VIBRATION OF THE FOOT SOLE AS AN INTERVENTION TO IMPROVE OLDER ADULTS' POSTURAL STABILITY

A Dissertation
Presented to
The Faculty of the Department
Of Health and Human Performance
University of Houston

In Partial Fulfillment
Of the Requirements for the Degree
Doctor of Philosophy
In Kinesiology

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by
Marius Dettmer

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ABSTRACT

Increase of postural instability is one of the significant issues related to aging, due to its relevance concerning risk for falls and associated impacts on life quality and health care costs in the U.S. Sub-threshold vibration stimulation, a passive, non-invasive countermeasure to sensorimotor decline has shown promising results related to the improvement of stability in healthy older adults and in neuropathic patients.

To date, no studies have systematically investigated the potential benefits or functional limitations of this vibration intervention, and potential interactions with healthy aging processes in more demanding postural tasks. Those tasks mimic real-life situations where postural stability is challenged and actual falls might occur in older adults. The objectives of this study were to compare postural performance and control characteristics between older and younger healthy individuals, and to investigate potential changes when a vibration intervention is introduced. The effects of aging, foot sole vibration, and potential interactions were investigated in (1) a sensory conflict postural task, (2) a dual-task environment, and (3) a postural perturbation task (support surface translation). The study was performed on 10 younger adults (25.1±2.3 years) and 10 older adults (78.6±5.4 years). Vibration to the feet was delivered via custom-made rubber soles with embedded vibrotactile chips.

Results indicate that (1) sensory conflict task characteristics are associated with age and vibration affects specific postural outcomes in the older group; the intervention improves postural performance when conflicting visual information is provided; (2)

specific outcomes are associated with age in dual-tasking, but vibration does not affect those outcomes; (3) age is associated with specific spatial outcome measures when a postural perturbation is introduced, older adults are able to maintain stability, although they allow for more sway throughout the task; vibration does not affect performance or control characteristics.

The study provides novel insight about the potential of sub-threshold vibration to the feet, and its effects on two different age groups. More research is needed to evaluate the potential of vibrating soles in more severely (balance-) impaired individuals.

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I. INTRODUCTION

Aging is known to cause multiple changes in anatomy and physiology of the human body. These changes are observed in all sensory systems that provide humans with information about body configurations and properties of the external environment. In general, there is a constant decline of sensory functioning and associated sensitivity to stimuli, which begins around the 4^{th} to 5^{th} decade of life with a more rapid decline during the 7^{th} decade. This decline, in addition to loss of cognitive/executive function, leads to problems in sensorimotor processing (Sturnieks, St George, & Lord, 2008). One of the remarkable abilities of the Central Nervous system (CNS) is an evaluation and subsequent down- or upweighting of sensory information emerging from the different sensory channels of the body (e.g. vestibular system, vision, tactile) based on the respective channel's reliability and importance in specific situations. Older adults exhibit less flexibility in shifting between reliance on specific sensory channels. Older adults rely more on certain sensory channels (e.g. vision in postural control) even if sensory information provided by that particular channel is unreliable. These limitations ultimately lead to decreased postural stability and the associated higher risk for falling.

Older adults are more prone to falls than younger adults. In 2007, there were approximately 1.5 million falls of older citizens (75 years of age and older) reported in the U.S., and approximately 400.000 patients required hospitalization (Siracuse et al., 2012). Approximately 30% of adults over the age of 65 suffer from falls every year (Shaffer & Harrison, 2007). It is remarkable that even simple falls from upright stance are associated with relatively high mortality and morbidity (Sattin, 1992; Siracuse et al., 2012; Speechley & Tinetti, 1991). It is now believed that the health care costs related to falls will rise to about 65 billion dollars per year by the year 2020 (Englander, Hodson, & Terregrossa, 1996). There are numerous effects that are directly related to the occurrence of falls in older adults including an increased perceived instability, fear of falling and loss of confidence in one's ability to maintain posture control (Fletcher & Hirdes, 2004). These factors can lead to a decrease in physical activity, which in turn is associated with loss of locomotion and postural control, loss of physical fitness and ultimately quality of life. Thus, it is crucial to evaluate factors influencing postural instabilities and to develop and implement new techniques of fall prevention and postural control augmentation in older adults.

Stochastic resonance (SR) is an observed phenomenon associated with induction of noise into a non-linear system that is applicable to natural- and man-made systems (Moss, 2004). SR describes the enhancement of neural information transmission and weak stimuli detection when noise is added to the system. Noise is usually defined as an unwanted signal or disturbance randomly occurring within a signal that contains desired information. However, in specific cases, the deliberate addition of noise can improve signal detection and transmission. In biological systems, the application of 'threshold SR' is based on the limits of sensory signals humans can consciously perceive. A 'threshold' is defined as the stimulus magnitude required to be perceived by the central nervous system. A beneficial effect in a system can be observed when combination and interaction of a) a specific threshold, b) a below-threshold stimulus (sub-threshold stimulus) and c) non zero-level noise (Gingl, Kiss, & Moss, 1995) cause a positive effect on system function.

The positive impact of SR on system functioning has been observed in a variety of sensory entities, and over a wide range of tasks. Tactile receptors and associated touch perception exhibit the beneficial features of SR enhancement. For instance, Collins et al. (1996) showed that random vibration enhances the detection of weak touch, for example when added to the foot soles (Wells, Ward, Chua, & Inglis, 2005). Since the effects could be observed over a wide range of frequencies, and specific frequencies are associated with different cutaneous receptor types (tactile receptors), it can be concluded that SR effects are observable in several tactile receptor systems of the human body (Mendez-Balbuena et al., 2012). The CNS relies heavily on the detection and perception of information gathered from different body parts, via a variety of sensory systems. There are a vast number of concurrent internal and external information collection processes that enable humans to a) perceive the environment, b) interact with it and c) adapt to changes in the environment. If detection and processing of this information can be enhanced via SR, this has significant implications for control of human motion, and specifically for human postural control.

Control of upright stance relies heavily on the perception of external constraints, perception of support surface features, internally and externally produced postural sway dynamics and torques (Balasubramaniam & Wing, 2002; Conforto, Schmid, Camomilla, D’Alessio, & Cappozzo, 2001; Horak, 2006). Control processes are also affected significantly by inter-individual differences (age, gender, pathologies). The vestibular system provides information about the current head orientation and linear and angular accelerations (Lackner & DiZio, 2005). The visual system provides valuable information about behavioral opportunities in the form of surface features, distances, and relationship between the person and the environment. Intrafusal fibers, found in muscles of the human body, provide muscle length (and rate of length change) information to the CNS. Joint and cutaneous mechanoreceptors send information about pressure and shear forces from the joints and skin surface. This complex array of sensory information and the subsequent multimodal integration within the CNS is crucial to form or generate what has been coined a 'body schema', which is an integrated neural representation of the body (Holmes & Spence, 2004). The concept has been used in a variety of scientific disciplines such as neuroscience and robotics as a theoretical basis to explore the processes associated with posture and movement control. The generated body representation, based on kinesthetic and proprioceptive information, is crucial for daily life navigation and skilled execution of planned motor actions. For postural control, the body schema is a representation of the perceived vertical position of the body, or what we consider "up". The schema integrates information about our limbs and the trunk relative to each other and our relationship to the environment into a coherent and functioning "gestalt" (Mergner & Rosemeier, 1998).

Availability of reliable sensory information is crucial for the development of an optimally functioning body schema. Manipulation of sensory feedback can improve or perturb the generation of a body schema and the perception of body verticality and ultimately interfere with or augment motor control (Kasai, Yahagi, & Shimura, 2002; Radhakrishnan, Hatzitaki, Patikas, & Amiridis, 2011). Improvements of sensory feedback (in terms of information transmission, sensory detection) generated from particular sensory sources can assist in forming an accurate body schema and improving postural awareness even when certain sensory channels are perturbed or less reliable, for example due to neuropathy (Hijmans & Geertzen, 2008).

The formation of a reliable body schema is highly important for postural control. The mechanisms of postural control are based on neural interactions and cognitive processes. However, the importance of cognition in postural control is highly dependent on task characteristics and external features. Simple, quiet stance on a stable surface primarily relies on unconscious and automatic processes, for example based on reflex control and modification of muscle stiffness to maintain balance (Marsh & Geel, 2000). The more difficult a certain postural task becomes due to a less stable support surface or external perturbations, the more conscious control has to be applied to maintain stability (Pellecchia, 2003). Basically, complex tasks require more motor planning and demand central orchestration of corrective responses (Brown & Shumway-Cook, 1999). Evidence for this phenomenon has been provided via experiments with dementia patients, who displayed difficulties in generating postural adjustments required in concurrent postural/motor tasks (Elble & Leffler, 2000; Hauer et al., 2003). In experimental dual-task testing models, a cognitive task is usually added to a postural task, and performance changes in one or the other task are interpreted as changes of cognitive processing or prioritization modification. Additionally, dual-task experiments provided evidence that cognitive processing in postural control increases when the postural task becomes more difficult (Wulf, Mercer, McNevin, & Guadagnoli, 2004).

One crucial process for effective postural control is the evaluation of sensory information and its integration into a body schema. This requires the up- or downweighting of sensory information, which allows for flexibility or adaptability concerning the sensory processing required for postural control. SR might have an influence on the process of sensory weighting by increasing reliability and sensitivity of certain sensory channel(s). This, in turn could lead to a higher reliance on those sensory channels augmented by SR and a change of the “prioritization” of sensory feedback channels in certain postural tasks, or for certain populations (e.g. those suffering from neuropathies and decreased receptor sensitivity). SR might not only impact the process of multimodal sensory weighting or integration, but could have a general effect on the amount of cognition devoted to postural control during a particular task.

Concurrent postural/cognitive tasking, as often experienced in daily life activities, can be influenced by changing features of either the one or the other task’s features. Increased effects of an additional secondary task have been repeatedly observed in older adults who have generally less cognitive capacity (meaning there are fewer available cognitive resources that can be allocated to either of the two tasks), but also more cognitive resources are automatically granted towards postural control than cognitive control. Mainly, this is due to a higher prioritization for postural control, with the major goal of prevention of falls in older adults. SR and its potential to augment sensory feedback could lead to improvements of sensory feedback flow, due to better detection and increased sensory transmission. This augmentation of feedback could in turn improve postural control efficiency, which would be associated with less cognitive demand, as expressed either in better cognitive or postural performance in concurrent tasks.

Another feature of the human postural control system is the ability to quickly respond to sudden perturbations, as might occur in real life situations such as a sudden stop when standing on a bus. There are several response stages to such perturbations. Without any temporal delay, muscle elasticity features support the maintenance of vertical orientation. Anticipatory postural adjustments, which are limb displacements and specific increased muscle activity generated prior to the perturbation (based on anticipation of perturbation characteristics), provide an additional, initial “cushion” to reduce any balance threatening effects, particularly during self-generated movement. Mono- and polysynaptic reflexes (30ms and 50ms latency after perturbation respectively) are compensatory reflexes that assist in maintaining balance. Other preprogrammed responses (latency of approximately 70ms) and voluntary corrective actions (about 180—250ms latency) based on sensory feedback ultimately lead to maintenance of the center of mass over the base of support (Horak, Henry, & Shumway-Cook, 1997).

Based on the potential benefits of SR for neural “efficiency” improvement, augmentation of sensory feedback could lead to improved reflex generation and anticipatory postural adjustments due to higher sensitivity and better localization of the center of mass during the postural task. Additionally, preprogrammed responses and voluntary adjustments may become more efficient, since sensitivity of receptors responsible for detection of body position (and displacement) is enhanced. Since quick responses to a perturbation are required, responses are generated earlier and with less delay, since receptors are close to their firing threshold prior to initial perturbation.

Evidence from experiments dealing with the human CNS's ability to respond to external perturbations has pointed towards two major strategies involved in processing of responses to postural perturbations. A so called ankle strategy is mainly applied when perturbations are fairly small. The ankle strategy is associated with the model of the human body as an inverted pendulum, which is bounded by the feet – with sway occurring about the ankles. Perturbations are compensated by exertion of force around the ankle (for ankle rotation), a process that relies heavily on sensory feedback. Larger magnitude perturbations are usually associated with a hip strategy, in which most compensatory action is generated around the hip region and the trunk, with more rigidity around the ankles. This "stiffening" of the lower legs results from co-contraction of agonist and antagonist muscles of the lower legs. This strategy allows for corrective responses that prevent falls more effectively and relies less on sensory feedback from the lower legs when facing balance-threatening perturbations (Halická, Lobotková, Bzdúšková, & Hlavačka, 2012). In patients suffering from sensory neuropathies and in many older adults, there is a shift towards predominance of a hip strategy even when facing smaller magnitude perturbations, which is associated with decreased energy efficiency (Horak, Shupert, & Mirka, 1989).

Older adults tend to lose sensitivity in receptors around the ankle and the feet, thus a reliance on an ankle strategy is potentially dangerous. Older individuals adapt to this by increasing lower leg muscle co-contraction ("Stiffening") and using more of a hip strategy. Since SR is capable of improving sensory functioning of lower leg tactile receptors, this augmentation may modify older adults' reliance on a hip strategy. Forces applied to a support surface can be used to identify whether an ankle or hip strategy is primarily used to respond to a perturbation.

To investigate the nature and characteristics of postural control, force plates have been used extensively in experimental research. The general analytic approach is to calculate a measure labeled the Center-of-Pressure (COP) which is based on exerted forces of the feet on the plate and assesses its features and patterns of motion. The estimated COP and its fluctuations (displacement) over time can then be used to evaluate postural stability characteristics. Traditionally, more displacement and motion of COP (for example increased sway path length/larger excursion towards hypothetical boundaries of stability or higher velocity) throughout experimental trials has been interpreted as an indicator of decreased stability and associated with higher risk for falls (Melzer, Benjuya, & Kaplanski, 2004). More recently, the various forms of linear measures of postural stability have been expanded to draw conclusions about postural stability while including temporal features of COP sway. For example, time-to-boundary analysis is applied to determine how rapidly the COP approaches theoretical limits of stability throughout the course of a task trial. More rapid approaches towards the boundaries are interpreted as phases of decreased stability, slower approach indicates higher stability (Ozdemir, Pourmoghaddam, & Paloski, 2013).

However, these linear measures are somewhat limited when researchers are trying to investigate underlying motor control characteristics or subtle changes of control processing. To gain additional insight into postural control processes, researchers and clinicians can utilize non-linear measures of postural control. As an example, approximate entropy (ApEn), a non-linear measure of regularity has been used to investigate COP fluctuations. ApEn is based on the regularity of COP signals, which can be described as the regularity of sway. The method of COP-ApEn analysis has shown to detect changes in motor control that might not be revealed by traditional linear analysis, and results have been interpreted as potential modifications of motor control or biomechanical constraints (Cavanaugh et al., 2006).

Several studies have indicated that decreased balance performance, for example due to disease/sensory neuropathies are related to deviation of ApEn from normal values for certain postural tasks. ApEn analysis could be helpful in the investigation of postural control and potential improvement of stability in older adults. Non-linear measures allow us to expand our knowledge beyond the question of how certain factors influence postural stability, but also how these factors influence motor processing itself. This is a crucial aspect in efforts to expand knowledge regarding postural control, but is also highly important for the evaluation of new diagnostic or rehabilitation tools (Cavanaugh, Mercer, & Stergiou, 2007).

1.1 Motivation

One major concern of the U.S. health care system is improvement of the health of older adults and maintenance of their independence. Falls are the leading cause of traumatic death in older adults (Galica et al., 2009) and therefore the prevention of falls and fall-related injuries in older adults is an important area of research interest. Falls are a factor causing enormous costs for short- and longer-term patient care and putting a significant burden on the health care system. Prevention of falls and related injuries is associated with increased quality of life by enabling older citizens to remain more independent.

Due to extended research efforts since the 1990's, today there is a better understanding of modifiable and consistent risk factors of falls. It is well known that aging has influence on the way postural control is managed in humans (Amiridis, 2003; Seidler et al., 2010; Shaffer & Harrison, 2007). Thus, current research efforts are aiming at either improving postural control by employing neuromotor training interventions or by utilizing assistive devices designed to improve complex and potentially impaired sensorimotor control in older adults.

Considering the high prevalence of falls in older adults in the U.S., there is an urgent need for design and development of new fall prevention, rehabilitation techniques and assistive devices for fall prevention, which have to be tested and implemented in health care of older citizens. One potential approach is to focus on the sensory impairments that are found in most individuals who are at risk for falling.

A promising technology that has emerged over the last few years is based on sensory improvements that can be achieved by applying unperceivable stimuli to sensory afferents (Priplata, Niemi, Harry, Lipsitz, & Collins, 2003; Priplata et al., 2002). The effects of stimulation of sensory receptors are based on the overarching term stochastic resonance (SR), which can be broadly defined as a mechanism improving performance of a non-linear system such as human sensorimotor control when inducing (e.g. vibration) noise (Collins et al., 2011; Collins, Blackburn, Olcott, Dirschl, & Weinhold, 2009). Stochastic resonance has been shown to be beneficial in signal processing mechanisms in a number of different biological systems in the past.

More recently, SR has been identified as a mechanism improving signal detection and transmission of information emerging from the tactile sensors providing information about body orientation in space (Magalhães & Kohn, 2011; Priplata et al., 2006). Specifically, receptors that provide pressure information on the plantar surface have been a major target for augmentation of sensory feedback (Galica et al., 2009; J. Hijmans & Geertzen, 2008) with the goal of stabilization of upright stance. It is yet unknown how noise (in this study referred to as sub-threshold vibration or noise-enhancement) induction affects postural control processing in older adults and under experimental task conditions, which are cognitively demanding and balance-threatening. Results from such experiments will shed light on potential benefits of vibration tools for older adults for modifying postural control and improving upright stability in situations where improved control is crucial for prevention of falls.

1.2 Problem Statement

All studies investigating the potential benefits of application of vibration noise have been conducted using quiet stance, static tasks, with other sensory sources mostly unperturbed or disrupted (eyes closed) and to our knowledge there is only one study that applied SR in a dynamic (walking) task. Only one study investigated vibration noise and its effect on subtle motor control features (as evaluated by non-linear analysis methods). To date, no studies have investigated the potential of sub-threshold vibration-induced sensor modifications in more demanding tasks. No studies have systematically investigated benefits and limitations of sub-threshold vibration under different, complex task conditions.

Such experimental results are crucial however when aiming at evaluating sub-threshold vibration as a potential countermeasure to age-related functional postural stability decline. Carefully designed experiments need to provide valuable datasets reflecting potential benefits and limitations of the technique in postural control tasks that are most demanding to older adults (e.g. conflicting sensory environments, concurrent processing requirements, and balance perturbations). The existing gaps of knowledge inspired the general approach of this dissertation and lead to the research questions that were addressed in this project:

Question #1: Does sub-threshold vibration on the soles of the feet improve older adults' performance in a postural task (visually sway-referenced sensory organization test) that requires sensory integration processing (a shift of reliance towards somatosensory information from the lower legs)?

Question #2: Does sub-threshold vibration on the soles of the feet improve dual-task (concurrent postural and cognitive tasking) performance in older adults?

Question #3: Does sub-threshold vibration on the soles of the feet improve the temporal and spatial features of corrective postural responses when facing a balance threatening external perturbation?

Question #4: Does sub-threshold vibration on the soles of the feet affect postural control in sensory integration tasks, dual-tasks or postural perturbation tasks?

Question #5: Is aging associated with postural performance and postural control in sensory integration tasks, dual-tasking or postural perturbation?

1.3 Research Objectives

The overarching research objective of the dissertation is to evaluate balance performance changes in older adults in dynamic, demanding situations when sub-threshold vibration is added. Three experiments were conducted to accomplish three distinct, but conceptually related objectives. Participants were 10 healthy, older individuals (age 70-85) and 10 healthy, younger adults (age 20-35). Effects of sub-threshold vibration were evoked using stimulation of mechanoreceptors of the soles of the feet. The purpose of each experiment is discussed in the following paragraphs.

Experiment 1

Experiment 1 was designed to answer questions #1, #4 and #5, where we collected and analyzed data from a postural task experiment, in which younger and older adults were exposed to a postural task that afforded individuals to change the extent to which specific sensory input from different sources needs to be "weighted". This "weighting" or "reweighting" describes a process that increases integration of reliable sensory information sources, while suppressing unreliable sensory information from other sensory sources.

For the prevention of falls, it is highly important that those sensory receptors that are more reliable in a given task are upweighted to a greater extent than those which are not reliable and provide potentially incorrect information about postural orientation. It is well known that older people more often than younger individuals struggle in tasks in which conflicting sensory information emerges from receptors, thereby requiring shifting of reliance away from less reliable sensors. Research has shown that older individuals rely on visual information for postural control more than younger individuals, due to a functional decline of other sensory sources, for example mechanoreceptors of the foot sole. Noise-enhancement of foot sole sensory information might help to improve signal detection and transmission from tactile sensors, which could help older adults in situations where other sensors are disrupted or provide unreliable feedback. This in turn could lead to decreased dependency and associated downweighting of visual information, as expressed in improved postural performance.

In this condition, participants were exposed to a sensory conflict with inaccurate visual information (sway-referenced surrounding/environment) and we investigated the effects of enhancement of another sensory source (foot sole mechanoreceptors) in this environment (Objective #1). Participants tried to stand as quietly as possible for 20 seconds, while sub-threshold foot sole stimulation was either turned on or off (randomized order of three trials on, three trials off). Balance performance was evaluated by computing an Equilibrium Score (ES), integrated time-to-boundary (iTTB) values, and anterior-posterior sway path length (APPlength) for each trial. Additionally, strategy scores were computed to determine hip- vs. ankle strategy (control) characteristics. To investigate more subtle differences in motor control processing, non-linear analysis of center-of-pressure data (ApEn) was conducted. We compared these variables when vibration was either turned on or off. Outcome measures were also compared between older and younger group. Additionally, potential interactions among the independent variables were evaluated.

Experiment 2

In experiment #2, designed to answer questions #2, #4 and #5, efficacy of sub-threshold vibration application on postural sway characteristics was investigated when a cognitively demanding secondary task was added (Objective #2). Since sub-threshold noise is believed to improve sensory detection and transmission, we hypothesized that this could affect the cognitive processing requirements for postural control.

Participants stood on a force plate with their eyes closed and were asked to perform a concurrent cognitive task (1-back task, verbal recall) while trying to stand as quietly as possible for 20 seconds (six trials of 20 seconds with randomized order of foot stimulation on or off). Postural stability and strategy were evaluated by analyzing ES, TTB, APPlength and strategy score (hip vs. ankle strategy) data. Performance in the secondary, cognitive task was evaluated by recording and analyzing response times during each 20s trial. To investigate potential subtle changes in motor control that are undetectable by linear measures, ApEn values were generated and analyzed for each trial. We generated comparisons between conditions when vibration was both turned on or off, and compared older vs. younger participants. We also investigated potential interactions among the variables.

Experiment 3

In experiment #3, designed to answer Question #3 and #5, we investigated the effects of sub-threshold noise in a postural perturbation task. Older adults tend to be less efficient compared to younger adults when generating adequate and rapid corrective postural adjustments when the support surface is moving in a sudden manner. Sensory detection and transmission declines due to aging are among the identified and significant contributors to non-optimal perturbation responses in older adults.

In this experiment, participants were exposed to repeated translational perturbations of the support surface with foot stimulation turned on or off, with the aim to investigate the potential effects of sub-threshold noise during postural perturbations (Objective #3). Sudden surface translations were applied to challenge the postural control system and to require participants to recover from a postural stability threatening perturbation in ten trials (backward translation with randomized order of five trials (one block) foot stimulation turned off, five trials stimulation turned on). We analyzed the maximal excursion of center-of-pressure (COP) from baseline levels (0.5 seconds before onset of perturbation), total APPlength per trial, and temporal characteristics of corrective response generation (response latency). We statistically compared between conditions where foot stimulation was turned either on or off. We also compared younger vs. older group and investigated interactions among the independent variables.

1.4 Research Hypotheses

For experiment 1, we expected that sub-threshold noise would enhance foot sole information and would improve postural stability by providing more accurate and more reliable sensory feedback that would be integrated for better stability. We expected that augmentation of tactile feedback from the foot soles would allow older individuals to better sense postural orientation and would affect sensory shifting to this more reliable source in case of visual impairment or error.

Hypothesis #1a: Overall postural performance as represented by measures of Equilibrium Score (ES), APPlength and integrated time to boundary (iTTB) across stimulus conditions is higher in younger adults compared to older adults

Hypothesis #1b: Postural control measures (ApEn and Strategy Scores) differ between older and younger adults

Hypothesis #1c: Application of sub-threshold vibration has a larger effect on ES, APPlength, iTTB, ApEn and Strategy Scores in the older group than in the younger group

Hypothesis #1d: Application of sub-threshold vibration increases ES in a sensory conflict postural task

Hypothesis #1e: Application of sub-threshold vibration decreases iTTB in a sensory conflict postural task

Hypothesis #1f: Application of sub-threshold vibration decreases APPlength in a sensory conflict postural task

Hypothesis #1g: Application of sub-threshold vibration affects ApEn values in a sensory conflict postural task

Hypothesis #1h: Application of sub-threshold vibration affects strategy scores in a sensory conflict task

For experiment #2, we expected that sub-threshold vibration would enhance detection and transmission of sensory stimuli. This would make postural control more efficient and affect performance when a cognitive task was added to the postural task. We expected to observe an effect on postural performance and cognitive performance.

