white as predicted.

According to the present results, the change from one postural strategy to the other could be better represented as a continuum. Results of the traditional COP measures reveal improvements in external focus and cognitive task conditions (when the external focus is far enough away from the body; Richer *et al.*, 2017b; 2018b) however the improvements in the external focus condition are not highly reflected in the dynamic measures. Furthermore, there are clear differences between SNS and DNS conditions in the dynamic measures. This suggests that although the external focus and easier cognitive task conditions led to improvements in postural stability, it might not have been due to a fully automatic control strategy. This was best evidenced in the wavelet transform. The easier cognitive task did provoke a shift to increased contributions from higher frequency bands and decreased contribution from the lowest band compared to baseline and focus conditions, however the DNS task provoked an even greater shift in that direction than the SNS condition. In rambling and trembling, the DNS condition provoked increased trembling, thought to represent spinal reflex contributions to sway, in young adults compared to the SNS condition. These findings both suggest that the DNS condition provoked a

more automatic control than the SNS condition. Another finding that provides evidence for this continuum is that external focus conditions yielded improvements in postural control compared to baseline and internal focus conditions in young and older adults (Richer *et al.*, 2017b; Richer *et al.*, 2018b), however the wavelet transform shows no difference between the external focus condition and the baseline and internal focus conditions in either group (Richer & Lajoie, 2018a). Furthermore, an increased sample entropy in external focus conditions was only observed in the ML direction compared to baseline standing (Richer & Lajoie, 2018a). Therefore, results provide evidence that a difficult cognitive task that continuously distracts young and older adults from postural control yields a very automatized postural control and that other conditions, such as an easier cognitive task or an external focus, reveal some automatic sway components.

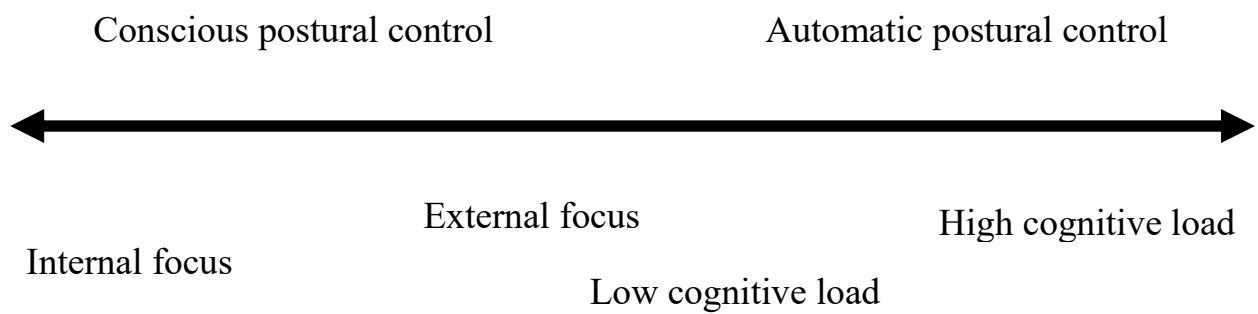


Figure 1. Automaticity of sway could be viewed as a continuum, with internal focus conditions provoking a more conscious postural control, cognitive tasks with a high cognitive load a more automatic postural control, and other tasks situated between.

The effect of cognitive task type and age on postural control

The present findings have conflicted with previous findings in a few different ways. Firstly, in certain cases, performing a cognitive task while standing has led to improvements in stability (e.g. Dault *et al.*, 2001; Swan *et al.*, 2004; Weeks *et al.*, 2003) while in other cases, the cognitive task leads to declines in stability (e.g. Pellecchia, 2003; Shumway-Cook *et al.*, 1997). In the present set of experiments, the cognitive tasks led to improvements. It is still unsure why these effects change from one experiment to the other, but it is likely due to the nature or type of cognitive task.