Hypothesis #2a: Overall postural performance across stimulus conditions is higher in younger adults compared to older adults

Hypothesis #2b: Postural control measures (ApEn and Strategy Scores) differ between older and younger adults

Hypothesis #2c: Application of sub-threshold vibration has a larger effect on dependent variables in the older group than in the younger group

Hypothesis #2d: Application of sub-threshold vibration increases ES in a dual-task experiment

Hypothesis #2e: Application of sub-threshold vibration decreases iTTB in a dual-task experiment

Hypothesis #2f: Application of sub-threshold vibration decreases APPlength in a dual-task experiment

Hypothesis #2g: Application of sub-threshold noise affects ApEn values in a dual-task experiment

Hypothesis #2h: Application of sub-threshold vibration affects strategy scores in a dual-task experiment

Hypothesis #2i: Application of sub-threshold noise affects cognitive performance in a dual-task experiment

For experiment #3, we expected that sub-threshold noise would enhance functioning of tactile sensors of the plantar surface in a postural perturbation task, which then would be reflected in spatial and temporal features of motor control (generation of corrective postural responses).

Hypothesis #3a: Postural performance across stimulus conditions is higher (as determined by smaller COP excursion, lower latency, and smaller APPlength) in younger adults compared to older adults

Hypothesis #3b: Application of sub-threshold noise has a larger effect on COP excursion, response latency, and APPlength in the older group than in the younger group

Hypothesis #3c: Application of sub-threshold vibration decreases APPlength in a platform translation perturbation task

Hypothesis #3c: Application of sub-threshold vibration decreases maximum COP excursion in a platform translation perturbation task

Hypothesis #3d: Application of sub-threshold vibration decreases response latency in a platform translation perturbation task

1.5 Dissertation outline

Chapter 1, Introduction – introduces the reader to the main topic and the general ideas of this dissertation. This includes a summary of the current state of knowledge in terms of SR, gaps of knowledge and limitations of former studies; ***Chapter 2***, Literature Review – in this chapter , the reader is provided with detailed information from existing literature related to the effects of aging on sensory systems in general, and on tactile afferents specifically. Influence of aging on specific postural control processes (dual-tasking, sensory integration, corrective responses to postural perturbations) are discussed in detail. The chapter closes with a summary of current knowledge about the efficacy of SR in postural control and the existing gaps of knowledge; ***Chapter 3***, Methodology – a detailed description of the procedures to be utilized in order to conduct this dissertation research project and the three experiments designed to answer the main questions; ***Chapter 4***, results from the study are presented, and ***Chapter 5***, discussion section – a detailed discussion of the observed results in perspective of earlier studies related to the series of the current experiments.

1.6 Potential contributions

The potential of sub-threshold vibration noise induced at mechanoreceptors of the feet to promote improved control of posture has not yet been adequately explored, particularly the conditions in which it may be most effective. The outcome of this study provides valuable insights suggesting benefits and potential limitations of noise-enhancement as a factor to improve balance in older adults.

Results from the proposed experiments expand existing knowledge about the role of mechanoreceptor input in certain, demanding task situations. The results provide insight into the complex mechanisms of aging-related sensorimotor loss and how sensory modifications can be used to compensate for negative effects related to sensory decline. This provides evidence that the technique and its implementation, for example, via design of vibrating insoles, has value for specific populations and for balance improvement in specific situations.

1.7 Definitions of Terms and Abbreviations

APPlength- anterior-posterior sway path length

ApEn - Approximate entropy

COP - Center-of-pressure

COM - Center-of-mass

COG - Center-of-gravity

CNS - Central Nervous System

SOT - Sensory Organization Test

TTB - time to boundary

iTTB - integrated time to boundary

SR - Stochastic resonance

SH - Shear force

MMSE - Mini Mental State Examination

PAR-Q - Physical Activity Readiness Questionnaire

II. LITERATURE REVIEW

This literature review highlights the current understanding of sensory processes required to control human posture and the effects of aging on each sensory information source. It is evident that there are gaps in knowledge regarding specific central and peripheral effects of aging on postural control. Additionally, it is not fully understood how the detrimental effects of aging can be counteracted by different techniques of neuromotor enhancement and how those techniques can be used to actually improve quality of life in older adults by enhancing postural stability.

The background review starts with a summary of the current view on the role of sensory feedback for establishing an internal model of verticality and how sensory feedback sources are affected by healthy aging processes. Subsequently, the emergence of the concept of stochastic resonance is discussed, with a specific focus on the potential of sub-threshold noise application in foot sole receptors.

2.1 Aging effects on sensory receptors and postural stability

Postural control underlies numerous neuromuscular structures, complex interacting mechanisms, and processes. Aging affects those structures and their functioning, which is reflected in a general decline of postural stability over the course of a lifetime. Postural balance performance is thought to decrease at a relatively young age with accelerated decline starting at about 60 years of age (Era et al., 2006). Balance performance decline is more prominent in experimental tasks that are complex and require complex sensorimotor processing. This is the case for example when participants are required to compensate for lack of sensory information flow from one or several channels. Other examples are tasks where wrongful or unreliable sensory feedback is provided by certain channels which in turn require down-weighting of such information.

2.1.1 Aging effects on visual, vestibular, and proprioceptive systems

One of the main concerns for postural stability impairments in older adults is the sensory decline that is being observed in healthy aging, which contributes significantly to observed postural performance losses: Accurate information emerging from several sensory entities of the human body is crucial for optimal postural control. It is necessary to understand the specific contribution of those sensory sources in order to understand the complex mechanisms of aging that ultimately affect postural control in the aging population. This chapter highlights the importance of each sensory channel for postural control, whereas specific focus is set on the important role of mechanoreceptors and how aging affects them.

We navigate our environment mainly based on visual information, which provides us with a picture of how our surroundings move in respect to ourselves, or how we move in respect to our surroundings. Visual information is based on two major systems: ambient and focal, whereas the latter is mostly responsible for determination of (self-) motion, e.g. in postural control. This egocentric processing allows us to determine how our postural orientation changes, since we interpret a swaying environment as a tilt of our body or postural sway. We perceive this as the body moving in a stationary, stable environment, an effect known as vection. Visual information for postural control is of high importance, as evidenced by an increase of postural sway in experiments, where individuals try to stand as quietly as possible: Closing the eyes or providing unreliable information about the visual environment leads to significant declines in postural performance (Paulus, Straube, & Brandt, 1984).

Research has shown that visual performance, depth perception, sensitivity and acuity decline during the sixth life decade due to healthy aging, these effects may be even aggravated by the many existing vision impairments that are based on either eye pathologies or are the result of other underlying problems, like hypertension or diabetes (Gittings & Fozard, 1986; Sturnieks et al., 2008). The associated functional declines lead to a lack of reliable depth- and contrast perception of the features of the environment, and associated impaired spatial orientation. Falls in older adults can be caused by these effects and visual impairments are a significant risk factor in older adults prone to falls (Lord & Dayhew, 2001).

In order to determine and interpret movement of the head and the body and to ultimately evaluate spatial orientation or acceleration, the vestibular system provides the CNS with multidimensional information. Postural control is partially dependent on this information, whereas the vestibular system directly affects postural correction via vestibulo-spinal, vestibulo-ocular pathways, and connections to higher motor centers. The vestibulo-spinal reflexes are mainly responsible for triggering muscle responses of the upper body and distal body sections, in order to improve balance and to stabilize the head (Angelaki & Cullen, 2008). To keep a vertical head position (which is crucial for determination of angular displacement), several other reflexes are required like the cervicollic and vestibulocollic reflex. The system consists of two main components, the otholitic system, including utricular and secular organs, assisting in evaluating linear accelerations and, graviception for determining head tilt. The semicircular canals provide pitch, yaw, and roll angular acceleration information of the head. Clinical experience and experimental research has shown that vestibular deficits significantly impair postural performance: Patients with known vestibular neuropathies exhibit severe symptoms of loss of postural control and orientation deficits (Carpenter, Allum, & Honegger, 2001; Horak, Nashner, & Diener, 1990).

Effects of healthy aging on anatomical and physiological features of the vestibular system have been the main focus of several studies. There is convincing evidence that older adults (>70 years of age) exhibit impairments of vestibular processing. The number of hair cells located in the labyrinthine pathways within the vestibular organ declines (Herdman, Blatt, Schubert, & Tusa, 2000), as does the overall vestibular sensitivity. As a result, the associated vestibular reflex parameters are modified in older adults (Johnsson 1981). Decreases or impairments in vestibular function lead to overall higher risk of falls and associated injuries in older people(Di Fabio, Emasithi, Greany, & Paul, 2001).

However, vestibular deficits might not always be directly related to a higher risk of falls in older adults, as evidenced by studies that did not find a higher occurrence of falls in people with vestibular impairments (Baloh, Enrietto, Jacobson, & Lin, 2001). This phenomenon is often observed in individuals with longer-term vestibular impairments: It is possible that the CNS is able to adapt over time and overcomes the existing deficits by shifting reliance towards other sensory sources providing spatial information associated with body orientation. It is possible that, over time, patients become better at using their other senses just as blind individuals often have elevated sensitivity regarding other senses (e.g. hearing, tactile perception). The existing results underline the importance of adequate sensitivity and information processing of alternative sensory sources, like the somatosensory or visual systems.

Proprioception is often referred to as the collection of sensory information emerging from receptors of the tendons, the joints, and the muscle spindles (depending on the respective definition, tactile sensory input is considered a sub-category of proprioception). Proprioceptors provide information about joint position or movement, and touch. Lower body proprioception is considered highly important for postural control due to the fact that this information source is more susceptible to small-magnitude stimuli, and therefore more sensitive to the perception of foot pressure velocity modifications (Fitzpatrick, Rogers, & McCloskey, 1994; Sturnieks et al., 2008). Specifically, when vision is occluded or less reliable, proprioception is highly important, as evidenced by experiments perturbing upright stability with small magnitude (below vestibular threshold) platform manipulations (Vaugoyeau, Viel, Assaiante, Amblard, & Azulay, 2007). The Golgi tendon organ is responsible for detecting muscle tendon tension (and changes in tension) that is either induced by passive or active stretching.

Joint receptors sense joint movement and position, based on mechanic stimuli occurring in the ligaments and the joint capsule due to movement (passive or active). Like mechanoreceptors responsible for tactile perception, slowly-adapting and rapidly-adapting receptors contribute jointly to the perception of joint features.

Muscle spindles (intrafusal fibers) within the muscle body contribute information about muscle length and the rate of length-change. Aging results in changes of muscle spindle features, like a general reduction of intrafusal fibers (Swash & Fox, 1972) which could affect the accuracy and efficiency of postural reflexes associated with muscle spindle function. Tactile perception around the joint is affected by aging processes as well: Several studies have shown that vibration perception is affected in older adults (Verrillo, Bolanowski, & Gescheider, 2002), potentially due to decreasing number of tactile sensors due to aging (Bolton et al. 1966). Older individuals are less able to determine accurate joint position, with overall lower sensitivity for joint movement (Thelen, Brockmiller, Ashton-Miller, Schultz, & Alexander, 1998). Low Choy et al. (2007) posit that sensitivity to vibration and joint-position sense in a toe-matching test were significantly decreased in individuals between 40 and 50 years old, with more reductions occurring in the 60 or 70 year old individuals.

The combination of aging-related loss of sensitivity and accuracy in proprioception has shown to have a significant effect in older adults and is considered an important contributor to postural control issues in the aging population. A summary of the morphological and functional features of sensory receptor decline (vestibular, visual, proprioceptive, and tactile) is presented in Figure 2.

2.1.1 The specific role of cutaneous receptors in motor control

Mechanoreceptors, as a subgroup of proprioceptors, are mainly responsible for providing information about pressure changes around the bottom of the foot. There are morphologically and functionally distinct receptors, slowly adapting Merkel disks and Ruffini's endings, rapidly adapting Meissner's corpuscles and Pacinian corpuscles (see Figure 1).

Investigations of cutaneous receptor information provision in human motor control have contributed significantly to a better current understanding of sensory processing mechanisms in the CNS. Some major functional aspects have been identified, like the role of afferents as proprioceptors and their role in modulation of movement control (Bent & Lowrey, 2012; Lowrey, Strzalkowski, & Bent, 2013; Perry, 2006)

The uniqueness of the plantar surface and mechanoreceptors of the sole of the foot is that it is a location on the body that directly connects humans to their environment. Plantar surface feedback has shown to be used to gather information about support surface characteristics in gait, but seems to be more important in postural control, by providing information about pressure changes and associated postural sway (Kavounoudias, Roll, & Roll, 1998; Zhang & Li, 2012).

It is likely that the different existing classes of mechanoreceptors are responsible for different tasks related to the control of upright stance based on their functionality and response ranges (see Figure 1).

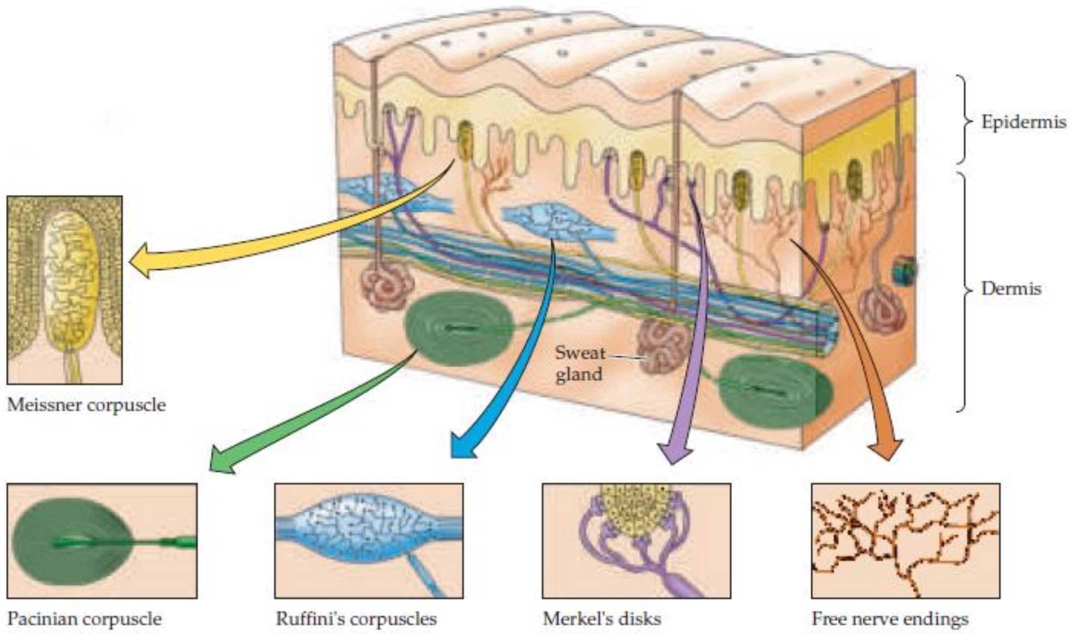


Figure 1: Different types of mechanoreceptors of the skin. Adopted from Purves et al. 2004

Whereas rapidly-adapting mechanoreceptors (Meissner, Pacinian corpuscles) are thought to be more involved in detection of shear forces, potentially associated with slips across the skin surface (Bent & Lowrey, 2012; Lowrey et al., 2013), force of external perturbation or gait events (toe off, heel strike), slowly adapting mechanoreceptors (Merkel cells and Ruffini endings) could be more important for “sustained indentation” features (Lowrey et al., 2013) and pressure changes around the foot sole surface and as a detector of body sway (Stål, Fransson, Magnusson, & Karlberg, 2003).

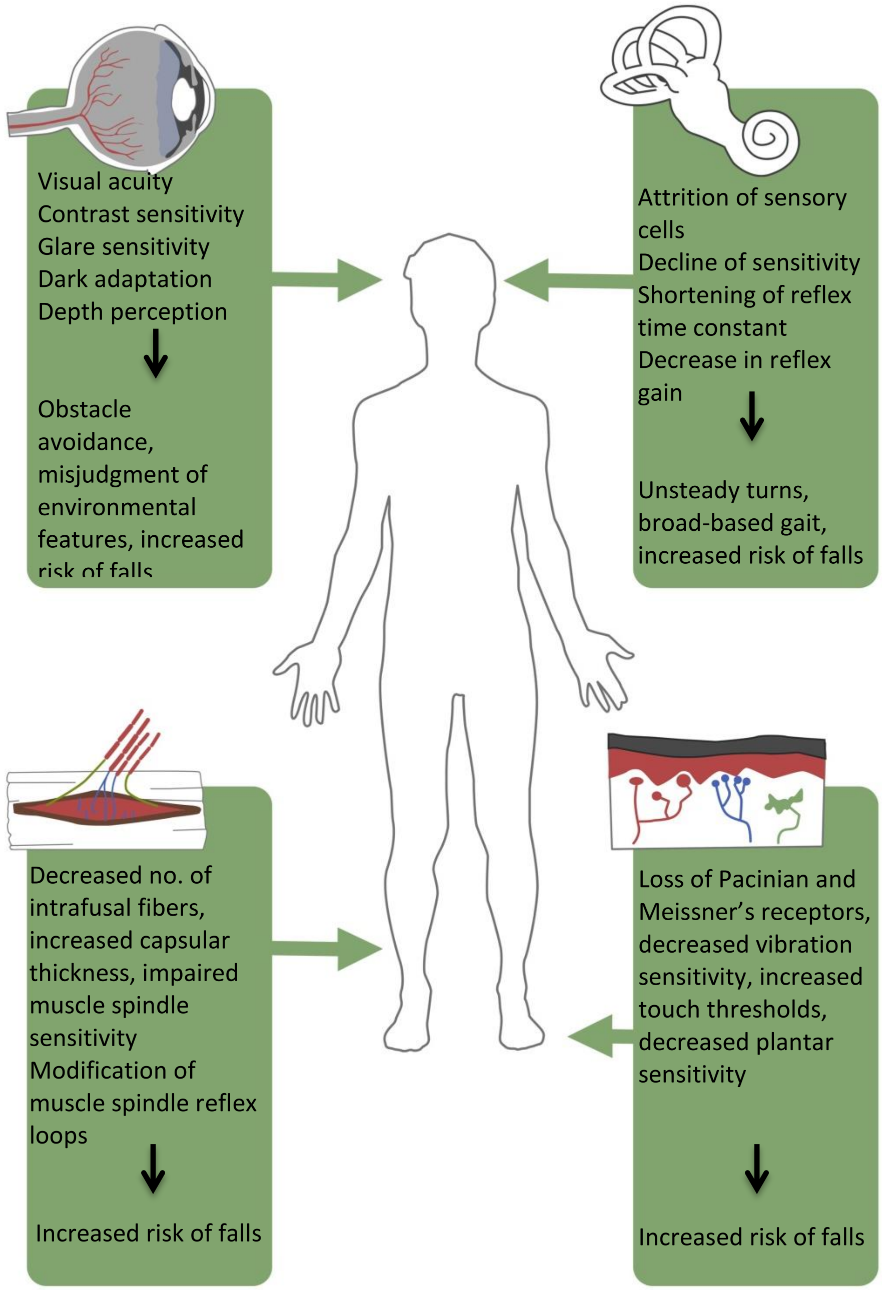


Figure 2: Effects of aging on morphological and functional features of selected sensory receptors (visual, vestibular, proprioceptive, and tactile), figure created based on information obtained from Shaffer & Harrison (2007)

The importance of pressure input from the foot sole has been highlighted in numerous studies that have aimed at investigating the effects of foot sole stimulation on posture. Maurer et al. (2001) summarized some findings showing that vibratory stimulation could evoke postural orientation effects, depending on vibration characteristics and location, (Kavounoudias, Roll, & Roll, 1999; Kavounoudias et al., 1998). Increased COP excursions and the perception of a body-“lean” can be evoked using this technique (Roll, Kavounoudias, & Roll, 2002). This makes foot sole afferents comparable to muscle spindle afferents around the ankle, which have been shown to be affected by vibration and in turn induce postural orientation changes (Ceyte et al., 2007; Kavounoudias, Roll, & Roll, 2001; Thompson, Bélanger, & Fung, 2010).

A different approach for investigating the role of foot afferents in motor control is experimental desensitization via anesthetizing or cooling of the plantar surface (Lowrey et al., 2013). Observed reductions of postural stability in static or dynamic postural tasks with desensitized/anesthetized foot receptors highlight the importance of cutaneous afferent information in postural control (Hong, Manor, & Li, 2007; Stål et al., 2003). Lack of cutaneous input due to desensitization has a significant influence on postural stability (Magnusson, Enbom, Johansson, & Pyykkö, 1990), but adaptation processes (sensory reweighting) can help to compensate for experimentally induced cutaneous afferent loss (Stål et al., 2003).

Kavounoudias et al. (1999, 2001) suggested that information from tactile and proprioceptive afferents (e.g. muscle spindles) is co-processed for evaluation of postural orientation and for establishing upright stance. According to the authors, foot sole pressure information is used by the CNS in a certain way, which is based on actively trying to cancel potential pressure differences between, for example heel and forefoot on stable support surfaces, and by activating lower leg reflex loops.

One major contribution of cutaneous receptors is the potential for reflex modulation and associated tuning of motor control mechanisms. The idea that reflexes play a crucial role in motor control and that lower leg muscle activity could be influenced by afferents in the foot is not new and has already been formulated in the early days of motor control research (Sherrington, 1910).

The current consensus is that reflexes, modulated via plantar afferent input, contribute significantly to postural stability (Fallon, Bent, McNulty, & Macefield, 2005; Roll et al., 2002). Stimulation of single, low-threshold plantar mechanoreceptors modulates muscular activity around the ankles, whereas this reflex coupling has been observed in all mechanoreceptor classes within the foot (SA I, SA II, FA I, FA II). Modulation of muscular activity has been shown for timing features of EMG spikes (Fallon et al. 2005). In general, cutaneous afferents from the foot sole are capable of affecting motoneuron excitability (Sayenko et al., 2007) through pre- and postsynaptic inhibition modulation processes, by influencing activity of Ia and Ib inhibitory interneurons(Conway & Knikou, 2008; Iles, 1996; Pierrot-Deseilligny, Bergego, Katz, & Morin, 1981). Stimulus-muscle response reflexes are differentiated as short-, medium- and long-latency reflexes (Diener, Dichgans, Bootz, & Bacher, 1984). Sayenko et al. (2007) suggested that mechanoreceptor input from the feet interacts with “complex spinal interneuronal circuits” for human motor control and affecting reflex responses.

They found that the soleus stretch reflex was significantly modulated by the influence of cutaneous stimulation (around the heel), with the largest effect within the first 1-15ms of the short-latency component (M1), associated with potential excitation of Ia afferent fibers. This finding is supported by other results showing reflex processes (inhibitory and excitatory) on sets of muscles on the ankle and the knee affected by experimental stimulation of plantar afferents (Gibbs, Harrison, & Stephens, 1995; Zehr, Komiyama, & Stein, 1997).

Wu & Chiang (Wu & Chiang, 1997) conducted a postural experiment with sudden toes-up platform rotation. They found evidence that cutaneous afferents mostly affect medium-latency components of the reflex mechanisms involved in compensatory neuromuscular activation. Conway & Knikou (2008) investigated the effects of cutaneous input on reflex mechanisms in spinal cord injury (SCI) patients. They found that cutaneous input (pressure) leads to inhibition of (long-latency) flexion reflexes of the legs, which could affect postural stability or locomotion as has been stated before (Duysens, Clarac, & Cruse, 2000).

Muise et al. (2012) investigated the interaction between vestibular reflexes and cutaneous input as a potential modulator. Desensitization of foot afferents lead to significant changes in medium-latency lower-leg responses to galvanic vestibular stimulation. It was concluded that cutaneous afferents are an important contributor to postural orientation and contributor to reflex (modulation) mechanisms.

According to recent findings, the contribution of plantar feedback to functional reflexes is not even limited to the lower legs: Bent & Lowrey (2012) found that cutaneous afferents affected interlimb reflexes. It is well known that sudden trips or slips result in low-latency, quick, compensatory arm movements (Marigold, Bethune, & Patla, 2003). The authors of the recent study found that there was a significant reflex coupling between single foot afferents and upper body muscles (posterior deltoid and triceps brachii), allowing for rapid corrective arm movements based on foot sensory feedback, with the goal to recover from postural perturbations.

Further investigations highlighted the importance of spatial factors and the kind of reflex to be investigated (Sayenko 2009): Whereas stimulation of a certain area of the foot can have an inhibitory effect on certain muscles (e.g. soleus muscle after metatarsal region stimulation), it can have an excitatory effect on the same muscle when a different region (heel) is stimulated (Nakajima, Sakamoto, Tazoe, Endoh, & Komiyama, 2006).

2.1.2 Effects of aging on mechanoreceptor morphology and functioning

The importance of mechanoreceptors for postural control is further indicated by the fact that somatosensory decline in the feet has been recognized as a major predictor of falls in older adults (Magnusson et al., 1990; Patel, Magnusson, Kristinsdottir, & Fransson, 2009). The morphological and functional effects of aging on this class of receptors have been studied extensively. Some major findings are presented in table 1.

Table 1: Effects of aging on Mechanoreceptor anatomy, physiology, and clinical testing outcomes (adopted from Shaffer & Harrison 2007)

Model	Pacinian Corpuscle	Meissner's Corpuscle	Clinical Cutaneous Testing
Human	↓ number with increasing age[80]	↓ concentration with increasing age[83]	Diminished vibration perception threshold testing[77,86–88]
	↓ vibration perception thresholds and perceived magnitude of vibration at frequencies that activate pacinian channels[81,82]	↓ size and number with increasing age[84]	Diminished monofilament testing[77]
		↓ number in the finger and impaired touch thresholds[85]	Diminished 2-point discrimination testing[89–92]

The number of Pacinian corpuscles (PC) declines with higher age as does the overall number of Meissner's corpuscles (MC) in older adults (Iwasaki, Goto, Goto, Ezure, & Moriyama, 2003). Research has shown that this morphological change affects vibrotactile sensitivity, for example at the soles of the feet and is most prominent in individuals over the age of around 72-73 years (Perry 2006). Parallel to this development, older individuals become more impaired considering discriminative touch perception, an effect that is more prominent in distal extremities (Stevens & Patterson, 1995). The aforementioned effects seem to have a direct influence on postural performance, as evidenced by aggravated decline of these measures in recurrent fallers (Melzer et al., 2004). This can lead to modifications and probably delays in compensatory stepping mechanisms or grasp reactions, based on the inability to "feel" changes of pressure at the soles of the feet (Melzer et al. 2004).

The pressure-evoked stimuli at the feet contribute significantly to the processing and modification of weight distribution and postural control, during postural tasks, for example single-stance balancing. The information provided by the mechanoreceptors assists in detecting the position of the center-of-mass over the base of support (Maki, Perry, Norrie, & McIlroy, 1999; Perry, McIlroy, & Maki, 2000). Aging decreases the overall functioning of mechanoreceptors and affects stimulus detection (Verrillo et al., 2002). A higher detection threshold of the mechanoreceptors represents a lowered ability to efficiently and quickly respond to potential perturbations and balance disturbances. Ultimately, this leads to a higher risk for falls in older adults.

The decline in postural control and reaction delays might not be solely due to sensory sensitivity impairments, but could also be due to impaired signal transmission to the spine and higher motor centers. Afferent signals emerging from mechanoreceptors of the foot sole are transmitted via the dorsal root ganglion, proximal axons transport information to the spinal cord. Aging affects anatomical and physiological parameters at this level as well: Density of axons declines just as myelin thickness decreases. This has an influence on nerve conduction velocity, which declines after the age of 40 (Taylor, 1984) but is more prominent at the sensory fiber level at that age. At an age of around 80 years, both motor and sensory pathways are severely affected due to aging processes. Spinal loop reflexes, which are crucial for automatic postural responses, are being modified, as evidenced by changes of H-reflex characteristics in older adults (Falco, Hennessey, Goldberg, & Braddom, 1994; Scaglioni et al., 2002).

2.2 Effects of aging in multimodal sensory conflict processing tasks

For optimal postural control, complex sensorimotor mechanisms and processes are required. Redfern et al. (2001) posit three major portions of postural control:

(1)The sensation of position and displacement, (2) processing of afferent signals and (3) selection and generation of adequate motor responses in order to ensure postural stability or to re-establish postural verticality.

Sensation of position and displacement is based on the sensory receptors discussed in the last section. Step 2, the processing of afferent signals, involves the integration of multi-channel information (multimodal information) emerging from the receptors providing information about body- and limb position and –movement. The integration process involves active weighting of sensory information emerging from receptors of the vestibular, visual, and somatosensory system. When certain sensory channels become unreliable due to internal or external factors, certain sensory channels are being re-weighted and the effect of perturbations of one channel is directly related to availability and reliability of other, remaining sensory channels. In addition, each sensory system has a certain (optimal) frequency range making it more or less reliable and valuable for the CNS in certain situations (Redfern et al. 2001).

Multisensory (or multimodal) integration is partially based on unconscious mechanisms that allow for suppression of certain sensory channels in favor of others, depending on task features. A sensory conflict describes the emergence of diverging sensory information from different sensory sources of the central nervous system. This can be caused by specific external constraints (e.g. standing on a stable support, while the visual environment moves) or be due to neuropathies and sensory decline.

The varying contributions of somatosensory, visual, and vestibular cues for postural control have been studied extensively. To gain a better understanding of the risk of falls in older adults and potentially associated sensory integration impairments, researchers have exposed patient populations and healthy older adults to conflicting sensory situations (Marsh & Geel, 2000). It was shown that aging affects mechanisms in the CNS responsible for integrating and orchestrating (available, reliable) information in order to allow for stable upright balance (Degardin et al., 2011). Doumas & Krampe (2012) showed that older individuals exhibit impairments of sensory shifting when sensory information is being disrupted but then made available again: In their postural experiments, older adults had difficulties when proprioceptive information was perturbed via vibration at the tendon; when vibration was then turned off, younger adults were better able to reintegrate the suddenly available afferent source. The observed effects are not limited to the proprioceptive feedback system, as evidenced by comparable results concerning sensory integration of vestibular and visual information (Deshpande & Patla, 2007).

It not known at this point, whether the concurrent decline of multiple sensory channels or central processing declines are mostly responsible for the postural declines observed in older adults, specifically in complex sensory conflict tasks: It has been shown that occlusion of certain sensory channels, experimental sensory flow reduction or sensory conflicts have a larger effect on older adults postural performance than on younger adults (Teasdale, Stelmach, & Breunig, 1991). Older adults are more affected than younger adults when somatosensory cues are perturbed, for example when muscle spindles are manipulated via tendon vibration (Teasdale & Simoneau, 2001), or when lower leg proprioception is affected by sway-referenced support conditions (Cohen, Heaton, Congdon, & Jenkins, 1996; Forth, Metter, & Paloski, 2007; Speers, Kuo, & Horak, 2002). In one of the first studies dedicated to the investigation of effects of aging on sensory integration mechanisms in postural control, Woollacott et al. (1986) found evidence for impaired or reduced peripheral sensitivity as a main contributor to the increased sway in older adults in complex (and conflicting) sensory situations. The authors concluded that this lack of sensitivity from sensory sources might be equally or more important than potential decline of central processes related to integration of sensory information. It is possible that the impairments in sensory inputs from the vestibular and somatosensory sources "force" the CNS to rely more on visual input and do not allow for efficient responses to multimodal stimuli occurring in postural tasks, like unexpected perturbations of the support surface (Bugnariu, Joyce, & Fung, 2007). Evidence from postural and sensory integration experiments indicates that aging leads to higher dependency on the visual system when performing postural tasks (Jamet, Deviterne, Gauchard, Vançon, & Perrin, 2007; Zhou et al., 2013). In experiments inducing optic flow manipulations, larger effects were observed in older participants' postural performance than in younger, vestibular loss patients (Mahboobin, Loughlin, Redfern, & Sparto, 2005).

As a potential explanation for the phenomenon, Bugnariu & Fung (2007) considered that changes in sensory inputs affect sensory thresholds when facing complex external stimuli (that include several sensory channels) and lead to heavier reliance on visual information flow. The authors conclude that this strategy of shifting towards visual reliance might be a natural process of strategy change related to aging effects, which can improve balance and prevent falls. However, this is only the case when visual cues are reliable, whereas it can have devastating effects on stability when visual information is disrupted, perturbed, or unreliable. It is to this date unclear if a somatosensory (tactile) augmentation in older adults would lead to dynamic reweighting of reliance on somatosensory channels, with an up-weighting of tactile input and down-weighting of visual information, potentially towards a more "natural hierarchy of sensory contributions" (Muise 2012).

2.3 Dual task processing and aging

Dual task processing has been the focus of numerous research endeavors, with major aims being the investigation of executive mechanisms, like concurrent processing, prioritization, and altered behavior patterns due to aging or pathologies. Based on experimental results, several major theories about dual-task executive processes have evolved. In motor control research, a dual task paradigm usually consists of a combination of a motor (e.g. postural task) and a cognitive task. It has been proposed that performance in either of two concurrent tasks is strongly dependent on available attention resources (capacity-sharing). Attention describes a person's capacity for processing information (Woollacott & Shumway-cook, 2002). Adding, for example, a secondary task can have a significant effect on performance characteristics, in either of the two tasks or in both. In concordance with this theory, the "bottleneck" theory proposes neuromotor processing channels which at times are "occupied" by one task and processing of a concurrent task has to be delayed or slowed down, until the processing units are open again (Sigman & Dehaene, 2006). The bottleneck phenomenon is specifically prevalent when common processing mechanisms are required for each individual task, but it is possible that dual-task performance is unaffected if neural processing units are different for each task and there is not much overlap, as described by multiple resource model theories (Wickens, 2008). However, it has also been proposed that higher similarity of information processed could positively affect performance in specific instances, by decreasing the amount of neural cross talk (Pashler, 1994; Pashler, & Johnston, 1998).

Motor- and specifically postural control in everyday life is usually combined with cognitive tasks and –activity that is unrelated to the ongoing postural control processes.

This could be generally referred to as dual-tasking of cognitive and postural activity. Postural control however, depending on task features, may require cognitive resources itself. It becomes more difficult at a higher age and is cognitively more demanding for older people than for younger people (Li, Krampe, & Bondar, 2005). This effect has been cited as a potential explanation for the weak predictability of outdoor falls based on experimental, quiet stance performance (Kelsey et al., 2010; Pajala et al., 2008). It is believed that an outdoor environment and the associated high levels of sensory information require more cognitive processing, which in turn could affect older adults' postural control, specifically those individuals with cognitive impairments (Kang, Quach, Li, & Lipsitz, 2013). In a laboratory setting, dual-task postural experiments have been used extensively to investigate the effects of cognitive demand on postural control and interactions among postural task features, effects on cognitive task performance and age. The dual-task paradigm is used based on one of the aforementioned assumptions which is that postural/sensorimotor control and cognition "compete" for resources of attention that are limited (Huxhold, Li, Schmiedek, & Lindenberger, 2006). In general, attention has to be divided to some extent between posture and cognitive tasks, depending on specific features of the individual and the tasks at hand.

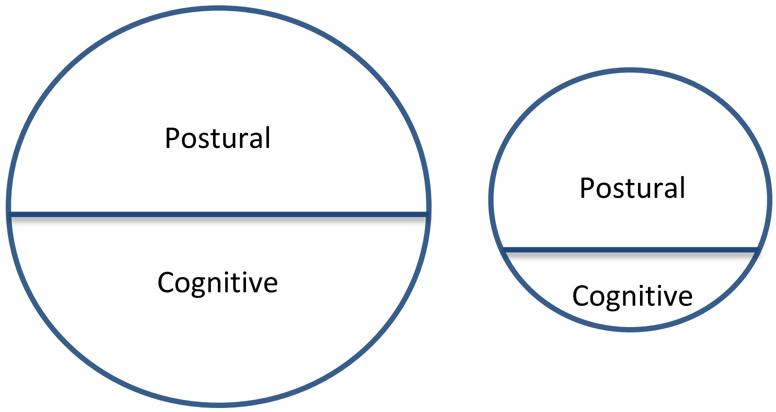


Figure 3: Hypothetical resource allocation in a dual task situation (demanding postural task and secondary cognitive task). Circle size representing available cognitive resources in younger (left) and older adults (right). Segments representing shifting of prioritization towards postural control in older adults. Modified from Krampe et al. (2003)

Healthy adults perform postural control in daily life mostly automatically, without having to think about these well-practiced tasks. In addition, in many instances there is a concurrent cognitive task involved, which rarely poses a problem for processing of either of the two concurrent tasks. Empirical evidence suggests that aging has a significant effect on processing of attention and attention capacity, which is reflected in experimental results showing differences between younger and older participants (Berger & Bernard-Demanze, 2011; Brown & Shumway-Cook, 1999; Olivier, Cuisinier, Vaugoyeau, Nougier, & Assaiante, 2010; Teasdale & Simoneau, 2001). Mainly, aging seems to require more attention for the motor control/postural task at hand, whereas complex secondary tasks lead to increased postural sway compared to younger adults. The specific attention allocation patterns inherent in older adults during sensorimotor/cognitive task processing (Figure 4) are based on the complex morphological and functional effects of aging in humans (Li & Lindenberger, 2002; Li & Dinse, 2002).

On a central processing level, atrophy of the motor cortical areas occurs, at levels of the cerebellum, basal ganglia pathways, the corpus callosum and a decline of neurotransmitter systems (Seidler et al., 2010).The parietal cortex is considered responsible for the generation of a body schema or concept of “body representation in space” (Huxhold 2006). This structure is significantly affected by aging processes, on a neuroanatomical and functional level (Labyt et al., 2003; Tisserand et al., 2004). Overall, there is a major decline in cortical structures limiting cognitive capacity. Related to motor control this, in turn, affects the required attention allocation for motor tasks or postural control (Figure 3).

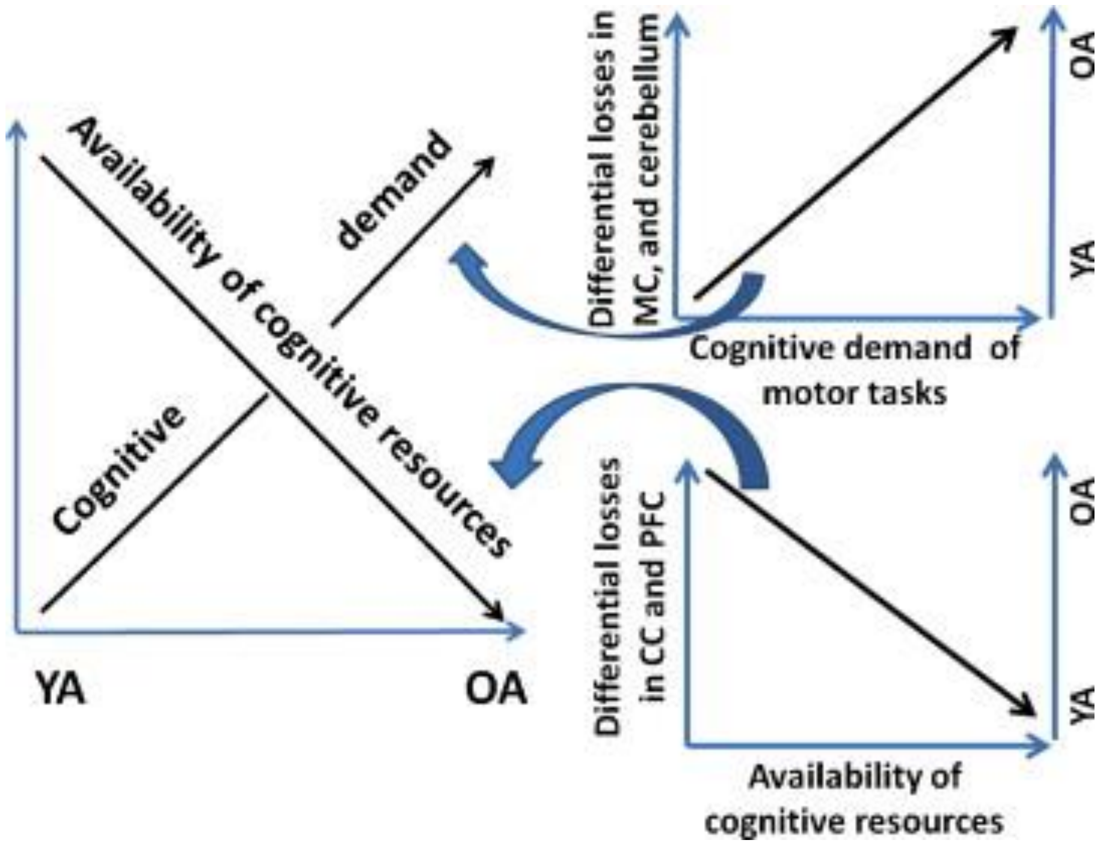


Figure 4: Supply and demand schema of aging related processes and cognitive resource management. Cognitive demand increases during motor control tasks, compared to younger adults, based on aging processes within motor regions of the brain. Prefrontal cortex (PFC) and anterior corpus callosum (CC) declines contribute to the observed effects due to their role in cognitive capacity. Young adults (YA); older adults (OA). Adopted from Seidler et al. 2010

As a second factor that contributes to age-related declines, the degeneration of peripheral sensorimotor structures and their functioning changes in the way older individuals have to process postural control. The investigation of these changes and the underlying mechanisms has been the topic of several dual-task research efforts recently (Lajoie, Teasdale, Bard, & Fleury, 1996; Li & Dinse, 2002). Aging of the sensorimotor systems involved in assuring postural stability are a main contributor to the increased prevalence of balance impairments and associated falls in older adults (Horak et al., 1989; Lacour, Bernard-Demanze, & Dumitrescu, 2008; Woollacott & Shumway-Cook, 1990). One of the reasons for higher attention investment required is the progressive decline in sensory systems (joint position sense, plantar mechanoreceptors, vestibular system, muscle spindle afferents, vision) and impairments in proprioceptive-spinal circuits (Lacour et al. 2008). Mainly, the detection of small fluctuations in postural orientation during upright stance becomes more difficult with increasing age (Berger & Bernard-Demanze, 2011).

2.3.1 Cognitive- and postural task characteristics and effect on dual-task performance

The features of cognitive tasks added to a postural task in order to invest attention requirements is highly dependent on task complexity. It has been shown that simple and easy cognitive tasks added to a simple postural task do not interfere and do not affect postural control negatively in healthy individuals. Although it sounds counterintuitive, simple cognitive tasks can lead to a shift of attention or focus towards the cognitive tasks which in turn can have sway-reducing effects in highly automatized postural tasks. On the other hand, the efficiency of a highly automatized task like quiet stance can be negatively affected when participants are instructed to focus on this process actively (McNevin, Shea, & Wulf, 2003; McNevin & Wulf, 2002; Wulf et al., 2004)

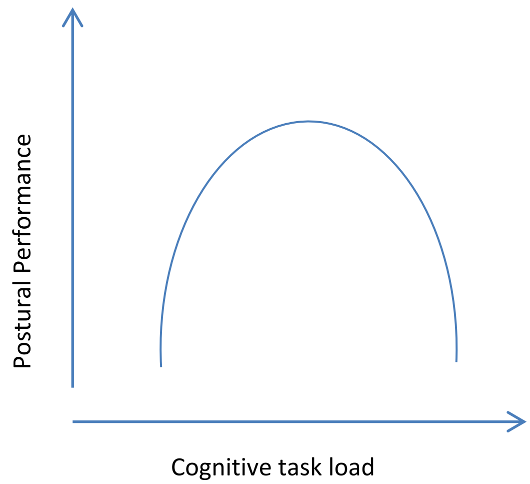


Figure 5: Inverted U-shaped relationship between postural performances in automatized postural tasks and concurrent cognitive task

For more demanding cognitive tasks (e.g. visuo-spatial), balance performance decreases (Andersson, Yardley, & Luxon, 1998). Based on experimental evidence, a theory has been proposed that describes the interaction between postural control and a secondary, cognitive task as a U-shaped curve (Figure 5). This represents a positive or negative effect of cognitive load on postural performance, based on postural and cognitive task features (Huxhold et al., 2006; Lindenberger & Baltes, 1997; Maylor & Wing, 1996; Melzer, Benjuya, & Kaplanski, 2001). A positive effect would be most prominent in simple postural tasks, where a shift of focus away from the task (e.g. trying to stand as quietly as possible) would lead to more automatic postural processing. It is believed that this is not the case for older adults though, since they require more conscious control even in simple postural tasks. A stronger, negative effect is expected in tasks where there is high interference between both tasks and cognitive task and complexity is high (Huxhold et al., 2006; Woollacott & Shumway-Cook, 2002). Older adults require longer periods of time to recover from perturbations of upright stance than younger adults, when a concurrent cognitive task (mental counting of correct addition problems) is added (Stelmach, Zelaznik, & Lowe, 1990). The nature of the cognitive task (and the specific domain of cognition it is associated with, e.g. attention, working memory, problem solving) plays a specific role, as spatial memory and backwards digit calls evoke higher responses in postural control than other secondary tasks, like random digit generation (Maylor & Wing 1996). Overall, there is a higher demand for attention resources during postural tasks in older adults (Maylor, Allison, & Wing, 2001; Shumway-Cook, Woollacott, Kerns, & Baldwin, 1997), which in part is based on an attempt to compensate for the decline of sensorimotor function (Doumas, Smolders, & Krampe, 2008; Krampe, Rapp, Bondar, & Baltes, 2003).

A common phenomenon related to aging and postural control is the prioritized division of attention and concurrent processing in specific task situations. As an example, older adults more often tend to stop walking when initiating a conversation with a walking companion (Lacour et al., 2008). This effect of shifting towards motor prioritization becomes more prominent in demanding-, postural perturbation and balance threat situations. Experimental results support the theory of a “posture-first”-strategy when facing balance threats, describing a focus of attention on the postural task in order to prevent falls in older adults, specifically those prone to falls (Shumway-Cook & Woollacott, 2000). Experiments exposing older adults to postural balance or gait stability threats, like heavy sway, obstacles or sudden change of surface rigidity, showed a significant prioritization of postural control over cognitive processing either independent of aging, or specifically in older adults (Mersmann, Bohm, Bierbaum, Dietrich, & Arampatzis, 2012; Shumway-Cook et al., 1997). Modification of prioritization in specific postural situations can be seen as a “behavioral plasticity mechanism” (Lacour et al. 2008) that is observable in healthy aging and sensory-impairment patients (Lacour, 2006).

One of the compensatory mechanisms (or strategies) related to the aforementioned decline in sensorimotor function has been identified through experiments investigating muscle activity and postural performance in older adults. Increased muscle co-contraction (a stiffness strategy) around the lower legs (ankles) has been shown to be prevalent in older adults in general, and attenuated in dual-task experiments, when older individuals often attempt to “freeze” their lower legs in order to decrease sway during quiet stance (Benjuya, Melzer, & Kaplanski, 2004; Melzer et al., 2001). This strategy might be mainly based on a strategic approach that shifts postural control away from less and less reliable sensory information towards more of a top-down approach, with motor commands independent of afferent feedback (Lacour et al., 2008; Laughton et al., 2003).

There is a large amount of evidence pointing at the significance of aging-related degeneration in central- and peripheral sensorimotor processing and its effects on postural control. This interacts with attention requirements and modified postural strategies in older adults, specifically in dual-task situations. It is possible to modify and improve sensitivity of sensory afferents, which has been shown to assist balance performance in older individuals and patients with neuropathies. However, it is still unclear to what extent this improvement of sensory afferent functioning might assist older individuals in performing postural tasks when additional cognitive processing load is added. No study yet has methodologically investigated whether augmentation of somatosensory feedback does improve dual-task performance in older individuals, or whether this intervention could lead to modifications of postural strategies in dual-task conditions.

2.4 Postural perturbation processing and aging

Establishing a secure upright body position with the center of gravity positioned vertically over the center-of pressure exerted by the feet on the support surface is a complex task. However, in healthy adults, most of the time, this postural control occurs without conscious control. More impressively, re-establishment of postural stability after postural threats (slips, surface rotations, -translations) does not pose an unsolvable task to humans either. Reflexive processes are involved that ensure adequate neuromuscular responses to the perturbation at hand in order to prevent falls. Conscious control is included in control after severe balance perturbance, and in anticipatory adjustments to upcoming perturbations and in learning to optimize the corrective responses that are required. Latash (1998) describes corrective postural reactions as "lines of defense" when facing postural perturbations, whereas different mechanisms are associated with specific response delays. Initially, the first postural line of defense consists of passive mechanisms based on muscle elasticity (-modulation) and anticipation of the perturbation (anticipatory postural adjustments) with no time delay. About 30ms after the initial perturbation, monosynaptic reflexes are observable, and at about 50ms polysynaptic reflexes are initiated. At about 70ms, pre-programmed reactions begin, which consist of sequences of EMG activation patterns in the lower leg. At about 150ms after the perturbation, more conscious, voluntary control and action is initiated.

To investigate postural control mechanisms under conditions that resemble real-life situations, investigators often expose participants to postural perturbances, measuring temporal and spatial characteristics of the subsequent balancing processes. Horak et al. (1997) have summarized that early motor control research has applied this experimental concept of disruption of equilibrium in animals and infants to investigate reflexes or reactions (Sherrington, 1910). Perturbation of the support surface often consist of sudden translation (Norrie, Maki, Staines, & McIlroy, 2002) or rotations around the ankle. The most prominent outcome measures in perturbation experiments are either based on biomechanical effects (kinematics or COP displacement) or trunk- and lower-body EMG characteristics. The generation of torque required to ensure postural stability during perturbation is associated with changes of exerted forces on the support surface via the feet, which leads to changes in COP position. The measured changes can be used to determine the onset of corrective responses and their magnitude (Müller & Redfern, 2004). Postural perturbations evoke muscular activation initiated at the lower leg first and in an ascending manner to more proximal muscles of the thigh and the trunk (Lin & Woollacott, 2005; Nashner, Woollacott, & Tuma, 1979; Nashner, 1977). The generation of responses to postural perturbances is based on anticipation of the perturbation, reflexes, and sensory perception. To generate appropriate corrective responses, it is crucial to determine the magnitude and other characteristics of the perturbation accurately. Subsequently, based on this multisensory integration process, correction strategies are determined and appropriate responses generated. The significance of sensory inputs to response patterns in postural perturbation compensation has been shown through numerous experiments including occlusion of sensory inputs in healthy individuals or in patients with sensory loss (Horak et al., 1990; Inglis, Horak, Shupert, & Jones-Rycewicz, 1994). This idea is supported by the finding that peripheral neuropathy patients feel more unstable during upright stance (Koski, Luukinen, Laippala, & Kivelä, 1998) and are more prone to falls that might have devastating effects (Cavanagh, Derr, Ulbrecht, Maser, & Orchard, 1992).

It is well known that static balance performance declines with aging (Lord, Clark, & Webster, 1991) and this performance decline is mirrored in results from postural perturbation experiments (Nashner 1977). A postural correction delay could be based on numerous factors, like neuropathy-related impaired sensory or motor signal conduction (Inglis et al. 1994), or effects of healthy aging (Stelmach, Teasdale, Di Fabio, & Phillips, 1989). Older individuals are overall less efficient in responding to postural perturbations and associated orchestration of corrective movements. Mansfield & Maki (2009) summarize the research efforts investigating changes of postural mechanisms due to aging, for example after sudden cable-pull and sudden platform translation

(Allum & Honegger, 1998; Beckley, Bloem, Remler, Roos, & Van Dijk, 1991; Brauer, Woollacott, & Shumway-Cook, 2001; Diener & Dichgans, 1988; Horak et al., 1989) or sudden release from a leaning postural position (Hsiao-Wecksler & Robinovitch, 2007). These experiments provide valuable information that is relevant to fall incidents in older adults: It is believed that about 50% of all falls are caused by sudden movements of the base of support (trips, slips) or because of an external perturbation affecting center of mass displacement over the base of support (Horak et al. 1997). Postural response characteristics to sudden platform perturbations have shown to be a significant predictor of future falls (Maki, Holliday, & Topper, 1994).