In 1985, Kerr and colleagues published an article highlighting the differential effects of two types of cognitive tasks. They demonstrated that performing a cognitive task while standing had no effect on postural control, but instead influenced cognitive task performance. Specifically, they found that postural control disrupted the spatial cognitive task, but not the non-spatial task. They suggested that the spatial task interfered with postural control since both tasks relied on visual spatial processing resources (Kerr *et al.*, 1985). In the present experiment, the cognitive tasks were always non-spatial and were presented auditorily. This would suggest that no interference occurred in the visual/spatial processing required for postural control, and might explain the differential effect of cognitive tasks. Other authors have similarly attributed differential effects of cognitive tasks to the modality, difficulty and type of cognitive task (Huxhold *et al.*, 2006; Pellecchia, 2003; Lajoie, Richer, Jehu, & Tran, 2016; Polskaia & Lajoie, 2016a; Polskaia & Lajoie, 2016b), or to the difficulty of the postural task (Lajoie *et al.*, 1993; Barra *et al.*, 2006).

The effect of age is also contrary to previous findings. For example, a recent investigation by Bernard-Demanze, Dumitrescu, Jimeno, and Borel (2009) compared the effect of performing cognitive tasks while standing in healthy young and older adults and revealed an opposite effect of dual tasking. Results demonstrated that even though baseline postural control was the same,

young adults improved their balance during dual-tasking, while older adults yielded declines in postural control while performing the cognitive tasks. Perhaps the complexity of the task can explain these differences. In fact, an experiment by Huxhold *et al.* (2006) demonstrated benefits of a cognitive task on postural control in young and older adults, however the beneficial effects diminished as the cognitive task complexity increased in older adults only. In the present experiment, however, the more difficult cognitive task presented increased benefits to postural control compared to the easier task. Another factor that may have impacted the present results was the health of participants. In fact, older adults were much healthier and active than most in their age range.

Altogether, one fact remains clear: although it has been evidenced that some cognitive tasks can promote automaticity in healthy young and older adults, not all cognitive tasks have the same effect. Therefore, future investigations should examine the effect of various cognitive task types, modalities and difficulties in young and older adults, with the use of both traditional and dynamic measures, to attempt to explain why these conflicting effects are observed.

The importance of dynamic measures of postural control

One fact that is evidenced by the experiments included in this dissertation is the importance of including dynamic, non-linear measures in the evaluation of postural control. These measures are often more appropriate to detect changes that may occur between groups or conditions. Several studies have already emphasised the importance of using these types of measures (Bernard-Demanze *et al.*, 2009; Cavanaugh, 2005; Cavanaugh *et al.*, 2007; Vaillancourt & Newell, 2000) since the dynamic measures highlighted changes that could not be observed by simply using the traditional COP measures. In the present experiment, the dynamic measures allowed a further understanding of the mechanisms responsible for the changes in postural sway. For a complete

understanding of postural control, it is therefore important to include both traditional COP measures and dynamic measures of sway.

Significant contributions

The first experiment confirmed that cognitive tasks could elicit improvements in stability in healthy older adults. Results from the second experiment suggested that these improvements were not due to stiffening of the lower leg to allow cognitive resources to be placed on the cognitive task instead of on postural control. The most important and significant finding of this thesis stems from the third experiment, which revealed a change in postural control strategy in the cognitive task conditions. Results revealed a shift to higher frequency bands and an increase in complexity of sway, indicating more efficient and automatic postural control. Several authors have previously suggested that improvements in cognitive task conditions were due to automatic postural control (Polskaia *et al.*, 2015; Bernard-Demanze *et al.*, 2009; Riley *et al.*, 2003; Donker *et al.*, 2007), initially proposed by the constrained action hypothesis (McNevin *et al.*, 2003; Wulf *et al.*, 2001a; Wulf & Prinz, 2001; Wulf *et al.*, 2001b). These claims have been supported by isolated evidence such as higher sample entropy in cognitive task conditions (Potvin-Desrochers *et al.*, 2017) and changes evidenced through wavelet analysis that suggest a more efficient postural control in young adults in dual-task conditions (Bernard-Demanze *et al.*, 2009). However, this dissertation is the first to provide concrete evidence of a shift toward a more automatic type of control that can be observed in several variables at once. Furthermore, findings provide evidence that the conscious/automatic control of posture is best viewed as a continuum, with difficult cognitive tasks provoking a more automatized control than an external focus or an easier cognitive task.