Whereas a well-functioning sensorimotor system is able to overcome perturbances with rapid, accurate muscular responses, in older adults, this efficiency is reduced. Lin & Woollacoot (2005) summarized that the responses become more inappropriate, insufficient or delayed (Gu, Schultz, Shepard, & Alexander, 1996; Lin, Woollacott, & Jensen, 2004; Stelmach et al., 1989) and it requires more time of older individuals to reverse the direction of the COP displacements as forced by the perturbation (Nakamura, Tsuchida, & Mano, 2001). In addition to the issues of sensory detection and perception in older adults, De Freitas et al. (2010) describe two neuromuscular contributors to the observed age differences, the increased time required in order to generate force production in the muscles, and increased time to reach the peak muscular activation when reacting to a postural perturbation.

2.4.1 The role of tactile sensors in postural perturbation tasks

Balance perturbations require adequate, quick, and efficient neuromuscular responses in order to assist maintenance postural equilibrium. From a sensory perspective, there are several afferent information sources contributing to the process. Vision is used in order to determine shifts of equilibrium, as is information from the vestibular system. Muscle spindle receptors detect changes in muscle length that are based on postural orientation shifts. Also, muscle spindles are part of a spinal reflex system that can have an effect on postural stability when external factors affect upright stance (e.g. when the support surface shifts unexpectedly). Joint receptors detect angle changes (e.g. at the ankle- or knee level) and mechanoreceptors provide useful information about pressure changes on the sole of the feet.

The determination of which sensors are contributing to what extent in such balance perturbance situations has been the topic of many research endeavors. Tactile sensory inputs have shown to be very useful when other sensory entities (vestibular, visual or proprioceptive) have been perturbed or are providing wrongful information (Lackner & DiZio, 2005). A major advantage of efficient tactile feedback is the low response time and subsequent associated postural stabilization mechanisms (about 85ms) that enable re-establishment of postural balance rapidly. Tactile feedback can be, in terms of processing speed, considered superior to the visual system (Rabin, DiZio, & Lackner, 2006). Another significant effect is the potential of tactile information to override other sensory information sources, like the visual or proprioceptive system (Lackner, Rabin, & DiZio, 2000; Rabin, DiZio, Ventura, & Lackner, 2008). Tactile, other than visual information, is processed primarily subconsciously and does require little cognitive effort for processing (Johansson & Westling, 1984).

Mechanoreceptors play a significant role in the process of generating dynamic responses, and increased postural sway and risk of falls is related to plantar surface sensory loss (Bloem, Allum, Carpenter, & Honegger, 2000; Inglis et al., 1994; Meyer, Oddsson, & De Luca, 2004). Stal et al. (2003) suggest that reduced plantar feedback would be a significant factor increasing risk of falls when adults are facing an unpredictable perturbation. Postural control is significantly influenced by even very short delays (about 20ms) of adequate responses (Halická et al., 2012; Marsh & Geel, 2000). This highlights the necessity of rapid, efficient, and reliable detection and transmission from lower-leg afferents for optimal compensation of postural perturbations. Earlier sensory detection is associated with earlier reactions to COP changes, ultimately leading to better postural performance (Priplata et al., 2003). An improvement of postural recovery has been shown when using polyethylene tubes around the plantar surface in an experiment that required of participants to generate a rapid stepping response due to support surface perturbations (Hijmans, Geertzen, Dijkstra, & Postema, 2007; Pyykkö, Jäntti, & Aalto, 1990). This indicates that enhancement of tactile information stemming from the feet could be beneficial in balance threatening situations.

2.4.2 Postural strategies

As humans are exposed to balance threats, there are several strategies associated in order to compensate for the perturbation and to re-establish secure upright stance. It has been shown that, based on external constraints and internal features of the individual, there are two main strategies when being exposed to sudden support surface translations (Nashner & McCollum, 1985). Comparable to postural strategies in other tasks, there is one ankle based strategy, which represents a bottom-up mechanism that strongly depends on sensory feedback from the legs and feet. This strategy applies the principle of an inverted pendulum. It is characterized by increased muscle activity around the lower legs compared to hip muscle activation. An alternative hip strategy represents a top-down approach that involves more muscle activity around the thighs (quadriceps femoris) and core muscles (e.g. abdominal muscles). Depending on task requirements and external characteristics (e.g. support surface features), healthy individuals is able to shift from either of the two postural strategies to another. However, older individuals tend to rely on a hip strategy approach more than younger adults, which overall seems to be due to a prioritization of prevention of falls over other aspects to consider: The ankle strategy is overall less energy-demanding than the hip strategy, but it seems to be more effective for prevention of falls, when sensory systems have declined. This assumption has been supported by evidence showing that patients with vestibular impairments tend to shift towards a hip strategy (Horak et al. 1990). Input from afferents of the foot and the ankle are required for adequate generation of corrective torque to compensate for balance threats. In case of potential neuropathies or sensory decline due to aging, these corrective processes are transferred to neuromuscular activation processes around the hip.

It is unclear whether changes of sensory reliability or sensitivity affect strategy changes in older adults. No study so far has investigated the effects of tactile sensory modification via sub-threshold vibration in a balance threat-task. It is unknown to what extent spatial (e.g. COP excursion) or temporal aspects (onset of corrective responses) are affected by provision of augmented somatosensory feedback.

2.5 Countermeasures for loss of receptor sensitivity and sensory functioning

The following section focuses on the current state of knowledge and scientific developments regarding potential enhancement of sensory information detection, signal transmission/conduction, mostly in regards to tactile receptors of the feet and the principle of SR.

One of the most common techniques to improve sensory function at the sole of the foot is modification of footwear, whereas several proprioceptive channels (muscle spindles and tactile receptors of the foot) can be affected via specifically designed shoes or sandals (Hijmans et al., 2007). One potential countermeasure to sensory decline is the use of compression shoes that may improve postural control due to afferent feedback improvements regarding foot and ankle position sensing (Hijmans & Geertzen, 2008). It has been established that soft soles, comparable to soft surfaces, make detection of pressure sensor information from the feet more difficult, and therefore have a diminishing effect on balance in older adults (Robbins, Gouw, & McClaran, 1992). Firm insoles or integrated tubing improve sensory feedback from the feet (Hijmans et al. 2008) and plantar stimulation via mechanical rotators over longer periods of time (10 minutes) has been shown to lead to improved performance in a subsequent postural task in older adults with reported loss of plantar sensitivity (Bernard-Demanze, Vuillerme, Berger, & Rougier, 2006). Palled et al. (2009) showed that postural sway could be reduced in older adults when wearing sandals with rubber nodules, thereby increasing cutaneous receptor information flow. Comparable results have been provided by experiments including the use of textured insoles or textured support-surfaces, where postural performance improvements were observed in younger (Corbin, Hart, McKeon, Ingersoll, & Hertel, 2007) and older adults (Hatton, Dixon, Rome, & Martin, 2011).

A more sophisticated intervention is the design of insoles that augment sensory processing by allowing direct modification of sensory detection mechanisms. A potential technique is the use of SR effects to enhance sensory detection from the soles of the feet.

2.5.1 Stochastic resonance

(SR) describes an effect whose foundation is based on the concept of "positive noise" for improvements of the sensorimotor system during human movement or posture. It is, at its core, related to the concept of internal and external noise, which is present, to varying extents, in all biological systems. Noise is a variability in measurable outcomes, which leads to discrepancies when measurements are repeated or when the actual outcome is to some extent affected by the inherent noise of the system. Just as in most cases in engineering, a total diminution of noise is virtually impossible in biological systems; a "healthy balance" between the pure signal and noise has to be maintained to ensure proper functioning. Noise does not necessarily have to be a disruptive factor for performance and function of a complex biological system as is the human body. The following chapter highlights the main ideas of the concept of SR and its potential for improvement of neuromotor processing in humans.

The negative connotation of noise in systems has been replaced to some extent in several fields of science, in favor of a view that declares noise and its deliberate application a potent tool for augmentation, modification, and improvement of system characteristics and processes. Extensive research has been conducted to determine the benefits and limitations in different scientific areas, specifically in the biomedical research field. Some researchers are still dubious about the overarching idea that inducing noise into a system could lead to potentially positive changes; therefore, sometimes the alternative term "induced variability" is used instead. It is crucial to highlight the importance of non-linearity in the concept of SR, since noise cannot be an improving factor in a linear-system, as often found in engineering concepts. However, stochastic noise is ubiquitous in biological-, specifically neural systems (Faisal, Selen, & Wolpert, 2008; M. McDonnell & Ward, 2011). The following conceptual equation summarizes the idea of stochastic resonance for biological system functioning:

Performance (noise+nonlinearity)>performance(nonlinearity) (McDonnell & Abbott, 2009)

We define the above concept in biological systems as a mechanism beneficial in signal-processing, whereas McDonnell & Ward (2011) suggest use of the term “stochastic facilitation”, which is a based on observations showing that a “proposed computational goal is better achieved in the presence of random fluctuations originating from stochastic biologically relevant noise than in their absence”. The most important feature is that an output signal becomes a better representation of the input signal when noise is added, in comparison to when there is no additional noise (McDonnell & Abbott, 2009). A maximization of effects requires appropriate noise amplitudes induced into the system; too little noise does evoke only smaller or no effects, whereas too much induced noise diminishes the potentially positive effects as well (Figure 6).

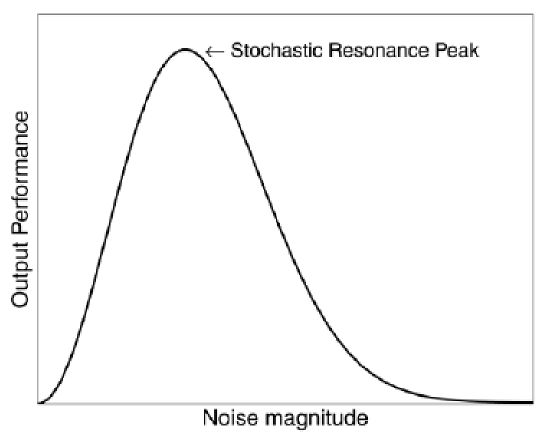


Figure 6: Effects of noise magnitude on output performance. Peak performance is achieved at optimal noise levels, maximizing stochastic resonance effects (McDonnell & Abbott 2009)

The complex neural systems and their interactions within living creatures have been one of the major targets of research, aiming at determining how SR could lead to changes within neural processing and potential improvements. Several groundbreaking experiments related to neural (sensory) processing, like the investigation of SR mechanisms in the mechanoreceptors of crayfish (Douglass, Wilkens, Pantazelou, & Moss, 1993) and cercal systems of crickets (Levin & Miller, 1996), lead the way towards investigations of human sensory systems, including scientific work investigating potential benefits on motor performance enhancement or postural improvements.

2.5.2 SR application in central and peripheral processing

Manjarrez and colleagues (2002) were the first to investigate the effects of SR on electroencephalographic (EEG) activity when mechanoreceptors were stimulated. The authors showed that EEG responses to tactile stimuli in the somatosensory cortex were improved when certain levels of noise were induced. More specifically, the signal-to-noise ratio (SNR) of the response when stimulating the skin resembled an inverted U-like function. There was an optimal noise magnitude level at which SNR peaked, underlining the importance of noise parameter adjustment to maximize potential positive effects. Another important finding was that SR seems to not only exist at a peripheral level (sensory neurons), but can also act on central processing centers. This finding was confirmed by other studies highlighting the potential of SR for higher-center processing optimization (Aihara, Kitajo, Nozaki, & Yamamoto, 2010; Kitajo et al., 2007).

More recently, investigators have aimed at using the principle of SR in a variety of different somatosensory sources with the ultimate goal to improve motor/balance performance (Figure 7). One of the most remarkable approaches is the induction of noise at the vestibular level to improve spatial orientation and perception of body verticality (Mulavara et al., 2011). The authors of the cited study found that appropriate levels of vestibular electrical noise stimulation could lead to significant postural improvements in healthy adults. In another study, electrical stimulation at the knee level in combination with a knee sleeve was shown to be beneficial for joint position sense in healthy adults and osteoarthritis patients (Collins, Blackburn, Olcott, Yu, & Weinhold, 2011; Collins et al., 2009). It should be noted that in all studies investigating benefits of SR, the induced noise levels are below a perceivable intensity. Participants did not consciously feel the stimulus as it is was generated.

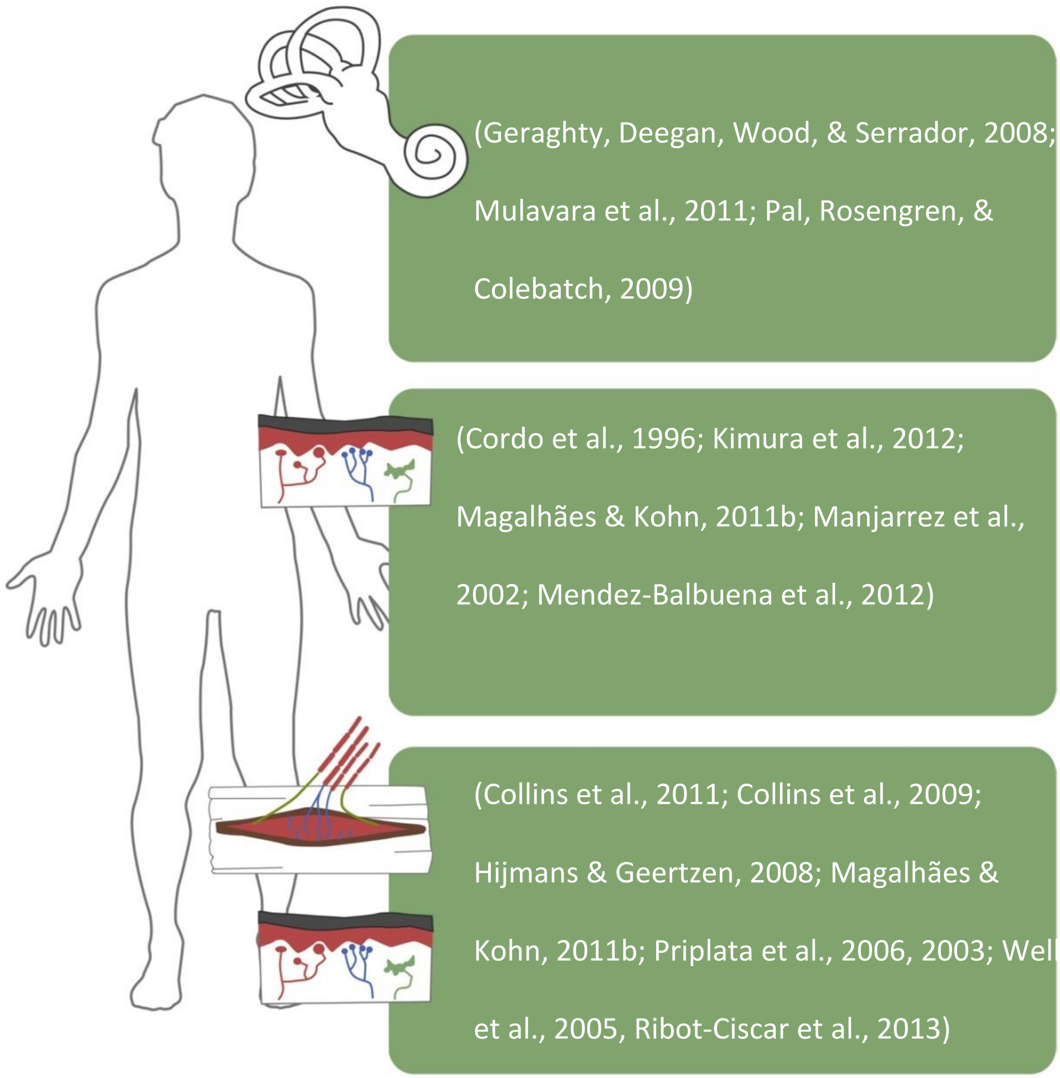


Figure 7: Selected studies of stochastic noise induction into sensory systems (vestibular system, joint receptors, tactile receptors, muscle spindles)

Tactile sensory afferent modification has been the major topic of several investigations with the specific aim of improving sensory (integration) processing: Mendez-Balbuena et al. (2012) found that sub-threshold vibration noise applied to the fingertip could assist participants' performance when compensating for a static force generated by a manipulandum in a sensorimotor task. The authors concluded that stochastic resonance lead to improvements in receptor sensitivity, but also to better "corticomuscular synchronization" as a representation of sensorimotor integration processes, which in turn has been associated with better motor performance (Baker, 2007).

Tactile cues from finger mechanoreceptors can assist in improving postural stability, as evidenced by postural sway declines when participants maintain light finger touch with a static surface (Bolton, McIlroy, & Staines, 2011; Johannsen, Wing, & Hatzitaki, 2007; Wing, Johannsen, & Endo, 2011). This knowledge and the addition of vibration noise was the topic of a recent series of experiments. In a study published by Magalhaes and Kohn (2011), healthy participants were asked to maintain light finger touch contact to a vertical surface while trying to stand as quiet as possible with their eyes closed. One major observation was that several postural sway measurements were affected significantly when sub-threshold vibration noise was added to the touch surface compared to the simple, light-touch condition. These results were confirmed in a comparable experiment that showed significant (anterior-posterior and medio-lateral) COP mean velocity decreases when vibration was added to the fingertip (Kimura, Kouzaki, Masani, & Moritani, 2012). The results are supportive of ideas to design assistive devices (e.g. canes or walkers) that would use principles of low level noise and stochastic resonance to improve patients' balance.

2.5.3 Postural control and foot sole receptor SR

One general assumption for utilization of noise-induction for biomedical purposes is that SR benefits sensory receptors' signal detection and -processing in order to ultimately improve (motor) output. With an appropriate level of noise added to the sensory signal, signals can be detected more easily, since action potential thresholds are reached more rapidly and reach threshold levels, whereas without the noise addition, external signals remain at sub-threshold levels and remain undetected (see Figure 8).

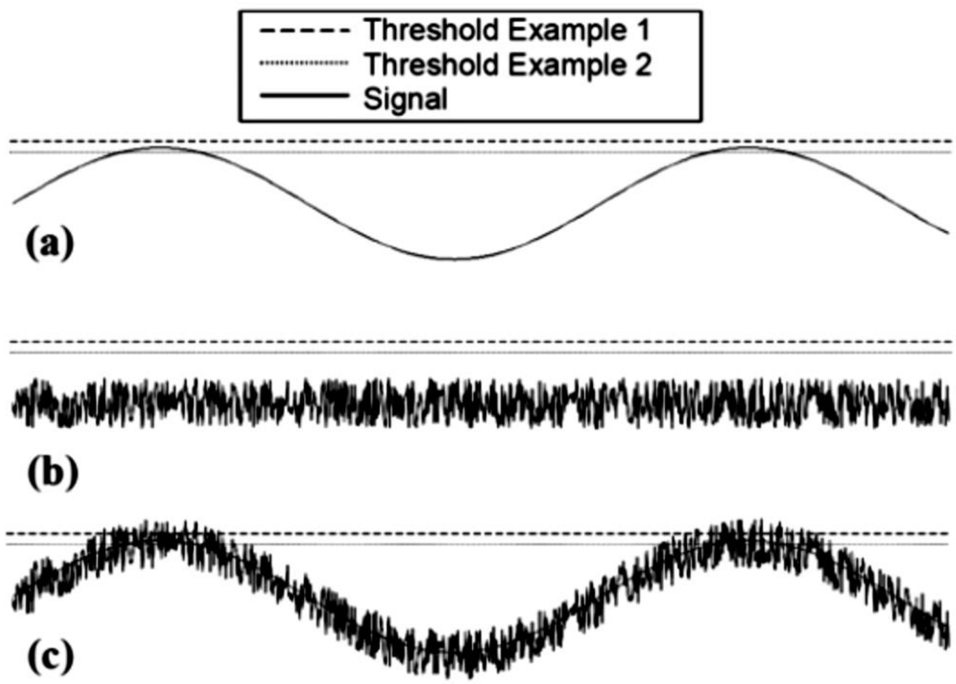


Figure 8: Stochastic resonance. (a) Sinusoid signal (solid line) with two examples of threshold (dashed line which is not reached and dotted line which is reached). (b) Noise signal below both examples of thresholds. (c) Mechanism of stochastic resonance. When the noise signal is added to the sinusoid signal, two important phenomena are noticed: (1) signal reaches threshold example 1 (dashed line), which is not reached under normal circumstances, and (2) signal reaches threshold example 2 (dotted line) earlier than under normal circumstances. Figure adopted from Hijmans et al. 2008

A number of studies reported positive results when applying low level vibration noise at the feet. Priplata et al. (2002) applied sub-threshold vibration to the plantar surface of the feet to improve signal processing of pressure information emerging from the soles during quiet, unperturbed stance with occluded vision. The authors showed that there are benefits for improving postural sway characteristics, and those benefits are more prominent in older than in younger adults (Priplata et al., 2003). This is thought to be mainly due to the degenerative effects of aging on sensory signal detection and –processing, highlighting the potential role of SR for improving balance of those mostly affected by neuromotor issues. The findings were confirmed when SR in mechanoreceptors was investigated in subsequent studies. Stroke- and diabetic neuropathy patients were able to improve their postural performance when adequate foot sole vibration noise was added (Priplata et al., 2006). Remarkably, among those individuals with the lowest baseline postural performance, the addition of noise had the greatest effect. This lead to the authors' conclusion that sensory enhancements via SR could be potent for improving balance in individuals who are at the highest risk for loss of balance and falls.

The effects of SR in the tactile receptors of the foot sole are not limited to postural sway characteristics. Other control characteristics of postural balance are influenced as well, as evidenced by increases in complexity of sway in older fallers (Costa et al., 2007). Since pathological states are associated with a loss of dynamical complexity, the authors conclude that foot stimulation might represent a powerful tool to modify internal motor control mechanisms for posture, specifically for neuromotor-impaired individuals.

In order to determine whether SR could be beneficial in more dynamic tasks, Galica and colleagues (2009) investigated the effects of SR on gait variability in older recurrent fallers, compared to non-fallers and a young control group. The use of vibrating insoles for enhanced signal-processing had a significant effect on reducing stride, stance, and swing time variability measures in older fallers, whereas older-non fallers' stride and stance time variability was reduced. The investigators concluded that SR foot sole stimulation affects signal-processing and motor control characteristics, specifically in older fallers. However, further research is required to determine if overall risk for falls could be affected by this.

The existing work in the area of stochastic resonance effects on postural control in older adults has been mostly limited to fairly static and simple tasks (quiet stance). In order to determine the efficacy of the proposed intervention for improving postural control in those at greatest risk for falls, it is necessary to evaluate if the known effects are also observable in tasks requiring more complex control, like in an environment providing conflicting sensory information, requiring concurrent processing of cognitive information or in situations in which individuals are exposed to sudden disturbances of balance. There is a gap of knowledge concerning the potential efficiency of tactile SR to assist individuals in more "life-like" situations that have detrimental effects on balance. The experiments designed for this dissertation aim at a better understanding of the potential effects of SR foot sole sensory feedback enhancement in certain postural tasks and the potential of sensory augmentation to improve balance in an aging population.

III. Methods

This study was conducted according to University of Houston policies concerning the protection of participants in human research. The protocol was approved by the University of Houston Committee for the Protection of Human Subjects (CPHS). All participants in the study signed an informed consent form before participation.

3.1 Participants

There were two groups recruited for this study, one healthy younger control group, and one older experimental group (10 participants per group). Younger participants were recruited from the University of Houston Campus and the Texas Medical Center (TMC) via flyers (Appendix E). Flyers were posted at the UH Health and Human Performance Department (HHP). Older participants were recruited by word of mouth and from retirement homes around TMC. Electronic versions of the recruitment flyer were posted on HHP and Center for Neuromotor and Biomechanics Research (CNBR) websites.

3.1.1 Inclusion criteria

To be included in the study, prospective participants had to be free of any significant medical conditions, which included both physical and cognitive impairments. Age range for inclusion in the study was 20-35 years for the younger age group and 70-85 years of age for the older age group. The age range for the older adults group was based on existing knowledge about the onset of sensory decline and associated higher risk for falls. It has been shown that there is an age-related acceleration of sensory decline around the age of 70 (Perry, 2006), therefore this age was chosen as the lower limit for inclusion.

Physical health and inclusion in the study were determined based on a modified version of the Physical Activity Readiness Questionnaire (see Appendix D). Answers to the PAR-Q were analyzed to determine whether participants could be included in the study, which was only if they answered either “no” to all question items (or reported health concerns that did not put them at any risk during the experimental trials and or could have affected postural performance) and reported to be in overall good health. If they reported current use of medication we further evaluated whether the medication would or would not interfere with postural performance. Due to the nature of the experiments, only individuals without cognitive impairments, as represented by a score of 27 or higher on the Mini-Mental State Examination (MMSE; Folstein, Folstein, & McHugh, 1975)– were included in the study (see Appendix C). An initial sensory detection test (for details see 3.3.2.1) was administered to ensure that older adults displayed an increased sensory threshold (touch/pressure threshold). Only those individuals displaying an increased threshold (compared to the younger group) were included in the study.

3.1.2 Exclusion criteria

Participants were excluded if they reported significant physiological problems based on question items on the modified PAR-Q. This included but was not limited to general health problems or severe sensorimotor impairments (e.g. neuropathies, chest pain upon exertion, dyspnea, infection, and functionally significant musculoskeletal dysfunction. Additionally, reports of Parkinson's disease, Multiple Sclerosis, and Traumatic brain injury would dictate exclusion from the study). Further exclusion criteria were: use of a walking aid (cane or crutch), reporting a history of fainting, reports of severe visual impairment, diagnosed with ADHD (Attention Deficit Hyperactivity Disorder), having taken medication prescribed for dizziness (e.g. Scopolamine and Valium) within one week of the experimental session, having taken medication that may cause drowsiness within 48 hours of the experimental session such as prescription pain medications, tranquilizers, sleeping pills, and antihistamines (e.g., Benadryl and Antivert). Due to the potential effects of obesity on postural stability, detection of tactile stimuli and suppression of the generated vibration from the C-2 tactors, individuals with a body mass index (BMI) > 30 kg/m^2 (BMI = 703 x weight (lb.) / $(\text{height (in)})^2$) had to be excluded.

3.2 Settings

The three experiments of the study were conducted at the University of Houston Center for Neuromotor and Biomechanics Research (CNBR), as part of The National Center for Human Performance, located at the Texas Medical Center on the McGovern Campus, Houston.

3.3 Apparatus and Procedures

3.3.1 Apparatus

3.3.1.1 Mechanical vibration of the foot sole

Vibrotactile stimulation of the foot sole was administered via vibrating chips embedded into a custom-made foam sole: Three vibration stimulators (C-2; Engineering Acoustics, FL) were integrated into a custom-made silicone rubber sole with a hardness of Shore 50A, a hardness that has been recommended elsewhere (Hijmans et al. 2007). There were three specific locations for the tactors under the feet, for exposing cutaneous afferents to tactile stimuli (Figure 9).

Figure 9: Position of tactors under the sole of the foot (1st and 5th Metatarsal-phalangeal joint region and heel)

The C-2 tactors that were embedded in the rubber sole are moving magnet motor devices with a diameter of 30.5mm, a height (in actuation direction) of 7.9mm and maximum displacement amplitude of about 0.635mm (Hijmans et al. 2007). The use of C-2 tactors as actuators has been established via foot sole stimulation experiments that exposed participants to low-level vibration noise (Priplata et al. 2002, 2003). Other authors suggested the use of C-2 tactors based on their dimensions, the possible frequency range that is available, and the range of amplitudes (Hijmans et al. 2007). All six tactors were connected to a control box including amplifiers, a memory bank for storing sequences of stimuli and the power supply (battery). The control box was connected to a PC via a USB connector. Custom-designed software was used to generate pseudo-random white noise vibration. For the current experiments, a white-noise signal was added to a generated sinusoidal signal band-limited to 1Hz to about 500Hz, thereby including vibration frequencies that encompass the response bandwidth of mechanoreceptors of the foot sole. The noise signal generated by this custom control script is comparable to the features of the noise-generation module that is part of the firmware provided with the tactor controller (see Figure 10).

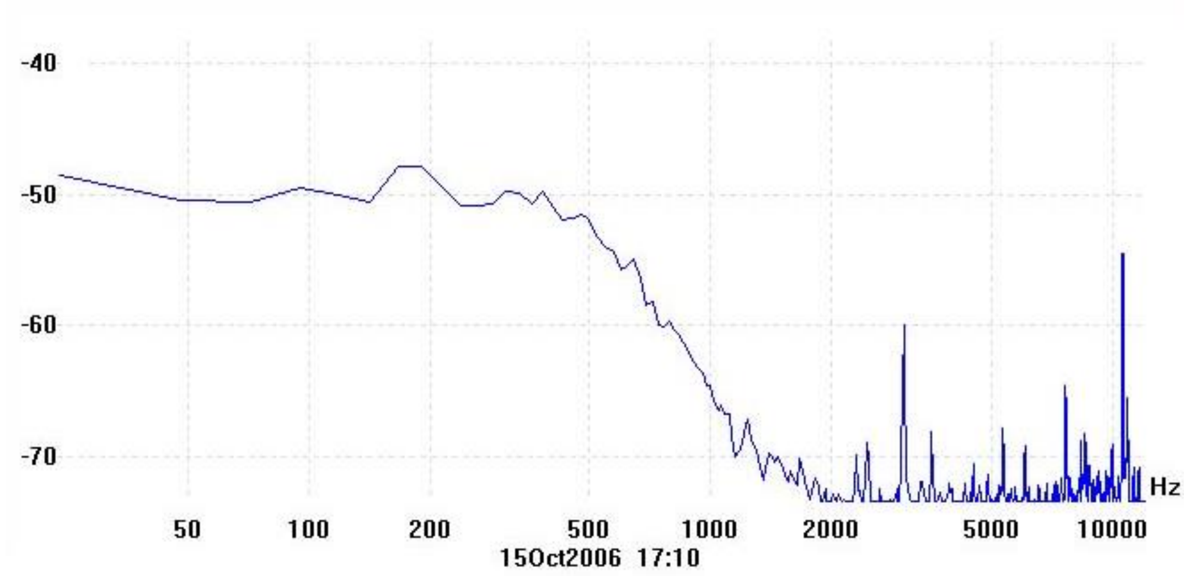


Figure 10: Power spectral density of white noise-generated by the C-2 tactors control module (figure provided by Engineering Acoustics Inc., FL)

The amplifiers for the specific tactors are based on audio amplifiers and are voltage devices. Magnitude of vibration stimuli (gain) are expressed in terms of voltage. The drive current is approximately 300mA (rms) at the highest gain (which is 4). The current can then be modified/reduced by the manipulating gain/voltage. In addition to the gain integer, an attenuation parameter (1-63) can be set that scales the gain between global levels (1-4). Therefore, the generated amplitude is based on two parameters: the global integer (1-4) and then a number 1-63 for the attenuation between global integers. Customized software was created to allow the investigators to manipulate stimulus magnitude as required using a guided user interface displaying magnitude of stimulus as % of maximum vibration output (see section 3.3.2.2).

3.3.1.2 Force data collection

Center-of-pressure data was computed based on force data acquired using a force plate system (NeuroCom EquiTest, NeuroCom Intl, Clackamas OR). The device consists of a dynamic 18" x 18" dual force plate and provides both rotation (±10^o from center, either toes-up or toes-down, maximum velocity of 50^o/s and translation capabilities (±6.35 cm from center, maximum of 12.7 cm in the forward-backward direction, maximum velocity: 20 cm/s). A visual surround can be programmed to move independently of the force plates via servomotors (±10^o from center, maximum velocity of 15^o/s). This allows for a type of postural investigation called computerized dynamic posturography (CDP). The NeuroCom system measures forces exerted by participants' feet while providing a safety harness to prevent falls in participants (see Figure 11). The NeuroCom system measurement device has been used in a wide variety of clinical and scientific studies related to postural control (Cavanaugh et al., 2007; Turnock & Layne, 2010; Wrisley et al., 2007). Force plate data was collected at 100Hz and processed via Windows-based software on a connected computer (Research module, NeuroCom software version 8.0, NeuroCom Intl. Clackamas, OR).

Figure 11: NeuroCom EquiTest system. From:

http://www.onbalance.com/images/photo-balanceBox.jpg

3.3.2 Procedures

3.3.2.1 Foot sensitivity testing

Sensory thresholds are elevated in most older adults, due to physiological and anatomical changes based on the effects of aging (Kenshalo, 1986; Perry, 2006). To determine whether potential participants should be included in the study, it was evaluated whether they actually displayed a decrease of tactile sensitivity. At the beginning of the experimental session, individuals were asked to remove shoes and socks and to sit in a chair. We applied a tactile sensation via a Semmes-Weinstein Monofilament (5.07/10G). The test was administered according to instructions provided with the Monofilaments and was based on a forced-choice method. The test locations were the first metatarsal of both feet. Four trials were performed on each foot. Older adults were included if their exhibited sensory impairments as indicated by an inability to feel the stimulus on either of the two toes in more than three out of four trials on each foot (Manor et al., 2012).

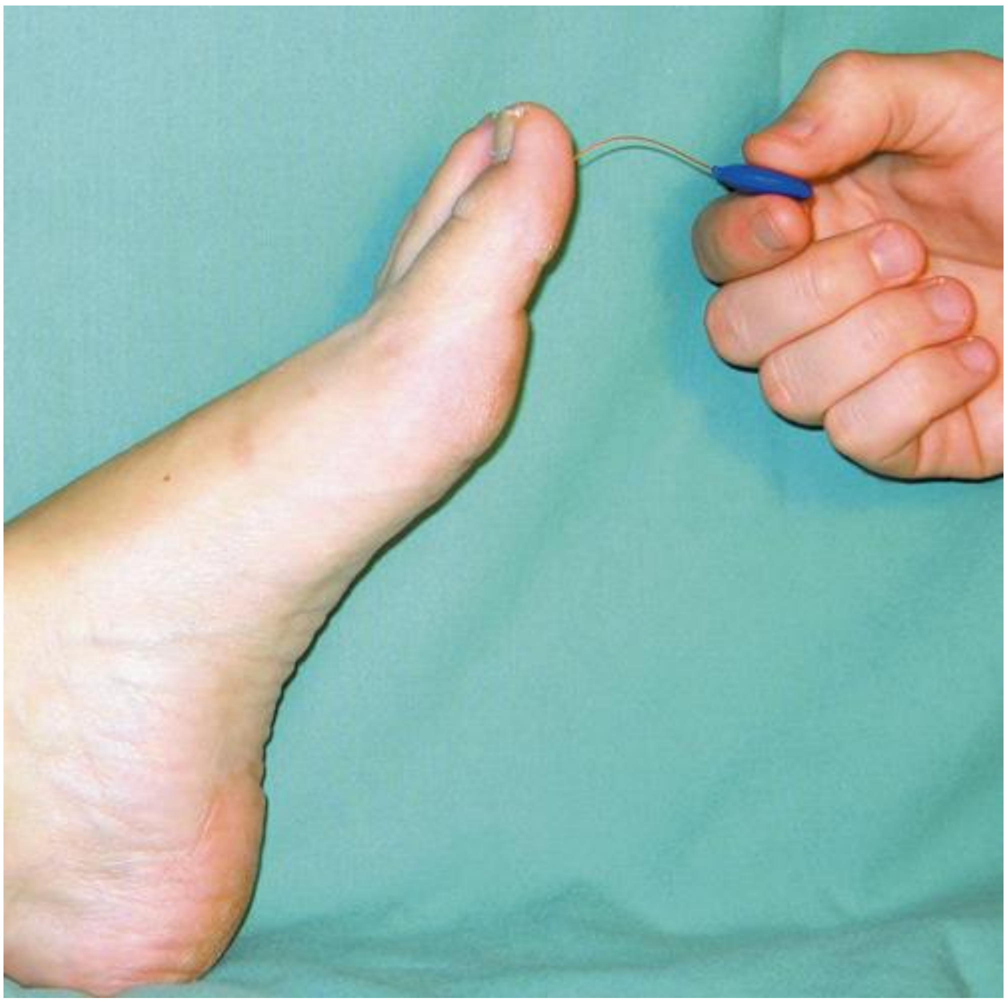


Figure 12: Semmes-Weinstein Monofilament testing for tactile sensitivity.

3.3.2.2 Stimulator fitting, familiarization

All participants of the study were accustomed to the rubber soles, which were custom-fitted to ensure positioning of the tactors at the foot positions described earlier (Figure 9). Participants were asked about their shoe size prior to data collection. Based on this information, the tactor sole was modified to fit the participant's foot (using silicone parts that could be inserted in the mid-foot section of the sole, to increase or decrease size. Participants were seated comfortably with their feet planted on the tactor surface. The necessity for potential adjustments was then determined via visual inspection by the principal investigator to ensure an optimal fit.

3.3.2.3 Sensory threshold evaluation

The sensitivity to vibrotactile stimuli to the foot sole plays a crucial role in postural control (Ushio et al., 2008) and for the proposed experiments, accurate and precise determination of vibrotactile sensory thresholds of participants was considered highly important due to several factors. First, the evaluation provided information about sensitivity differences between the younger and older group, also, it helped to identify interindividual differences. Secondly, evaluation allowed the determination of the experimental stimulus magnitude/amplitude (approximately 90% of sensory threshold intensity). A stimulus intensity level of 90% has been shown to be effective to elicit the desired effects of sub-threshold vibration and has been used in previous studies that have included sub-threshold vibration noise to the feet (Hijmans & Geertzen, 2008; Priplata et al., 2006; Priplata et al., 2002).

To determine the 90% threshold level, participants were asked to stand on the rubber sole containing the tactors. Vibration stimuli of about 5s duration were presented at intervals of several seconds. The threshold was determined by a "method of levels" (Shy et al., 2003) binary search method. Participants were asked to indicate when they could feel the vibration under the sole of the foot ("forced choice"). A large stimulus was provided (one that is detectable) followed by an undetectable one. The next stimulus magnitude was calculated based on the midpoint of the first two. If a participant was able to detect this new stimulus, the next stimulus was based on the midpoint between the former, undetected stimulus and this detected level. The final threshold was then evaluated based on a predetermined range between undetected and detected stimulus (Perry, 2006). Figure 13 summarizes the threshold evaluation protocol.

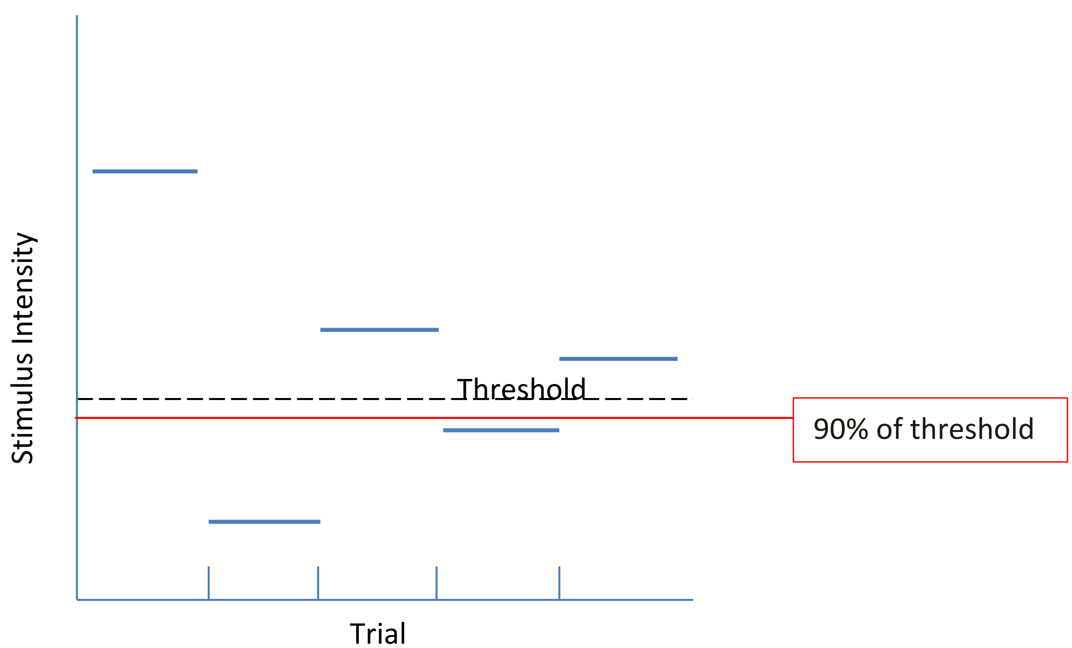


Figure 13: Stimulus threshold evaluation. Stimulus is applied initially at high (detectable) and low (undetectable) intensity. Participant indicates whether vibration can be felt ("yes" or "no"). Subsequent stimuli are applied at midpoint between former stimuli.

3.3.2.3 Experiment #1

The aim of this experiment was to investigate the effects of tactile augmentation via stochastic resonance in a postural control task that introduces a sensory conflict. Participants stood on the vibrating soles, placed on top of the force plate of the NeuroCom. Foot position was determined by the NeuroCom system and was based on the participant's height. Once the feet were in place, the investigator used a tape measure to determine the distance from heel to toe, as needed for later calculation of the hypothetical distance-to-boundary. A harness was attached in order to secure participants in case of a fall. As in the other two following experiments, participants wore over-the-ear headphones (providing white noise sound) during experimental trials to cancel noise generated by the NeuroCom parts that move during experimental trials (visual surrounding or shifting force plate). Participants stood on the force plate for six consecutive 20s trials, with 30s breaks between each trial. Vibration condition was randomized across participants into blocks of three trials. That is, three consecutive trials either with or without vibration. The surrounding visual environment of the NeuroCom was sway-referenced, so it rotated according to the postural sway of the participant. Since the surround rotates according to the participants' sway, vision was no longer a reliable determinant of postural orientation since it tilted in phase with the individual. At the beginning of each trial, participants were instructed to:

"Stand quietly for the next twenty seconds", “Your visual environment will move”

“If you feel as if you are losing your balance, please take a step

Participants were given an auditory “Go”-signal indicating the start of the trial.

After a block of three trials, there was a two-minute resting period, during which participants were asked to sit in a chair.

3.3.2.4 Experiment #2

In Experiment 2 investigated the effects of augmentation of tactile sensory information in a dual-task environment. Participants were asked to perform an “n-back” mental task. During each 20s trial, participants were presented with a series of words via headphones (first word was presented at beginning of each trial, each subsequent word was presented in intervals of 4 seconds). Participants were asked to repeat the word that was presented before the current one (1-back task). After a short familiarization to the cognitive task, there were six trials of 20s with 30s breaks between trials, and a two-minute break between blocks of trials (one block with vibration, one block without vibration). Sub-threshold noise was provided to the feet according to randomization as conducted in experiment 1. Participants were instructed to:

“Stand quietly for the next 20s”

“Starting with the “go” signal, remember the presented word and repeat the respective word as soon as the next one is presented”.

“Try to react quickly and to speak clearly”

“If you feel you are losing your balance, please take a step”

Custom-designed software based on speech recognition was used to evaluate response time. After a block of three trials, there was a two-minute resting period, during which participants were asked to sit in a chair.

3.3.2.5 Experiment #3

Experiment 3 was designed to investigate the effects of sensory augmentation of foot sole afferents on balance performance in a postural perturbance task. Participants stood on the rubber sole containing the vibrating tactor elements. The support surface moved (translation of support surface) in posterior direction for three consecutive times with a small displacement (familiarization trials). During these initial trials, participants were familiarized with the sensation of the translating platform. The next 10 trials were the experimental trials in blocks of five trials with stimulation either turned on or off (order of blocks randomized). The trials consisted of customized translations (400ms duration) with amplitude matched to the participants’ height, to elicit a sway equivalent of about 3.2 degrees. The amplitude of displacement (in inches) was calculated and generated by the NeuroCom system using the equation:

$$2.25 * (height/72),$$

which is the standard for the clinically established Motor Control Test (Neurocom, 2009).

There was a break of two minutes between the two blocks and participants were instructed to:

“Stand quietly during the trials”

“The surface you are standing on will move under you, try to maintain balance”

“If you feel that you are about to fall, please take a step”

3.4 OUTCOME MEASURES AND DATA ANALYSES

3.4.1 Data Reduction

All outcome measures (except for verbal responses in experiment #2) were calculated from measurements recorded via the force plate during experimental trials. An additional outcome measure was the recording of data from the secondary, cognitive task in experiment 2. Computation of outcome measures was performed using custom-developed Matlab v. 7.9.529 (The Mathworks Inc., Natick, MA) analysis scripts. The primary outcome measures were: Equilibrium Score (ES), integrated area of TTB (iTTB) below an arbitrary 10s threshold, anterior-posterior way path length (APPlength), approximate entropy (ApEn), maximum Center-of-pressure excursion, response latency, strategy score and cognitive performance (error rate and reaction time). Outcome measures were averaged for each subject over one block of trials (vibration on or vibration off). Statistical analyses of outcome measures were performed using SPSS v. 20 (IBM Corp., Somers, NY).

3.4.1.1 Equilibrium Score (ES)

ES was generated from force plate data of each trial (20 seconds @ 100Hz, 2000 data points) via NeuroCom 8.0 software (NeuroCom, Clackamas, OR). An ES was computed for each trial using the following equation:

$$ES = \frac{12.5-[\theta_{max}-\theta_{min}]}{12.5} * 100 \qquad ,$$

where the angular difference between calculated maximum anterior-posterior COG displacements (θ_{max} and $\theta_{\min}$) and a theoretical maximum were compared. 12.5 degrees are usually considered the theoretical limits of stability for healthy individuals. The result is provided as an inverse percentage of 0-100 (NeuroCom 2001). No movement results in an ES of 100, whereas a fall results in a score of 0. This clinically accepted outcome measure has been used extensively in motor control research (Cavanaugh et al., 2007; Turnock & Layne, 2010; Wrisley et al., 2007). Computation of the ES allows for comparison of an experimental group with a large existing database of healthy populations of different age groups. There are several limitations to the use of ES. The score is based on assumptions about the theoretical limits of stability for certain heights and for certain age groups, however, in reality, these limits might deviate in a group significantly. The formula also disregards biomechanical factors like mass of the subject or generated ankle torque and should potentially supplemented by other postural outcome measures (Chaudhry, Bukiet, Ji, & Findley, 2011).

3.4.1.2 Integrated Time to boundary (iTTB)

Time-to-boundary (TTB) analysis is valuable for postural control studies, since it incorporates velocity of the COP as a factor. Whereas ES is based on theoretical limits of stability and the maximal excursion towards those limits, TTB evaluates the speed of the COP approaching certain stability limits. This allows investigators to make conclusions about dynamic stability during postural tasks.

For this computation, force plate data (100Hz) was used to generate COP time series of both antero-posterior and lateral direction. Associated Center-of-mass (COM) locations were estimated via low-pass filtering (second order Butterworth; fc=0.86Hz) the COP data, a method that has been described elsewhere (Black & Nashner, 1984; Doumas & Krampe, 2010; Hasan et al., 1996). Velocity of COM in anterior-posterior direction was then calculated based on earlier work (Ozdemir et al., 2013). Stability boundaries in the anterior-posterior direction were estimated based on the outer limits of a rectangle involving the foot support base and the initial foot length measurements (see Figure 14).

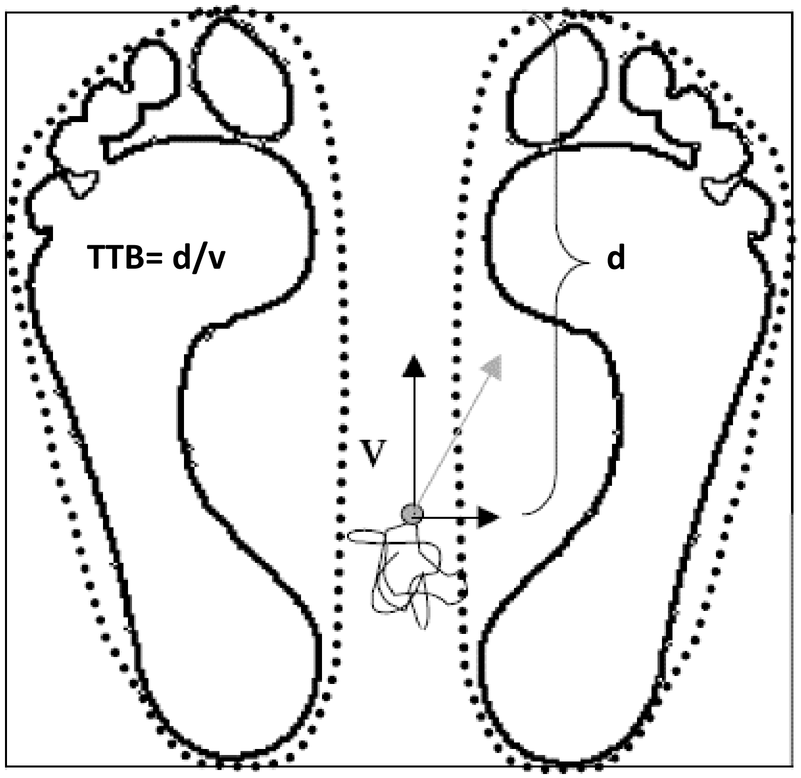


Figure 14: Hypothetical limits of support stability as indicated by a rectangle. The distance (d) of COP to the hypothetical limits of stability and the velocity of the center-of-mass (v) is used to generate time-to-boundary (TTB) values. Modified from Van Wegen et al. (2002)

The distance to boundary (d) was estimated as the distance between the instantaneous COM location and the defined stability limits (boundary) in either given anterior-posterior direction at any moment. The measure has been used in a variety of settings (Haibach, Slobounov, Slobounova, & Newell, 2007; Slobounov, Moss, Slobounova, & Newell, 1998; Slobounov, Slobounova, & Newell, 1997; Slobounov, Haibach, & Newell, 2006) and has shown to be a valuable tool in motor control research, by being able to identify otherwise undetected changes in control characteristics (Forth et al., 2007). Since a common measure (minimum time to boundary) only detects the moment of highest instability, we calculated a different outcome measure that better describes balance performance over the course of a trial. The integrated area of TTB (iTTB) below a 10s-threshold (see Figure 15) has been introduced recently (Ozdemir et al., 2013) . This measure represents an estimation of general instability in each trial and is expressed as a fraction of the total area beneath the threshold.