Limitations

In experiments two and three, healthy and active older adults were recruited. In fact, about half the participants were involved in hockey teams and often played more than one game a week. These participants likely had a healthier postural control system than others of the same age. This is not an accurate representation of the older adult population. For this reason, it is important to be careful not to generalize the present findings to other, unhealthier older adults. Further experiments will need to be conducted in frail older adults or those who are prone to falls to see if similar effects can be observed. It is probable that automatic components won't be observed in individuals with unhealthy postural control systems.

A limitation accompanied with any attentional focus testing is that the rate of attention placed on the requested cue cannot be directly measured. To circumvent this, participants were asked to provide a rating of their attention on the task, however as these were subjective they might not be an accurate representation of the actual focus. A similar limitation in the cognitive task conditions is that the task is done silently, therefore it is impossible to verify if participants continuously concentrated on counting the numbers or simply guessed the answer at the end. To attempt to control for this, acceptable error scores were implemented, however the possibility that answers were guessed was always present. However, results demonstrate effects of external focus and cognitive task conditions which suggests that participants properly followed instructions.

Finally, using silent cognitive tasks also presents an important limitation, which is that it is difficult to accurately measure cognitive task performance. It would have been interesting to compare cognitive task performance in single- and dual-task conditions to observe any interactions that may have occurred between attention placed on the cognitive task and on postural control.

However, it was decided that a non-verbal task was preferable, since verbalization has been shown to impact postural control (Dault *et al.*, 2003).

Conclusion

With the use of dynamic measures of sway, it was possible to support the idea that improvements in stability observed in cognitive task conditions are due to a shift to a more automatic type of postural control. Particularly, results reveal that the cognitive tasks provoked a shift to higher frequency bands suggesting a change in sensory systems involved in postural control, and led to higher complexity of sway in both young and older adults. The only way to fully confirm this automaticity would be to examine neural activity while standing in various conditions, however current technology does not yet permit this. This research therefore presents important evidence of two types of postural control. It also demonstrates the importance of including dynamic measures of postural control to get a complete representation of the structure and composition of sway and how it changes across conditions.

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Appendix I – Research Ethics Board approval letter

File Number: H02-14-16

Date (mm/dd/yyyy): 05/15/2014



Université d'Ottawa **University of Ottawa**
Bureau d'éthique et d'intégrité de la recherche Office of Research Ethics and Integrity

Certificate of Ethics Approval

Health Sciences and Science REB

Principal Investigator / Supervisor / Co-investigator(s) / Student(s)

<u>First Name</u>	<u>Last Name</u>	<u>Affiliation</u>	<u>Role</u>
Yves	Lajoie	Health Sciences / Human Kinetics	Supervisor
Nadia	Polskaia	Health Sciences / Human Kinetics	Co-investigator
Natalie	Richer	Health Sciences / Human Kinetics	Student Researcher

File Number: H02-14-16

Type of Project: PhD Thesis

Title: Postural control mechanisms in young and older adults

Approval Date (mm/dd/yyyy)	Expiry Date (mm/dd/yyyy)	Approval Type
05/15/2014	05/14/2015	Ia

(Ia: Approval, Ib: Approval for initial stage only)

Special Conditions / Comments:
N/A

1

Appendix II - Sample size calculation

Sample size calculations were done with the following formula (Rigby, & Vail, 1998):

$$n = \frac{2 \times (\text{standard deviation})^2}{(\text{clinically worthwhile difference})^2} \times 7.8$$

Where n = number of subjects per group and 7.8 = number representing .80 Power (1- β) and 0.05 Significance level (α).