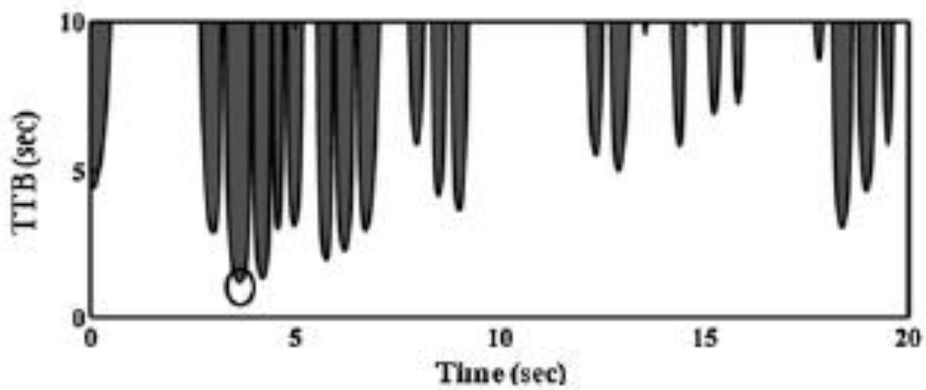


Figure 15: Time-to-boundary measures in a 20-second trial, grey area represents total area below threshold (10s) and minimum TTB value (grey circle). Modified from Oezdemir et al. (2013)

3.4.1.3 Anterior-posterior sway path length (APPlength)

Sway path length is an indicator of the overall sway distance throughout a single trial. It is one of the traditional outcome measures of postural control and has been used in a variety of studies with healthy and patient populations (Doumas & Krampe, 2010; Elliott, FitzGerald, & Murray, 1998; Pellecchia, 2003; Rugelj, Tomšič, & Sevšek, 2013; Thedon, Mandrick, Foissac, Mottet, & Perrey, 2011; Ushio et al., 2008). Whereas other measures of postural performance or stability focus on instances of maximum sway angle (ES) or a combination of COP displacement and velocity (iTTB), APPlength describes the total displacement of the COP in anterior-posterior direction throughout a single trial. This allows for the detection of different characteristics of postural sway. Longer sway-path length has traditionally been attributed to less postural stability. However, it is possible to interpret path length findings as a feature of more exploratory behavior. The use of sway parameters as potential indicators for this exploratory behavior (with an associated goal of increasing sensory feedback flow or to evaluate stability boundaries) has been noted before elsewhere (Albertsen, Temprado, & Berton, 2010; Balasubramaniam & Wing, 2002; Kelsey et al., 2010; Turnock & Layne, 2010) . Calculation of this outcome measure was conducted by summarizing the total displacement of COP (as calculated from force plate data) for each 20s trial.

3.4.1.4 Approximate entropy (ApEn)

ApEn is a regularity statistic determining the predictability/regularity of variation in a time-series (Pincus & Goldberger, 1994; Pincus, 1991). Computation of ApEn generates a single value per time-series that describes the predictability of the sequence. Values approaching 0 represent a high predictability (high regularity), whereas values approaching 2 represent less predictable, less regular and more chaotic time-series. Three examples are provided below (Figure 16). In this example (Ocak, 2009), three signals (1000 samples each) were generated to demonstrate ApEn differences. In the first example, the authors combined two sine waves (sampled at 200Hz with frequency components at 1 and 2Hz). For the second signal, data from intracranial EEG measurements was used (during seizure activity). The third time-series represents a normally distributed random noise sequence. Computation of ApEn resulted in a value of 0.25 for the deterministic signal, 0.76 for the semi-deterministic signal (EEG) and 1.50 for the random signal. The first signal is more predictable (higher regularity) than the second signal, which is more predictable than the third signal.

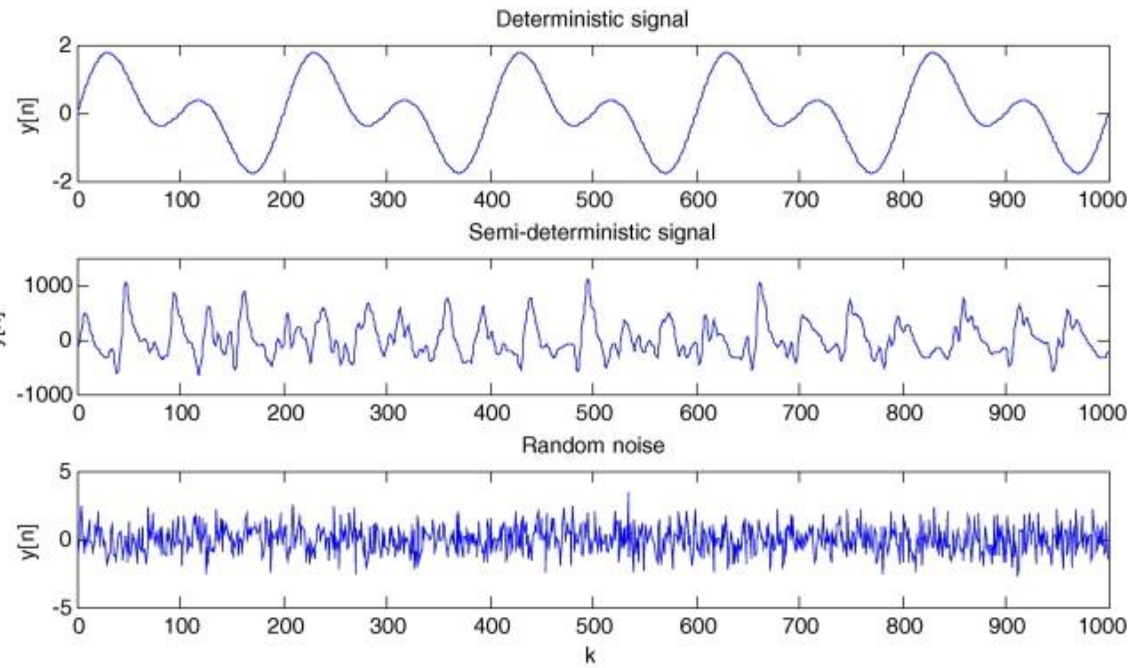


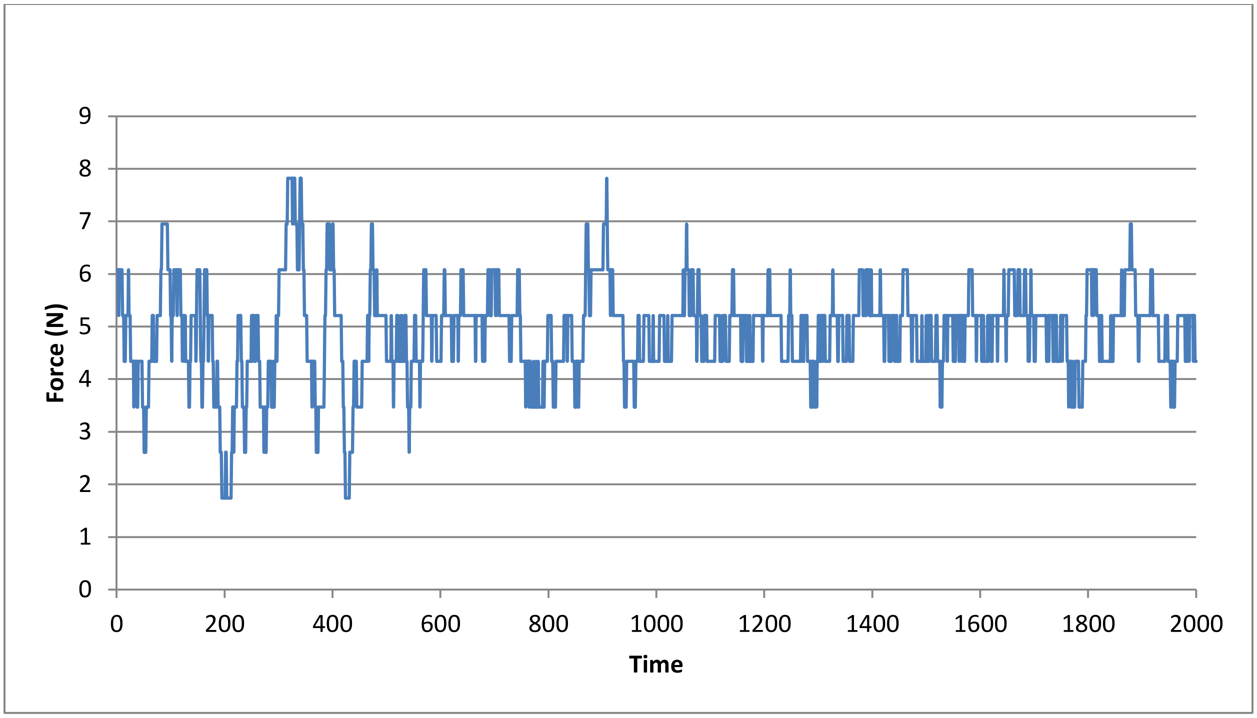
Figure 16: Example test signals (1000 data points each). A deterministic signal (top), a semi-deterministic signal from a biological system (middle), and a random-noise signal (bottom). Adopted from Ocak (2009)

Evaluation of regularity in biological systems has been the focus of numerous biomedical studies. In motor control research, ApEn analysis has shown to enable the detection of changes in control that might not be revealed by linear analysis, and results have been interpreted as potential modifications of motor control or biomechanical constraints (Cavanaugh et al., 2006) or indicators of sensorimotor impairments. ApEn is widely considered a useful supplementary analysis technique to traditional outcome measures of postural stability (Cavanaugh et al., 2006; Harbourne & Stergiou, 2009; Hong et al., 2007; Turnock & Layne, 2010).

A description of the computation method can be found elsewhere (Ocak, 2009). ApEn measures were calculated using a customized MatLab code and anterior-posterior COP-displacement data for each trial of the experiments (#1 and #2). The data was processed with the following settings in the MatLab analysis: A series length of 2 (m= 2 data points), an error tolerance window of 0.2 times the standard deviation of the respective time series (r= 0.2); and a lag value of 10, which in turn reduces the effective sampling rate from 100Hz to 10 Hz (Cavanaugh et al. 2006). A single ApEn value for each trial was obtained, which was then used for further statistical analysis. Using approximate entropy as a non-linear analysis tool, it has to be identified if the COP time series data are deterministic. All data points in the time-series were transformed using a specific transformation algorithm (Theiler, Eubank, Longtin, Galdrikian, & Doynefarmer, 1992). This creates a surrogate set of data, and surrogate and original data (ApEn) were then compared via t-tests (α= .05). Since there were significant differences between the sets of data points for each pair of COP time-series, it was demonstrated that the original data was non-random and partially deterministic.

3.4.1.5 Ankle versus hip strategy: strategy score

The strategy score is a representation of the movements around the upper body and hips and the lower body (ankles) that are generated for maintenance of postural stability. The underlying rationale for the computation of the strategy score is that movements generated around the ankle are associated both with low sway frequencies (<0.5Hz) smaller COG accelerations and shear. Movements generated around the hip result in higher sway frequency (>1Hz) and are associated with larger COG accelerations and larger shear forces. The peak-to-peak amplitude of the shear oscillation is compared to the maximum possible shear of 25 pounds, and expressed as a percentage value (Figure 17). A score of about 100 indicates a strategy based solely on an ankle strategy, and 0 would represent a strategy solely based on hip movements.



$$1 - \frac{SH_{max} - SH_{min}}{25} * 100$$

Figure 17: Raw shear force data of a typical 20-second quiet stance postural trial (100Hz). Maximum and minimum shear forces (SHmax and SHmin) are used for computation of the strategy score

The strategy score has been used in a variety of experimental settings and has shown to be highly reliable, for example when evaluating balance in transtibial amputation patients (Jayakaran, Johnson, & Sullivan, 2011)

3.4.1.6 N-back cognitive task: Response time

For evaluation of cognitive performance in experiment #2, participants' responses in each trial were analyzed. Data was collected using custom-made software that provided timed presentation of words (pool of 26 words, modified from military alphabet). The software used speech recognition to record both reaction time and correctness of responses during each trial. The main outcome of the cognitive portion of the experiment was a response time measure, with response times averaged over all four responses of each trial.

3.4.1.7 Corrective postural response Latency

In experiment #3, one measure was the temporal (latency) analysis of the evoked, active neuromotor responses. Latency quantifies the time between translation (stimulus) onset and initiation of the patient's active response (force response in each leg). The onset of force activation is based on a sudden change of the position of the center of force due to force generation at the feet. This “take-off” instant is directed forward for backwards translations (Shepard, Schultz, Alexander, Gu, & Boismier, 1993). The measurement of latency based on force plate data has to be adjusted, since the responses measured by the force plate are lagging compared to a measurable EMG response around the ankles by about 30-50ms (Horak & Nashner, 1986; Nashner, 1977). To determine the actual onset of an active, corrective response, we used a modified version of a method applied to COP data in the past (Müller & Redfern, 2004). This included an analysis of the derivatives of the COP time-series and subsequent visual inspection of the data. This method is based on the observation of four-zero crossings in the second derivative (acceleration) of COP position data which is considered the “passive recovery” phase that does not include active generation of torque for compensation of the perturbation (but is based on passive structures). The onset of active recovery is defined as the first zero-crossing of the first derivative (velocity) after this first phase (Müller & Redfern, 2004). This concept is described in the figure below

(Figure 18), which shows COP data (position), its two derivatives (velocity and acceleration), and estimated onset of active corrective responses.

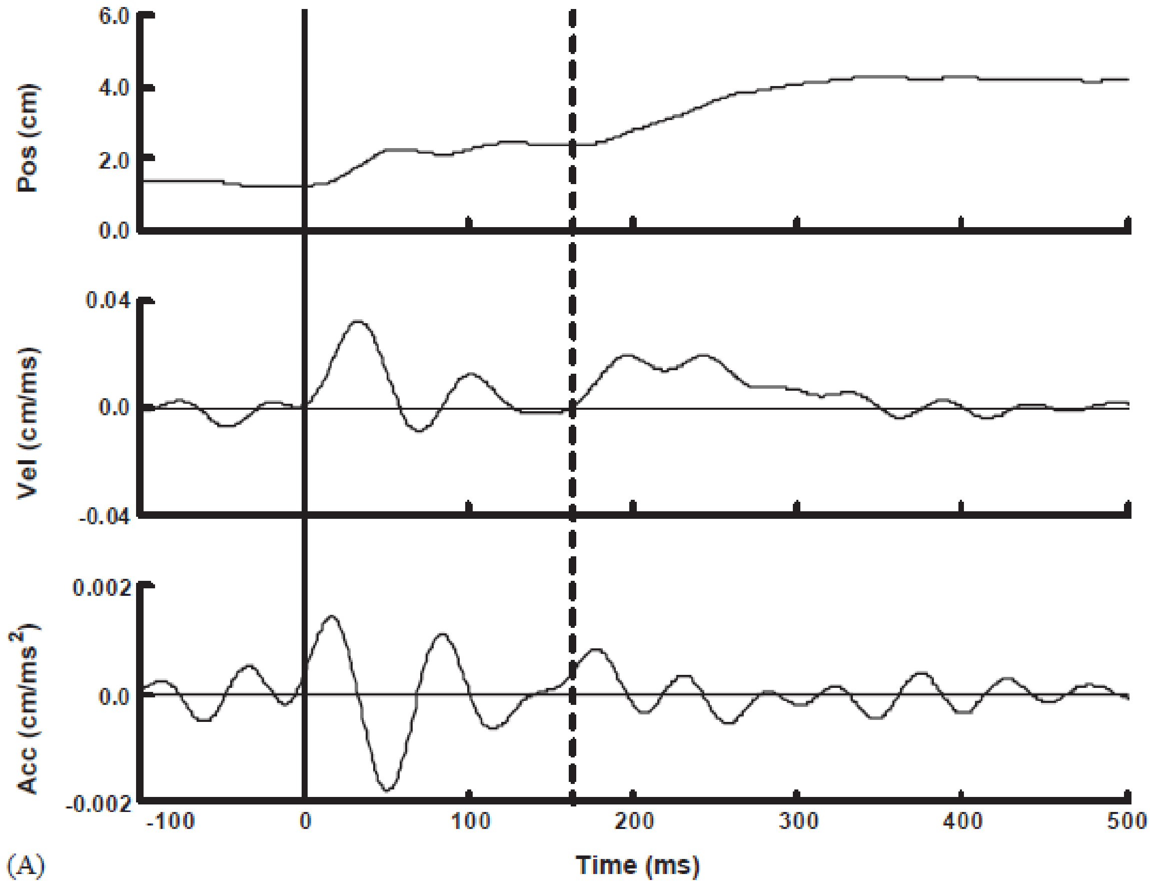


Figure 18: COP time-series and derivatives. Solid line represents the onset of postural perturbation; dashed line represents the onset of active corrective response. Adopted from Mueller & Redfern (2004)

Since we observed a lack of a zero-crossing after the onset of perturbation in many cases, we performed (as had been done in earlier work) a visual inspection of the data to determine the onset of the active response.

3.1.4.8 Maximal COP excursion

To determine the effectiveness of any corrective responses, we measured and analyzed both APPlength (see chapter 3.4.1.3) and maximal COP excursion in anterior-posterior direction. COP-excursion was based on the maximum value for anterior-posterior COP displacement during each trial. Initial COP-position was defined as average COP position in the .5 seconds before onset of support surface translation. A custom MatLab script was used to find the point of maximum excursion throughout each trial (in relation to baseline position). Maximum anterior-posterior COP displacement was then averaged over five trials (one block) per subject, a method applied before elsewhere (Halická et al., 2012).

3.4.2 Data Analysis

For analysis of potential relationships between individual sensory thresholds and performance measures, Pearson's product-moment correlation coefficients or Kendall's tau rank-correlation coefficients were computed and tested at $\alpha<.05$ significance levels. The three experiments represent mixed (within-between) ANOVA designs. There were two independent variables (age, vibration), with one between-groups factor (age) and one within-group factor (vibration). The mixed-model approach allowed the analysis of main effects (vibration and age) and potential interactions (age by vibration) to test the main hypotheses. Prior to computation of ANOVA statistics, data were analyzed to evaluate whether all required assumptions (for mixed ANOVA analysis) were fulfilled. Lack of sphericity of the data warranted the use of degrees-of freedom modification via Greenhouse-Geisser correction. Non-normal distribution of data or lack of equality of variances in the data warranted the use of alternative, non-parametric statistical analysis. The Wilcoxon signed-rank-test was applied to analyze relationships between pairs of related samples, the Mann-Whitney U-test was used for comparisons of pairs of independent samples, and Friedman's ANOVA was applied to compare (k) related samples. Significance of statistical comparisons was tested at $\alpha<.05$, level.

IV. Results

4.1 Participants

Twenty adults participated in the study. The younger group consisted of ten participants (five male and five female participants, age range 22-29, mean age 25.1 ± 2.3, mean weight 148.3 ± 27.2lbs, mean height 165.6 ± 9.6 cm). The older group consisted of ten participants (2 male and 8 female participants, age range 71-85, mean age 78.6±5.4, mean weight 151.1±35.2lbs, and mean height 165.6±10.6 cm). Anthropometric data and initial vibration threshold test results are summarized below (Table 2).

Table 2: Anthropometric characteristics of younger and older experimental groups

	N	*Gender*	*height*	*weight*	*age*	*foot length*	*% of vib*
younger	*10*	*f 5 m 5*	*165.6 ±9.2*	*148.3 ±27.2*	*25.1 ±2.3*	*25.4 ±2.3*	*2.1 ±0.6*
older	*10*	*f 8 m 2*	*165.6 ±10.6*	*151.1± 35.2*	*78.6 ±5.4*	*25.4 ±1.6*	*23.2 ±21.8*

4.2 Vibration threshold

Prior to the experimental data collection, a vibration threshold test was conducted with each participant to determine the vibration amplitude required for stimulation of the foot soles at about 90% of perceivable (threshold) vibration. The results are expressed as a fraction of the maximal vibration amplitude as determined by the vibration controller unit. The younger age group showed high sensitivity of the foot receptors, requiring only very low vibration amplitude. The 90% level of threshold in the younger group (2.1% ± 0.56) was significantly lower than in the older group (23.2% ± 21.8), t(9.012), p=.013, indicating lower vibration sensitivity at the foot soles in the older adults group. No significant correlations were found in any of the three experiments concerning measures of postural performance (without vibration) and sensory threshold.

4.3 Experiment 1

Initial analysis of the data did not reveal significant group- or vibration condition effects, except for significant differences between older and younger groups' strategy scores, F(1, 18)=9.234, p=0.007. Upon visual inspection of ES data for each participant, it was found that there was one particular outlier, who exhibited a very high performance without vibration, but a significantly lower performance with vibration added (see Figure 19). Since this drop cannot be attributed to the effects of sub-threshold vibration, it was decided to reanalyze the data with this specific participant excluded.

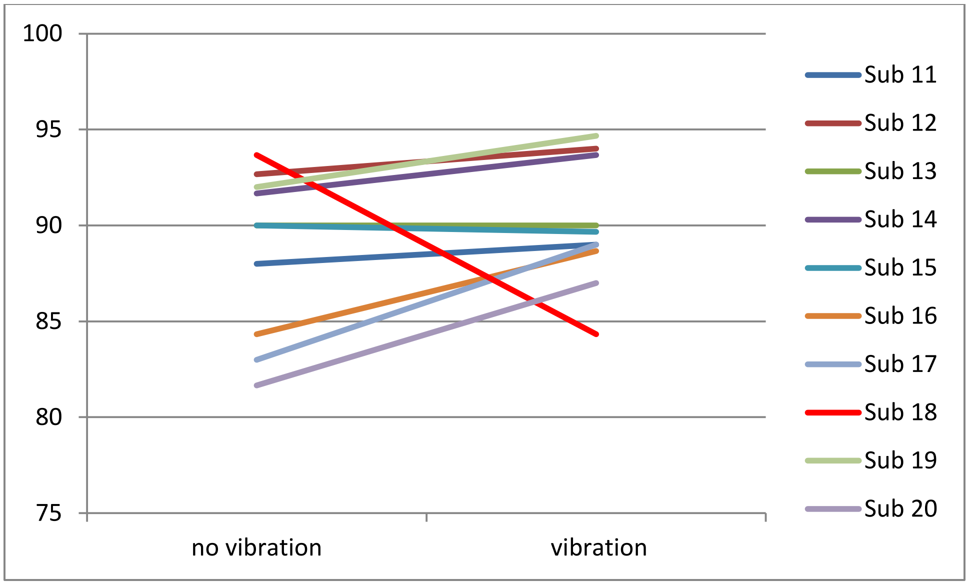


Figure 19: Mean ES for each participant of older group in both vibration conditions. Subject 18 was considered an outlier for this experiment

Postural performance data for n=20 (10 younger adults, 10 older adults) and n=19 (10 younger adults, 9 older adults) including averages over three trials and standard deviations is summarized in Table 3.

Table 3: Postural performance of older adults (OA) and younger adults (YA) in sensory conflict experiment, n=19. Results including outlier (n=20) in brackets

	ES		*iTTB*		*APPlength (in cm)*	
	YA	*OA*	*YA*	*OA*	*YA*	*OA*
No vibration	92.3±3.7	88.18±4.1 (88.7±4.3)	1.8±3.3	5.2±4.1 (4.7±4.2)	12.1±3.7	25.6±10 (24.3±1)
vibration	91.9±3.1	90.6±2.8 (90.0±3.3)	2.1±2.8	3±3.3 (3.5±4)	12.3±3.2	19.6±9.1 (21.3±1)

Upon reanalysis of the data following deletion of the outlier, it was found that older and younger adults differed significantly concerning APPlength without vibration, U=9.0, p=0.02, but not with vibration added (Figure 20). APPlength was affected significantly by vibration only in the older group, F(1, 8)=11.119, p=0.01

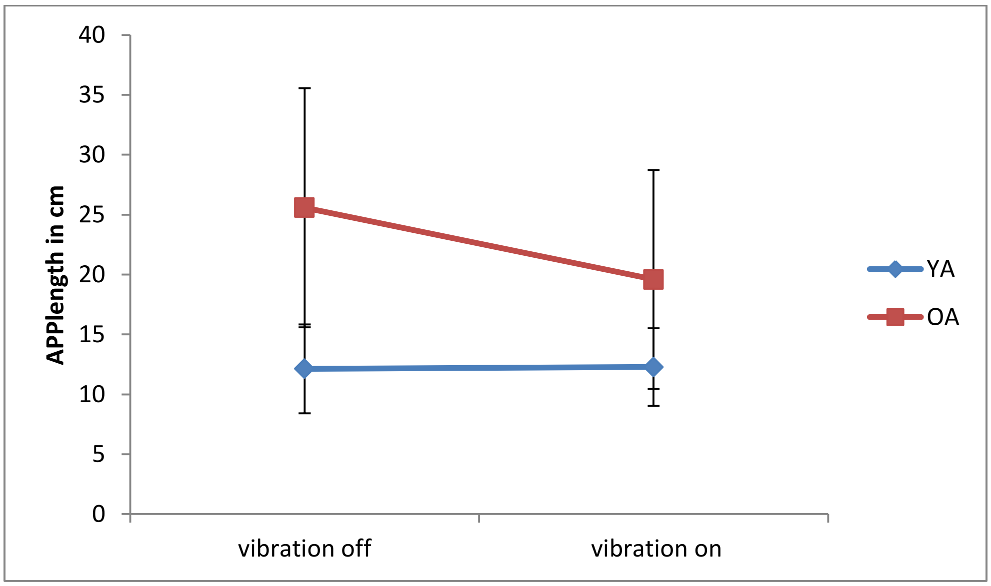


Figure 20: APPlength means (over three trials) and standard deviations in younger adults (YA) and older adults (OA)

The same pattern was observed for ES, where ES was significantly higher in the younger group than in the older group without vibration, U=14.0, p=.010, but not with vibration added. Further analysis of vibration effects in the older group revealed that there was a significant effect of vibration in the older adults group on ES, F(1, 8)=10.606, p=0.012 (Figure 21).

The postural performance results indicated age group differences for ES and APPlength, but not for iTTB. Additionally, an effect of vibration was only observed in older adults, and limited to outcome variables ES and APPlength.