To determine standard deviation and clinically worthwhile difference, a recent paper using similar conditions was used (Potvin-Desrochers *et al.*, 2017). Difference between average sway area for the two conditions used in the present experiments (SNS and baseline) in young adults was used to determine clinically worthwhile difference, and the standard deviation of the SNS condition was used to perform the calculation.

$$n = \frac{2 \times (1.281)^2}{(1.124)^2} \times 7.8$$

$$n = 20.3$$

For this reason, sample size was set to 20 participants per group.

Appendix III - Health status questionnaire

Participant code: _____

Age: _____ Sex: _____ Height: _____ Weight: _____

Do you walk with an assistive device? Yes: _____ No: _____

Please check any of the following that you have or had:

Parkinson's Disease	_____	Osteoporosis	_____
Multiple Sclerosis	_____	Osteoarthritis	_____
Stroke	_____	Arthritis	_____
Heart Attack	_____	High Blood Pressure	_____
Vertigo	_____	Other	_____

Have you fallen in the last 6 months? Yes: _____ No: _____

If yes, how many times? _____

Please describe your fall(s):

Have you had any injury or surgery to the lower limbs? Yes: _____ No: _____

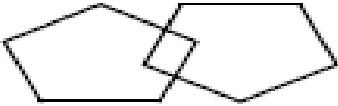
If yes, please describe:

Please list your medications and their purpose:

Appendix IV – Mini mental state examination (MMSE)

Patient's code: _____ Date: _____

Instructions: Score one point for each correct response within each question or activity.

Maximum Score	Patient's Score	Questions
5		“What is the year? Season? Date? Day? Month?”
5		“Where are we now? State? County? Town/city? Hospital? Floor?”
3		The examiner names three unrelated objects clearly and slowly, then the instructor asks the patient to name all three of them. The patient's response is used for scoring. The examiner repeats them until patient learns all of them, if possible.
5		“I would like you to count backward from 100 by sevens.” (93, 86, 79, 72, 65, ...) Alternative: “Spell WORLD backwards.” (D-L-R-O-W)
3		“Earlier I told you the names of three things. Can you tell me what those were?”
2		Show the patient two simple objects, such as a wristwatch and a pencil, and ask the patient to name them.
1		“Repeat the phrase: ‘No ifs, ands, or buts.’”
3		“Take the paper in your right hand, fold it in half, and put it on the floor.” (The examiner gives the patient a piece of blank paper.)
1		“Please read this and do what it says.” (Written instruction is “Close your eyes.”)
1		“Make up and write a sentence about anything.” (This sentence must contain a noun and a verb.)
1		“Please copy this picture.” (The examiner gives the patient a blank piece of paper and asks him/her to draw the symbol below. All 10 angles must be present and two must intersect.) 
30		TOTAL

Interpretation of the MMSE:

Method	Score	Interpretation
Single Cutoff	<24	Abnormal
Range	<21 >25	Increased odds of dementia Decreased odds of dementia
Education	21 <23 <24	Abnormal for 8th grade education Abnormal for high school education Abnormal for college education
Severity	24-30 18-23 0-17	No cognitive impairment Mild cognitive impairment Severe cognitive impairment

Interpretation of MMSE Scores:

Score	Degree of Impairment	Formal Psychometric Assessment	Day-to-Day Functioning
25-30	Questionably significant	If clinical signs of cognitive impairment are present, formal assessment of cognition may be valuable.	May have clinically significant but mild deficits. Likely to affect only most demanding activities of daily living.
20-25	Mild	Formal assessment may be helpful to better determine pattern and extent of deficits.	Significant effect. May require some supervision, support and assistance.
10-20	Moderate	Formal assessment may be helpful if there are specific clinical indications.	Clear impairment. May require 24-hour supervision.
0-10	Severe	Patient not likely to be testable.	Marked impairment. Likely to require 24-hour supervision and assistance with ADL.