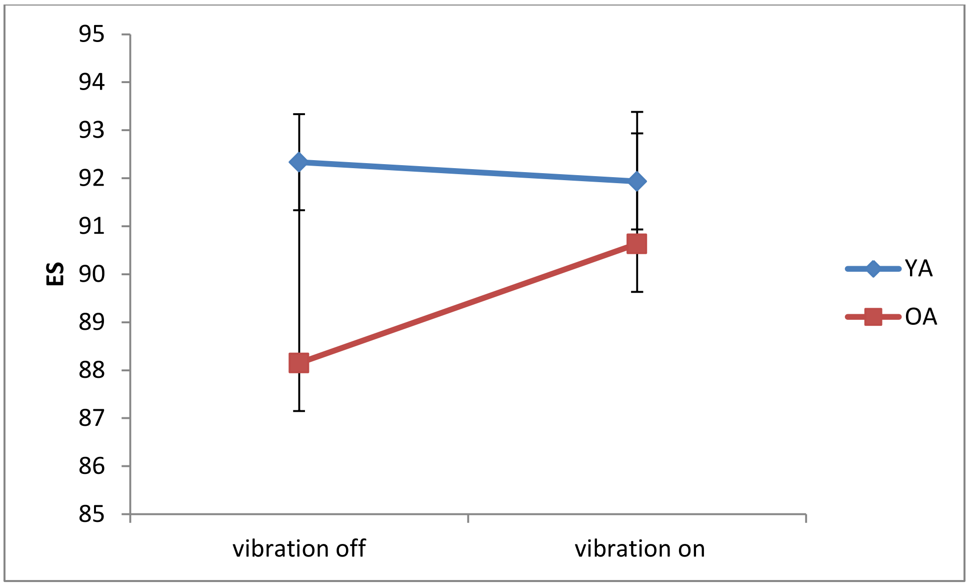


Figure 21: ES means (over three trials) and standard deviations in younger adults (YA) and older adults (OA)

In addition to performance, postural control characteristics were analyzed based on Strategy Scores and ApEn. A summary of the means can be found in Table 4. Analysis of strategy scores revealed a significant group effect, $F(1, 17)=8.313$, $p=0.01$ and a group by vibration condition interaction, $F(1, 17)=4.481$, $p=0.049$. Further analysis showed a significant effect of vibration on Strategy Scores, $F(1, 8)=7.540$, $p=0.025$ (

Figure 22) in the older group. There were no significant group or vibration effects on ApEn.

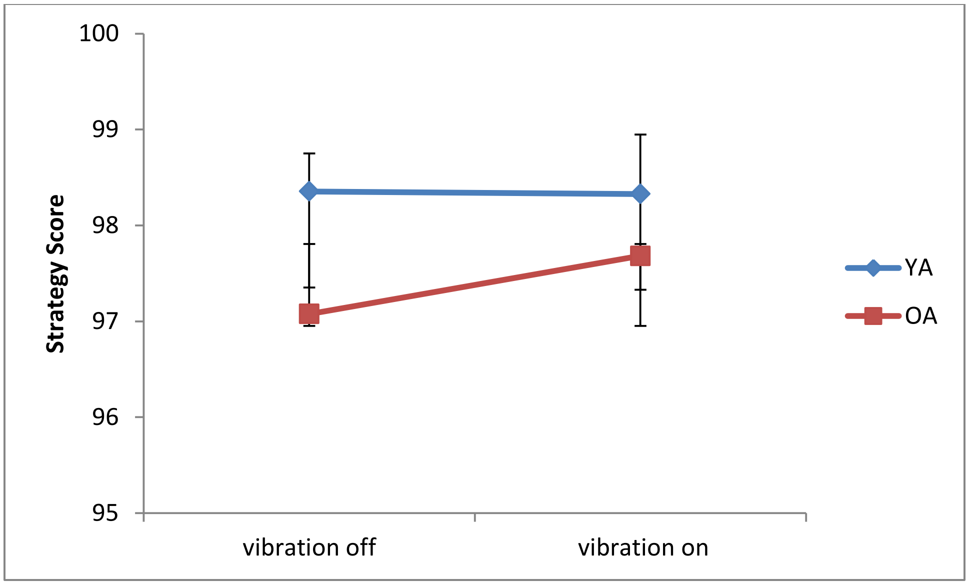


Figure 22: Strategy Score means (over three trials) and standard deviations in younger adults (YA) and older adults (OA)

Table 4: Postural control measures of older adults (OA) and younger adults (YA) in sensory conflict experiment (n=20)

	Strategy Score		*ApEn*	
	YA	*OA*	*YA*	*OA*
No vibration	98.5±0.4	97.1±0.9 (97.3±1)	0.59±0.1	0.67±0.18 (0.67±0.18)
vibration	98.3±0.6	97.7±1.1 (97.5±1.2)	0.57±0.11	0.67±0.16 (0.66±0.15

4.4 Experiment 2

Outcome measures related to postural performance were not different between groups, except for APPlength (Figure 23), which differed between older and younger adults both without vibration, U=18, p=0.015 and with vibration, U=15, p=0.007.

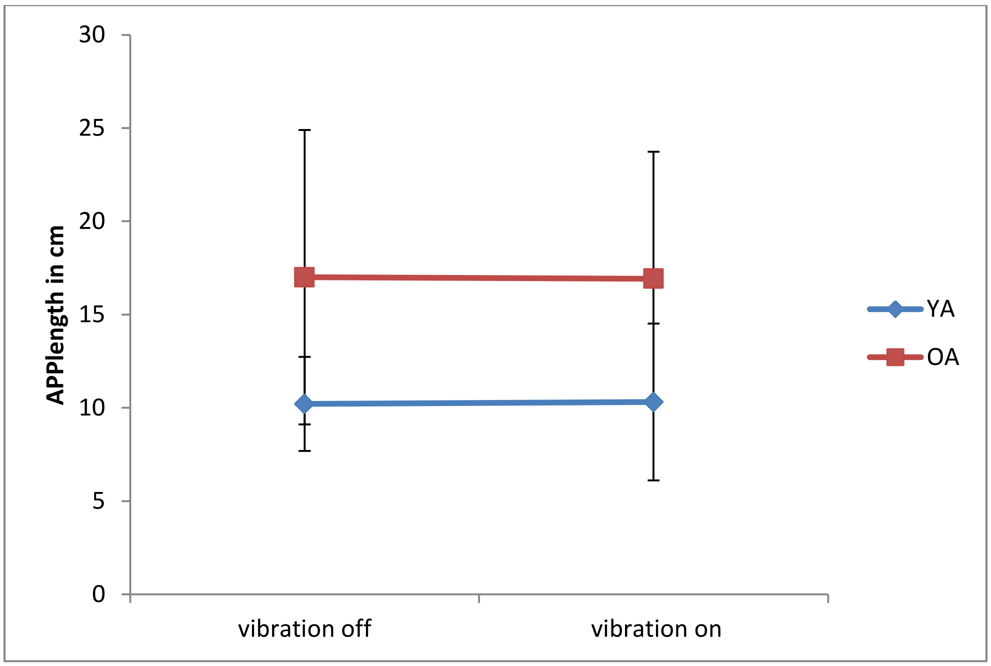


Figure 23: APPlength means (over three trials) and standard deviations in younger adults (YA) and older adults (OA) during dual-tasking

Results for Experiment 2 are summarized below (Table 5). Vibration did not significantly alter performance in either age group.

Table 5: Postural performance of older adults (OA) and younger adults (YA) in dual-task experiment (n=20)

	ES		*iTTB*		*APPlength (in cm)*	
	YA	*OA*	*YA*	*OA*	*YA*	*OA*
No vibration	91.7±5.8	91.8±2.9	1.4±1.8	2.6±4.2	10.2±2.8	17±7.9
vibration	92.8±3	92.7±2.3	1.6±3.1	2.4±3.6	10.3±3.9	16.9±6.8

Postural control characteristics as measured by Strategy Score and ApEn did not differ between groups and were not affected by vibration (see Table 6 for summary).

Cognitive task performance as measured by response latency was significantly higher in the younger group, both without vibration, U=1.5, $p<0.001$, and with vibration, U=6, $p<0.001$. There were no effects of vibration or interactions.

Table 6: Postural control measures and response time (1-back test) of older adults (OA) and younger adults (YA) in dual-task experiment (n=20)

	Strategy Score		*ApEn*		*Response latency (in sec)*	
	YA	*OA*	*YA*	*OA*	*YA*	*OA*
No vibration	98.5±0.7	97.9±1	0.62±0.1	0.68±0.16	1.7±0.1	2.1±0.3
vibration	98.5±0.6	97.8±1.1	0.62±0.06	0.69±0.13	1.8±0.1	2.2±0.3

4.5 Experiment 3

Analysis of the data revealed that COP displacement characteristics (and associated first and second derivative, velocity and acceleration) in response to perturbations did not show consistent zero-crossings as anticipated. This would have been a requirement for analysis according to methods described by Mueller & Redfern (2004). Alternatively, onset of corrective response was estimated based on directional changes of the of the first and second derivative, which still required a significant amount of visual inspection of the data traces, and cannot be considered a reliable and consistent way of analysis. Results from this outcome measure are reported, but interpretation of the data is constrained by the potential flaws of the data analysis method (Table 7).

Maximum COP excursion was not significantly affected by age or by vibration. Older adults did not exhibit further maximal excursions of COP than younger adults. Vibration did not alter excursions in the experiment in either age group.

APPlength was significantly greater in older adults than in younger adults (Figure 24), $F(1, 18)=7.482$, $p=0.012$. Over the course of each trial (2.5s), older adults' total COP displacement was on average larger than in younger adults. Vibration did not affect this displacement in either age group.

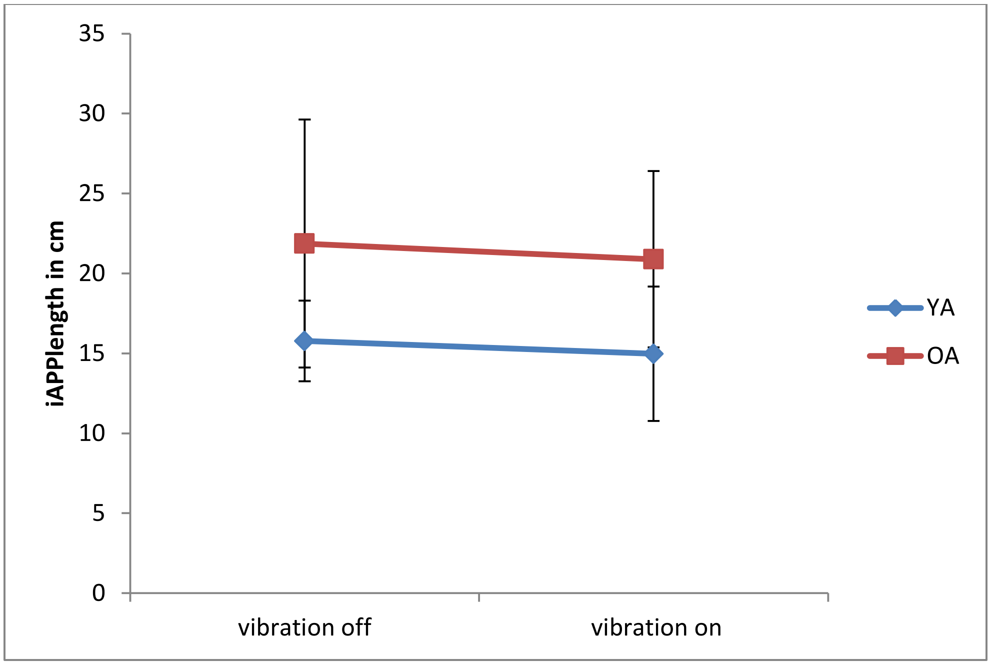


Figure 24 Comparison of APPlength in postural perturbation task between older adults (OA) and younger adults (YA)

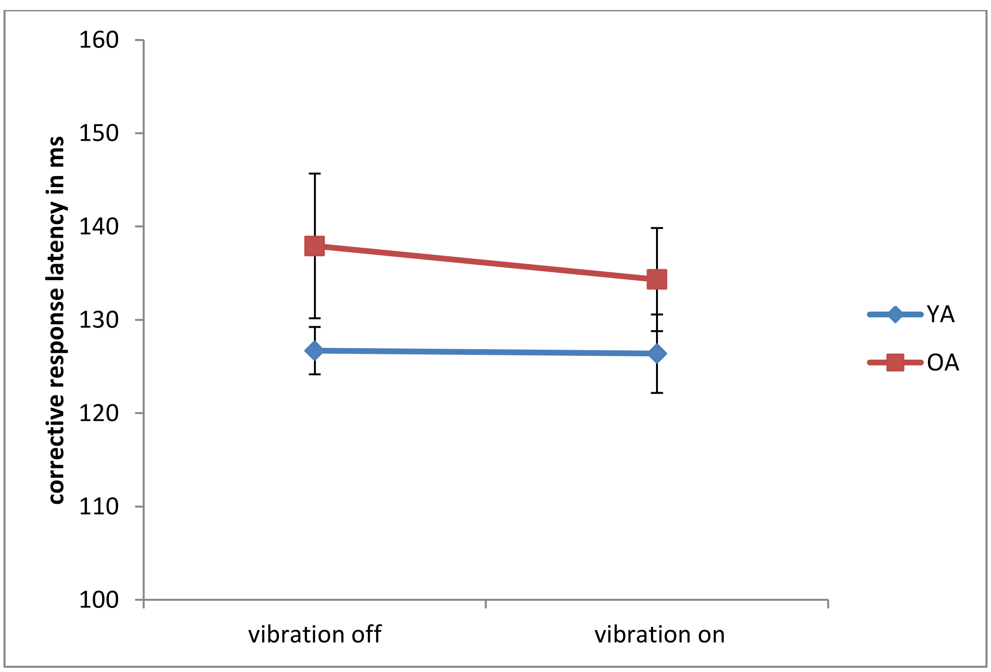


Figure 25: Latency of corrective responses in postural perturbation task between older adults (OA) and younger adults (YA)

Table 7: Summary of results from experiment 3. YA= younger adults, OA=Older adults (n=20)

	Maximum COP excursion (in cm)		*APPlength (in cm)*		*Latency (in ms)*	
	YA	*OA*	*YA*	*OA*	*YA*	*OA*
No vibration	5.95±0.6	5.95±1.4	15.77±2.5	21.87±7.8	126±7	138±11
vibration	5.8±0.9	6.16±1.4	15.0±4.2	20.88±5.5	126±5	134±13

Latency of corrective responses (Figure 25) was different between groups, when vibration was absent, U=18.5, p=0.015.

V. Discussion

The overall goals of the current series of experiments were to investigate the association of aging and outcome measures in a variety of different postural tasks. These experiments included a sensory conflict, a dual-tasking, and platform perturbations. We further applied sub-threshold vibration to explore its effects on postural performance and postural control in those tasks and to compare its effects between older and younger adults.

5.1 Tactile sensory threshold and aging

As shown in the initial threshold testing procedure for the experiments, older adults exhibit a significantly higher sensory threshold than younger adults. This observation is in concordance with earlier work that showed a significant decline in plantar-surface sensitivity due to aging (Kenshalo, 1986). A steep incline of this development has an onset at around 70 years of age (Perry, 2006). The observed decline affects the generation of compensatory neuromuscular responses and is associated with increased risk for falls (Sturnieks et al., 2008). The tactile systems of the foot sole can be considered a dynamometric map, whereas the CNS interprets pressure distribution and pressure changes, from different regions of the feet, or even between feet (Kavounoudias et al., 1998). Since balance performance relies on the quality and accuracy of sensory feedback, lower sensitivity of the foot sole receptors leads to inadequate information about pressure characteristics and associated sway. This would affect an individual's ability to respond adequately to external perturbations or to plan corrective responses (Perry et al., 2000).

Although this was beyond the scope of this study, sub-threshold mechanical vibration could directly affect vibration thresholds in older adults, as has been shown in earlier work (Wells et al., 2005). Those authors concluded that an increased flow of information as a result of utilizing SR could positively affect sensorimotor functionality in older adults (Liu et al., 2002; Wells et al., 2005).

5.2 Experiment 1

Experiment 1 was designed to investigate the association of aging with a complex postural task that included a sensory conflict, and the potentially differential effects of vibration on a number of different postural measures. Participants were asked to stand quietly on a force plate for repeated trials of 20s duration. During each trial, the visual surrounding was sway-referenced, thereby eliminating reliable visual cues.

5.2.1 Age-related Associations

We hypothesized that age would be associated with performance and control characteristics in this experiment. Older adults exhibited slightly decreased postural performance compared to younger adults, as evidenced by lower ES and greater APPlength. This confirms earlier results related to a postural performance decline with aging (Cohen et al., 1996; Forth et al., 2007). In our experiment, participants were required to resolve a sensory conflict, in that available visual information was not useful for determining the body's orientation. This resulted from the fact that the visual surround moved in a manner proportional to the pressure applied to the support surface so that the participants did not experience a visual flow field and therefore could not visually detect self-motion. This specific task may be challenging to older adults due to a number of sensory- and motor-related aging processes (Bugnariu et al., 2007). Maurer et al. (2001) proposed the idea of two different main aspects of foot sole cutaneous signals, the evaluation of the body's orientation in space and investigation of support characteristics. Aging affects the function of foot sole feedback, and earlier results suggest that sensory decline affects threshold characteristics when facing "complex multimodal stimuli". This in turn could lead to an increased shift of reliance towards vision. During optimal visual conditions, this might be a valuable strategy to compensate for somatosensory decline, but it affects postural performance and even poses a risk when visual information is not reliable (Bugnariu et al., 2007).

Results from the strategy score analysis showed that older adults in general exhibited a slightly more hip-based strategy than younger adults. This is expected when visual information is unreliable and has been shown to be a typical response in older adults (Liaw, Chen, Pei, Leong, & Lau, 2009). Numerous potential reasons for an increased hip-dependence and strategy adaptations have been identified in earlier work involving healthy older populations and neuropathy patients. Decrease of sensory feedback and lack of proprioception from ankles and feet are major contributors to the observed effects of aging (Horak et al., 1990). It is known that younger adults control quiet stance mostly through forces generated around the ankles, potentially to increase feedback from cutaneous- and spindle receptors and thereby decrease neuromotor effort (Gatev, Thomas, Kepple, & Hallett, 1999), whereas older adults show increased hip movements and hip muscular activity, specifically in demanding tasks (Amiridis, 2003). The aging-related shift towards a hip strategy may represent part of a set of compensatory mechanisms, like the aforementioned co-contraction of the lower leg musculature, which leads to stiffening of the lower limb, and associated decreased reliance on proprioceptive feedback (Benjuya et al., 2004). However, the differences between groups, although being significant, were minimal (about 1.4 points in the Strategy Score). It is debatable whether this small difference has physiological or functional relevance. The reason for the small group differences presumably can be attributed to the overall high function in the older adults group.

As a relatively new way of analyzing postural data, we applied iTTB for evaluation of postural performance. iTTB is a variable building on an established postural stability measure referred to as 'time-to-contact' or 'time-to-boundary' (Haibach et al., 2007; Slobounov et al., 1998; Slobounov et al., 2006). Results from iTTB data analysis did not support our initial hypothesis, which was that older and younger adults' iTTB would differ. This is most likely due to overall high performance in the older group, which was unexpected, but also due to the temporal-spatial limits we applied in the analysis. We considered time-to-boundary values of less than 10 seconds as reflecting potential functional values in that lower values would be indicators of higher instability in upright stance (whereas more instances of time-to-boundary lower than 10s would increase iTTB). Due to the novelty of the technique, no standard time-to-boundary threshold has been established yet. However, due to the overall higher performance than expected in both groups (specifically in the older group), the 10 second limits to time-to-boundary was reached much less frequently than expected. Our results are similar to those reported by Ozdemir et al. (2013). In the Ozdemir et al. study, postural performance in sighted and blind individuals was tested on stable and sway-referenced surfaces (age range 20-65 years of age). Although the current study exposed participants to a slightly different task (sway-referenced visual surround), young participants in our study were able to maintain postural stability as expressed in iTTB at even higher levels than the sighted young adults in the Ozdemir et al. experiment (including quiet stance on a stable surface and an upper limit for time-to-boundary set to 10s). This may be due to a lower age range (of the younger group) in our study compared to Ozdemir et al.

Postural control characteristics, as measured by the nonlinear measure of ApEn, did not significantly differ between age groups, indicating that regularity of COP sway did not differ between older and younger adults. The ApEn values observed in the current study are similar to earlier work investigating regularity in a variety of SOT conditions (Cavanaugh et al., 2007). The finding that age was unassociated with ApEn in the context of the current postural task contradicted our expected results, since results from earlier postural studies suggested that changes in predictability of a time-series (ApEn) reflect aging processes, and suggesting a decrease in availability of sensory information or adaptability of the system (Manor et al., 2012). In comparison, earlier evidence showed decreased regularity in older adults in specific postural tasks (Borg &

Laxåback, 2010). In the cited study, the investigators observed larger differences between older and younger adults; however, it is unclear which inclusion criteria were applied in the earlier study. Inclusion criteria were set fairly strict in our study, allowing only the recruitment of healthy, highly functioning individuals. It is possible that our high functioning group differed from the group recruited in the Borg & Laxåback study.

Usually, the observed differences in ApEn can be interpreted as: (1) an aging-related mechanism that decreases or increases sway complexity; or (2) ApEn could be an indicator of a different motor strategy. In the latter case, more muscle co-contraction in the lower legs and associated stiffness around the ankles would lead to a less complex motor output. The older group in this study, despite exhibiting elevated sensory thresholds, was able to perform at levels that were not different from the younger group. The limited decline of sensorimotor abilities in our older group potentially was too small to require the use of a different postural control strategy. The pressure distribution and changes thereof sensed due to sway activity seemed to be sufficient in this group to provide the CNS with enough information to interpret and integrate sensory information for postural control in a manner similar to the younger participants.

5.2.2 Effects of sub-threshold vibration

We hypothesized that the addition of SR-based stimulation would affect *performance* and *control* in this postural task, and that there could be an interaction effect between vibration condition and group. Our results showed a lack of vibration effects on sway parameters in the younger group which is in concordance with most existing literature. Priplata et al. (2002) showed an effect on sway parameters when adding noise to the foot sole, however, this effect was larger in older than in younger adults. Additional results suggest that postural control (due to sensory feedback) is already near optimal in younger adults (Wu et al., 2007), thus a SR intervention might not result in additional foot sensory information such that performance is positively impacted. Based on results from earlier experiments, including participants with diabetes and stroke patients, it can be argued that the benefits from SR vibration applied to the feet are related to initial baseline performance: those individuals who exhibit larger postural sway and instability during baseline trials benefit more from the intervention than those with near-optimal control (e.g. healthy adults between the ages of 18-35).

Our findings support the idea of benefits of a vibration intervention mainly in older patient populations with lower balance performance. Balance performance was slightly improved by the intervention, as ES increased in the older adults (by about 2.5 points). Although this difference appears small (considering the ES continuum of 100 point), it has to be noted that no-vibration performance in the older group was already high. With the addition of vibration, older adults approached the performance level of younger adults. This demonstrates that postural performance can be improved when augmentation of sensory feedback is induced in an older adults group.

The effects of sub-threshold vibration intervention observed in the current study are not as pronounced as in earlier studies (Gravelle et al., 2002; Priplata et al., 2002). Our results are more comparable to the smaller effects Hijmans et al. (2008) reported in a study with neuropathic and healthy adults performing postural tasks (eyes open versus eyes closed and added concurrent cognitive task). These authors found an effect of vibration mainly in the patient group, and in more challenging task conditions, but not in the age-matched healthy group. Hijmans et al. concluded that the larger effects reported in earlier studies might to some extent stem from a different approach to balance evaluation. They reported that earlier experiments applied a single shoulder marker for determination of postural sway, which might have contributed to the results compared to methodological approaches based on force plate data. A marker attached to the shoulder section would only be reliable in conditions where a perfect inverted pendulum model of human postural control is assumed, without any hip or upper body contribution.

One of the outcome measures in this experiment was ES, which is based on peak-to-peak sway angles. Sway has traditionally been interpreted as an indicator of postural stability, however, it is also possible to view sway as an indicator of a functional strategy that augments information detection and flow in postural control (Bringoux, Nougier, Barraud, Marin, & Raphel, 2003; Thedon et al., 2011). In view of this perspective, postural performance data from our experiment could be interpreted as an indicator of improved sensory flow from foot sole mechanoreceptors, requiring less "exploratory" sway to determine body orientation. This idea is supported by APPlength data from the older age group that showed a decrease of the sway path length with addition of vibration. It is possible that sway is not solely an indicator of postural instability, but potentially represents an effort to increase feedback from the foot plantar surface and lower legs. The decrease of anterior-posterior sway path length in older adults could indicate that less sway was required to enhance feedback, since the intervention had affected/enhanced sensory flow. This would represent a decrease of required exploratory behavior to gather sensory cues for determination of postural orientation and subsequent control.

Alternatively, the sensory augmentation from the foot soles might affect the process of sensory reweighting that is required in the specific task. It is mandatory for effective postural control during the visual sway-reference task that visual information is suppressed in the CNS and an upweighting of somatosensory information occurs. There are inter-individual differences regarding this process, which could be related to functioning levels of the specific sensory systems and selection processes. Peterka & Black (1990) showed that even in the case of unreliable (sway-referenced) visual cues, some individuals still suppress vestibular or somatosensory cues while relying on (false) visual information, leading to higher instability. The reasons for this persistence on visual dependency in the face of incomplete or inaccurate visual information are not yet known, but it would be valuable to investigate whether improved somatosensory feedback could affect this phenomenon in visually dependent individuals.

Postural control as expressed by the Strategy Score was significantly affected by vibration in the older group. Vibration affected postural control so it more resembled that of younger adults. The higher score with vibration added showed a slight shift towards more of an ankle-based strategy. Although the effect was relatively small, this could indicate that more emphasis was put on using sensory feedback and a bottom-up strategy incorporating the (augmented) sensory feedback from the feet. Closed-loop based postural control, including the constant analysis of sensory feedback, could become more efficient with the effects of SR added via sub-threshold vibration in an experimental older group of participants

ITTB as an indicator of postural stability was not affected by addition of vibration. Although there was a tendency of lower average iTTB in the older age group with vibration added (5.2±4.1 without vibration versus 3±3.3 with vibration), this finding was not statistically significant. It is possible that the limits set to evaluate instances of postural instability (in the case of our experiments under 10s of time-to-boundary) were not optimal for finding differences between either groups or vibration conditions. However, a limit set higher could have detected differences but would not necessarily have been an indicator of instances of postural instability that threatened balance. A limit set lower (e.g. 1s) would detect only instances of more rapid approaching of stability limits, but the overall high performance in both group would have resulted in a high number of zero-values (indicating there were no instances where the COP approached the hypothetical, spatial limits of stability rapidly at any time).

ApEn was not affected by sub-threshold vibration in the current experiment. It is likely that the changes observed in other measures when adding vibration are due to the different aspects of postural features detected by each measure. ApEn, which is based on regularity of the time series, differs from Strategy scores, which are computed based on shear forces exerted to the force plate through the feet. Temporal dynamics of COP variability in the current experiment are either not affected by vibration per se, or the effects are too small to be detectable.

5.2.3 Summary

Results from the sensory conflict experiment provide evidence that aging is associated with specific measures of postural control and motor performance, whereas not all measures are representative of this association. The different measures of postural performance in this experiment show how specific outcome measures may be able to detect different features of postural stability and performance. ES are based and therefore limited to peak-to-peak sway angles in each trial, whereas APPlength is not necessarily affected by several large COP excursions but by COP displacements throughout a whole trial. ITTB takes velocity and hypothetical limits of stability into consideration, but is dependent on set limits of temporal stability as defined before data analysis. Therefore the different analysis tools investigate different features of postural performance, which may explain some discrepancies between results for each outcome measure.

An intervention based on foot-sole vibration could have value for improving balance in sensory conflict tasks, whereas improved sensory transmission and detection could lead to a better integration of somatosensory cues in situations where increased reliability of those cues is required. It is expected that older adults rely more on visual information than younger adults in some tasks, mainly due to decline of lower leg feedback structures and functioning. It is possible that the observed improvement of postural performance is a reflection of improved sensory feedback. Lower-leg and plantar surface feedback is then favored over visual feedback in integration processes of the CNS and used to a greater extent in postural control in the sway-referenced environment provided in our experiment.

More research is needed to determine the efficacy of the intervention in individuals who are prone to falls or exhibit significant loss of postural performance.

5.3 Experiment 2

The second experiment was designed to investigate the effects of aging and vibration on dual-task performance and control characteristics. Participants were asked to quietly stand on a force plate while listening to words via headphones. They were asked to memorize words and recall them quickly, as soon as the next word was provided. Performance in the cognitive task and in the postural task was analyzed, as well as postural control measures.

5.3.1 Age-related Associations

We hypothesized that age would be associated with performance and motor control in a dual-task situation, and that outcomes would differ between conditions where vibration was either applied or not. We expected that the effects of aging on mental capacity and the sensorimotor decline observed with aging would affect outcomes related to one or both components of the dual-task.

Older and younger adults' balance performance differed significantly as reflected by greater APPlength in older adults. It is possible that this effect is based on older adults allowing for more sway to gather more sensory cues from the lower legs and to ultimately improve postural stability. If APPlength increases are considered potential indicators of postural instability, these results could be interpreted as evidence for less stability in the older group when facing a dual-task environment.

Results from iTTB and ES analysis did not reveal any group differences. The fact that older adults performed at similar levels to younger adults is unexpected, but understandable when further analyzing the task, the outcome variables, and the group of older adults that served as participant in the study. The n-back task performed concurrently in this experiment while trying to maintain quiet stance was designed to divert attention from postural control processes. It has been shown in younger adults that a fairly simple cognitive task (as is the 1-back task applied in our study) can actually lead to improved posture, associated with even less sway than in a single-task. The underlying idea is that an internal focus in an overlearned, mostly automatic and selforganized task like quiet standing (e.g. based on the instruction “stand as quiet as possible”) could interfere with the motor system, (Huxhold et al., 2006; O’Reilly, 2006; Verrel, Lövdén, Schellenbach, Schaefer, & Lindenberger, 2009). The cognitive task in our experiment may have shifted the participants’ focus towards an external cue, and automatic postural processes ensured maintenance of postural stability. This could explain why our results are contrary to earlier findings that suggested that older adults allowed about 40% increase of instability in favor of maintaining high performance in a concurrent cognitive task (Doumas et al., 2008). Doumas and colleagues administered a cognitive task that was more demanding and taxing on working memory than the task applied in the current study. It is expected that increasing difficulty of the cognitive task would have most likely shown pronounced age differences, based on increased resource competition.

However, we observed a potential trade-off in the cognitive domain. We analyzed the response times in the n-back task administered in this experiment and we hypothesized that there would be a difference between older and younger adults. Our results confirmed that older adults needed longer to respond in the simple 1-back test compared to younger adults. It is possible that this observation indicates a trade-off between posture and cognitive processing, whereas longer response times were accepted by older adults to maintain high levels of postural performance.

Alternatively, the trade-off may be a reflection of general aging processes between cognitive features, whereas older adults maintain accuracy of their responses (as observed in our study) while allowing for greater response times. This phenomenon been observed before (Mattay et al., 2006). Mattay and colleagues observed that reaction times were greater, but response accuracy was the same in older and younger adults. This finding was accompanied by higher prefrontal cortex activity in the older adults, potentially as a countermeasure to aging processes in the cognitive system (Grady, 2008). It is possible that this increased cortical activity could make a difference when postural tasks (the primary task) become more difficult, for example when the visual surrounding or the support surface is sway-referenced. Those tasks would require more conscious control of posture, and aging effects become more pronounced, as has been shown with more demanding secondary tasks (Mattay et al., 2006).

The current results indicate that the older group accepted a trade-off regarding response time in favor of accuracy, a phenomenon that can occur when investigating both measures of accuracy and reaction time (Remaud & Boyas, 2012). An alternative explanation is that the longer response latency in older adults could stem from prioritization differences due to aging. Participants were given the instruction to respond as quickly as possible, while standing as quiet as possible. Potentially, a higher prioritization was given to the postural task, affecting response times in this group. It is known that older adults have the ability to reallocate cognitive resources according to either instructions or due to strategic decisions, e.g. postural stability over cognitive performance (Li et al., 2005; Riediger, Li, & Lindenberger, 2011).

There were no wrong responses in either of the two groups, but it is possible that this would have changed if participants would have focused more on response time than on accuracy. Alternatively, a more demanding 2-back test would have probably caused incorrect responses (Mattay et al., 2006).

In contrast to our initial hypothesis, measures of postural control were not different between younger and older adults, as indicated by similar ApEn and strategy scores. This means that older and younger adults mainly used the same strategic approach to perform the dual-task. Concurrent processing of a cognitive task did not affect older adults in a manner that required them to change characteristics of attention "sharing" to the task differently from younger adults. There arguably was no need for the older group to change the postural strategy compared to younger adults, as would have been evidenced by differences in strategy scores. For more demanding postural/cognitive tasks, more of a top-down strategy, including increased stiffness of the lower-leg musculature (Kang et al., 2013) and less ankle/more hip rotation is expected, which is more pronounced in older adults. However, considering the nature of the experimental tasks in the current study, the need to adopt of a top-down approach to postural control was not required.

The idea of adaptations of control not being required was supported by results from ApEn analysis. In the current task, temporal dynamics of COP variability were unaffected by age. ApEn seems to be dependent on amount of attention invested in postural control or a secondary task (Cavanaugh et al., 2007; Donker, Roerdink, Greven,

& Beek, 2007). It can be concluded that the group of older adults included in this study did not adjust postural control to accommodate the requirements posed by the secondary cognitive task, as would have been indicated by changes of our entropy measure. Although ApEn has been shown to detect effects of the addition of a secondary task, even when initial postural sway was minimal (Cavanaugh et al., 2007), it might not be an optimal measure to investigate healthy aging effects in dual-tasks.

5.3.2 Effects of sub-threshold vibration

We had hypothesized that sub-threshold vibration would alter postural performance, control characteristics, or cognitive performance, specifically in the older group. Our initial hypotheses concerning potential effects of sub-threshold vibration on dual-tasking, specifically in the elderly, were not confirmed.

Aging requires the allocation of more mental capacity or cognitive resources directed towards postural control or gait (Krampe et al., 2003; Lacour et al., 2008; Lajoie et al., 1996). The enhancement of sensory feedback, especially about small excursions of the COP, could have effects on postural stability. This was not the case in the current experiment. The lack of any effects of vibration on either postural or cognitive measures indicates that the subtle enhancement of sensory feedback was not sufficient to affect outcomes. However, the overall high performance levels of the older adults group indicate that there was little necessity for improvement since performance mainly did not differ from the arguably near-optimal performance in the younger group (without vibration). It is unclear if the intervention used in this study could have positive effects if performance levels were lower, for example in patient populations and recurrent fallers. Additionally, it would be valuable to investigate if the intervention does have an effect in those individuals that suffer from mild or more severe cognitive impairments (and on their cognitive or postural performance).

The connection between postural stability, dual-tasking and cognitive impairments has been previously identified. As has been concluded from findings in a recent study including a large number of older adults (n=717), it is possible that dual-tasking performance correlates more with fall risk among individuals that suffer from pathological conditions than those who are healthy (Kang et al., 2013). The older group recruited for the current study consisted of high-functioning individuals, who live mostly independently and do not have any identified cognitive impairment. Earlier research has shown an age-dependent increase in the correlation between cognitive/intellectual abilities and sensorimotor function (Li & Lindenberger, 2002), with an increasingly negative age-dependent correlation between sensorimotor fluctuation and cognitive abilities (Li, Lindenberger, & Sikström, 2001). The group in our study exhibited higher sensory thresholds, but were very similar to the younger group on performance and postural control measures. Therefore, the high levels of cognitive function and sensorimotor function retained by this recruited group allowed for performance and control that was virtually indistinguishable from the younger group, with vibration having no effects on outcomes in either group.

5.3.3 Summary

Age is associated with certain aspects of postural control and performance in dual-tasking, however, differences between older and younger adults may be fairly small, depending on task complexity and characteristics of the older population tested. In this investigation dual-tasking was not affected by potential enhancement of sensory feedback from the foot soles via sub-threshold vibration.

5.4 Experiment 3

Experiment 3 was designed to investigate the differences between older and younger adults when facing postural perturbations. Further, we aimed to evaluate if a vibration intervention could affect temporal and spatial measures of postural performance and postural control, with the ultimate goal to improve performance when facing balance threats. Participants were instructed to quietly stand on the force plate, which then moved repeatedly in the posterior direction (posterior translation). Repeated trials were performed and spatial and temporal postural outcome measures analyzed.

5.4.1 Age-related associations

Our hypothesis was that older and younger adults' postural performance would differ, which was confirmed in one of the three outcome measures (APPlength). The effectiveness of neuromuscular responses when facing support surface perturbations depends on generation of muscular contractions of the lower body, and on the accuracy or adequacy of those responses. The main goal of the passive and active mechanisms in place for those situations is the avoidance of a fall; the prevention of excessive shifting of the body's COM. Alternatively, humans can react quickly by applying a stepping strategy to maintain balance (increasing the area of the base of support). In our study, participants were instructed to not step, if possible (no individual had to actually generate a stepping response in any of the trials), and therefore balance maintenance was based on a quick response strategy.

Our results from analysis of maximum COP excursion suggest that age is not necessarily associated with the maximum displacement of COP when facing postural perturbations. The observed similarities between older and younger adults may be due to a number of compensatory mechanisms and strategies. Although it is known that reaction times, muscular strength, and muscular coordination are affected by aging, excursion of COP during perturbations might be controlled in older humans by increasing the magnitude of muscular responses compared to younger adults, to counteract the surface translation. This is possible since the overall joint torques required to maintain balance in quiet stance or when facing perturbations are still generated by older adults (Gu et al., 1996). Alternatively, potential modification of balance strategies supports counteracting the sensorimotor effects of aging, as indicated by increased agonist-antagonist co-contraction associated with increased lower leg stiffness (Carpenter, Allum, Honegger, Adkin, & Bloem, 2004). Additionally, a reversal of muscle activation order (proximal-to-distal) has been reported as another strategy in older adults (Woollacott et al., 1986).

Results from perturbation studies in older adults are controversial, since some research has shown that aging does not affect COM measures (de Freitas et al., 2010), whereas other evidence suggests that aging increases COM and COP displacements in backwards- or forward platform perturbation (Gu et al., 1996; Nakamura et al., 2001; Okada, Hirakawa, Takada, & Kinoshita, 2001). Results from the current study support De Freitas et al. (2010) findings. De Freitas and colleagues found changes in onset of postural musculature EMG activity in older adults when facing postural perturbations and due to aging (starting at the fifth life decade). However, changes in EMG activity due to aging were not reflected in changes of kinematic measures (joint angle excursion for ankle, knee, and hip, maximum displacement of COM, and COM time-to-reversal after onset of perturbation). De Freitas results could be interpreted to suggest that earlier onset of neuromuscular activity is an adaptive strategy that enables older adults to maintain overall postural control strategies similar to those used by younger adults. Results from the current study provide evidence for the ability of healthy older adults to effectively maintain postural balance, similar to younger adults.

The findings regarding maximum COP excursions were accompanied by a lack of differences between older and younger group concerning corrective response latency. The measure was computed using a method described in an earlier study (Mueller & Redfern, 2004), but the determination of a definite onset of a voluntary corrective response proved to be more complex than expected. The authors of the earlier study had described characteristics of the first and second derivative of COP in a postural perturbation experiment, which then had been used to determine the instant when the muscular response to the perturbation causes an acceleration of the COP to reverse direction of displacement. The results from the current study showed this characteristic trace of COP derivatives required for the analytical method described in the former study only in few cases, whereas in many trials there was a lack of zero-crossings, or no observable breaking point to evaluate the onset. Thorough visual inspection of the datasets allowed for correction of the calculated onset times, but it is possible that the onsets of corrective responses as defined by this method are not particularly reliable.

Our final results differed from the Mueller & Redfern's study in that the average onset of voluntary corrective responses in the current data set was observed earlier after the onset of the postural perturbation. In our study, onset of corrective responses was observed primarily within the range of 120-140ms, whereas group averages in the earlier study were between 155-165ms. This discrepancy could be due to methodological differences between the two experiments. In the former experiment, the amount of translation was fixed, whereas in the current study, translation amplitude was calculated based on each participant's height. Additionally, in the current study, participants knew prior to each trial the perturbation's direction (posterior translation), whereas in Mueller & Redfern's study, 50 consecutive trials of randomized (25 anterior versus 25 posterior translations) order were conducted. Not having accurate knowledge of the direction of the impending perturbation would logically eliminate the ability to implement anticipatory activity that may have influenced response latency. Conversely, the current participants knew what direction the perturbation was to occur and could prepare accordingly. This would, in turn have an effect of response onsets. It is also possible that over the duration of 50 perturbation trials, onset of fatigue could have negatively affected latency over time and lead to results that were different from the ones in the current study.

In the current experiment, groups differed in APPlength, with the older adults displaying more COP total displacement over the course of each trial (2.5 seconds). This result is not in concordance with results from maximum COP excursion analysis. This may indicate a loss of postural stability with aging when facing perturbations of the support platform. Alternatively, it is possible that APPlength in our case is not an indicator of decreased postural performance, but an indicator of more exploratory behavior in the older group. As mentioned before, sway does not necessarily have to be regarded as a negative “by-product’ of postural control, but as a means of increasing sensory feedback. Sway stimulates muscle spindles and cutaneous receptors of the foot, which in case of experiment 3 are important contributors of sensory cues. This sensory information is then used to determine postural orientation and to generate effective responses. Potentially, the younger group required less sway since their sensory feedback operates at near-optimal levels, whereas older adults required this strategy for better performance.

5.4.2 Effects of sub-threshold vibration

The vibration intervention applied in both older and younger adults did not have significant effects on any of the analyzed outcome measures in this condition. Sensory feedback is considered crucial for the generation of corrective responses (with adequate force production) and the generation of postural adjustments, even before the onset of the perturbation. Relatively strong perturbations as administered in this experiment may not be affected by a fairly subtle improvement of sensory feedback. It is possible that SR effects are more likely to appear (per definition), when otherwise undetectable, small magnitude stimuli occur.

The neuromuscular responses following large excursions caused by the perturbation are controlled in a way that is not being affected by small detection improvements. However, it is still possible that over time (e.g. more trials), participants could benefit from enhancements of foot sole feedback to better prepare (e.g. a leaning strategy) for the perturbation and to learn to exploit the enhancement of foot sole feedback.

Alternatively, a reason for lack of effects is that in our study, participants performed at a very high level without application of vibration, and very similar performance levels compared to the younger group. Since the effects of SR may be dependent on baseline levels of performance (or sensory impairments), the group recruited for this study could have consisted of too “high-functioning” individuals.

5.4.3 Summary

Age is associated with some aspects of control in postural perturbation tasks, but age may not be associated with all balance outcome measures. Sub-threshold vibration appears to not enhance overall performance of participants in this specific task, independent of age.

Chapter VI. Summary, Limitations and future directions

6.1 Summary

The current study provides novel insight into age-related associations and potential of sub-threshold foot vibration for affecting or improving measures of postural performance and postural control. This is the first time a study investigated behavior of healthy older and younger individuals concerning postural characteristics in a series of demanding postural (or dual-) tasks, and the interaction of age and a potentially balance-enhancing intervention.

The custom-built rubber sole with integrated vibrotactile devices was shown to be an effective way to apply a low-level stimulus to the foot soles. Future designs of soles or insoles should be based on the parameters chosen for this study in terms of integration of vibrotactile devices, hardness of the sole and positioning of the tactors. The custom-built software for control of the vibrotactile devices showed to be simple and efficient. The sole design could be useful for other research related to both sub-threshold vibration research, or for applying perceivable vibration sensation, as an intervention of augmented feedback.

Results from experiment 1 showed that there are significant differences in postural performance between older and younger adults in a sensory conflict task; however, the observed differences were small, perhaps due to the health of the recruited sample. A sub-threshold vibration intervention may help to improve postural performance, but the current data suggests that the degree of improvement may depend on the current sensorimotor function levels of the individual.

Results from experiment 2 showed that a healthy, active group of older adults may be able to perform comparably to a younger adults group in a dual-task environment. That is, postural performance outcomes may not be different between older and younger adults; but cognitive processing may differ and be more demanding for older adults. This possibility is reflected in the increased response latencies in the n-back test observed in the older group relative to the young group. Vibration does not have an effect on performance and control characteristics, which may be due to the high-function levels of the older group or the nature of the dual-task features applied in the current study.

Results from experiment 3 show distinct differences between older and younger adults in a postural perturbation task, however, these differences depend on the choice of outcome variables to be analyzed, since aging might not be associated with changes of maximum excursion of COP, but in APPlength. Vibration does not affect performance or control in either a younger or high-functioning older adults group.

In general, effects of a subtle vibration intervention on postural performance and control characteristics appear to be highly context-dependent, as evidenced by effects of vibration in experiment 1, but not in experiments 2 and 3. This reflects how an intervention based on vibration could have value in specific contexts, but potential benefits may be limited to certain situations.

The discrepancy observed between different performance outcome measures highlights the importance of including a variety of different measures in postural control research. Although a number of different outcome measures may be predictors of falls, they detect and evaluate different components of postural performance and should be in concordance with experimental hypotheses. Analysis of a variety of different measures including spatial and temporal components is valuable to gain further insight into posture, and potential effects of aging or interventions.

6.2 Limitations

Several limitations have been identified either before or throughout the course of the study. First, the vibration applied at the foot soles was applied based on earlier designs and methodology from pioneering work in the field. Most studies used a three-point vibration application (1st and 5th metatarsal, heel). The most effective way to apply vibration would be to distribute vibration throughout the entire sole, which is difficult to achieve with the current design. The design of the rubber sole in the current study was based on earlier designs and incorporated suggestions from other researchers in the field.

Alternatively, it could be very efficient to have a single vibrotactile device underneath the first toe, which had the highest tactile sensitivity. This could potentially improve small sway detection compared to the less sensitive locations chosen in this study. The application of vibration was further limited to the same amplitude for all six vibrotactile devices embedded in the sole. There are significant differences in tactile sensation thresholds for different locations of the foot sole. For optimal use of SR, it would be valuable to adjust vibration amplitude based on the respective tactile device's position under the foot. The initial threshold test (vibration test) is based on the most sensitive location under the foot (1st metatarsal in the current study). The 90% amplitude chosen for stimulation during the experiments therefore is based on this specific location's sensitivity, whereas the amplitude does not correspond to 90% of vibration threshold at other locations. This means there could be a stimulus of only about 60%, for example, around the heel, which would affect the SR mechanisms we sought to evoke.

The recruitment of participants is another limitation that has to be considered and probably affected results and associated conclusions to be drawn from the study. Considering the exclusion and inclusion criteria we established, only healthy older adults with high levels of function were recruited. Although those individuals may exhibit higher sensory thresholds and slight decline regarding postural performance compared to younger individuals, differences were relatively small. Considering the idea of SR interventions being mainly effective in a more impaired sensorimotor system, function levels were too high too potentially to be able to observe changes in two out of three experiments.

Experiment 2 confronted participants with a dual-task environment, requiring concurrent postural and cognitive tasking. The current study was limited to the 1-back task, which may not be sufficiently taxing on the working memory system to affect postural control. 2 or 3-back tasks could have provided different results related to performance and aging.

Another limitation is the statistical power in the current study, based on the low number of participants. There is fairly high variability regarding most outcome measures in the older group, a higher number of participants would have provided more power, both in regards to comparison with younger adults and in regards to effects of the vibration intervention.

6.3 Future directions

Tactile SR has been shown mixed results in the past, with several studies reporting significant effects of the intervention on balance outcomes in a variety of populations. However, most evidence hints towards effectiveness only in more severely impaired individuals (stroke patients, diabetic neuropathies, recurrent fallers) and in more demanding tasks. Those individuals suffering from the aforementioned conditions usually are already using countermeasures or training interventions for prevention of (further) falls, for example walkers, canes, balance training etc. The question therefore remains whether SR interventions could be a valuable addition, or whether the results from our study concerning high-functioning individuals are indicating that future falls in healthy older adults could be prevented.

Further research could aim at investigating the effects of the presented intervention in individuals suffering from mild or more severe cognitive impairment, which could interfere with postural control in dual-tasks. It would be valuable to evaluate whether the intervention can affect performance in those individuals, compared to the current results in healthy older adults (experiment 2).

More sophisticated (in-sole) designs should be tested in a variety of populations, for example with insoles that take sensitivity gradients under the foot sole into consideration or make use of the more sensitive toe areas. As recent research has shown, there might be potential for applying sub-threshold vibration to other regions of the body in order to improve balance, for example to the fingers during light-touch. Future research could target different body areas, or combine foot vibration with vibration added through the hands (e.g. a walking cane).

VII. References

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Appendix A

UNIVERSITY OF HOUSTON
CONSENT TO PARTICIPATE IN RESEARCH

PROJECT TITLE: Vibration of the foot sole as an intervention to improve older adults' postural stability

You are being invited to participate in a research project conducted by Marius Dettmer from the Department of Health and Human Performance at the University of Houston. The project is part of Mr. Dettmer's doctoral dissertation. It is conducted under the supervision of Dr. Charles S. Layne.

NON-PARTICIPATION STATEMENT

Your participation is voluntary and you may refuse to participate or withdraw at any time without penalty or loss of benefits to which you are otherwise entitled. You may also refuse to answer any question. If you are a student, a decision to participate or not or to withdraw your participation will have no effect on your standing.

PURPOSE OF THE STUDY

The purpose of this study is to investigate if vibration applied to the foot sole during different upright stance tasks may improve balance. The duration of the entire study will be approximately 6 months.

PROCEDURES

All experiments will be conducted at the Center for Neuromotor and Biomechanics Research (CNBR) at the National Center for Human Performance (NCHP) in the Texas Medical Center. The CNBR is one of the UH research labs associated with the Department of Health & Human Performance. You will be one of approximately 20 subjects to be asked to participate in this project. There will be two groups, one younger participant group (ages between 18-35) and an older age group (70-85 years of age).

If you are willing to participate in the study, we will ask you to fill out a modified version of a Physical Activity Readiness Questionnaire (PAR-Q) and ask you about your height and current weight. The purpose of this is to evaluate if you meet all of the inclusion criteria for participants in this study. If you have severe impairments or a medical history that would put you at risk when participating, we would terminate the session at that point. If you meet the criteria, we will conduct a short, standardized test involving several questions and tasks. This is called a Mini-Mental State Exam which we will use to determine if there is any severe cognitive impairment that would require us to preclude you from the study. If there is such impairment, we would terminate the session at this point.

After this exam, we will test your foot sensitivity. We will use a small plastic filament to pinch the ball of both of your feet several times. This will not elicit any discomfort, but we will ask you whether you can feel that sensation. Based on your responses, we will determine whether you can be included in the study. You will then be asked to stand on a foam sole that has little vibrating chips embedded. We will turn on the vibration and ask if you can feel the vibration at different intensities. Once we have performed this test, we will start the first experiment.

For this experiment, you will be asked to step on a platform that allows us to measure forces exerted around the feet, called a force plate. You will stand on the foam sole including the vibrating chips. For each experiment, you will put on a harness that we will attach to a steel frame to prevent falls. For the first experiment, you will be asked to stand as quietly as possible with your arms crossed in front of your chest. On a "go" signal we will start measuring data while you try to stand quietly for 20 seconds. During this time, your visual environment will be tilting with you, according to your sway. You will perform six trials (three trials with vibration, three without) of this task, with breaks in between trials. You will be given another break after this experiment.

At the beginning of the second experiment, you will be asked to stand on the force plate again, on the foam sole. You will be asked to stand as quietly as possible during each of the trials, while performing a cognitive task. This means, you will be asked to memorize and repeat words you will hear via headphones. As in the first experiment, you will be asked to perform six trials (three trials with, three trials without vibration) and you will be given breaks in between trials. After finishing six trials, we will start the third experiment. You will be exposed to several sudden translations of the support surface. This means that the surface on which you stand will be shifting suddenly, which will require you to react to the shifting to maintain balance. On a "go" signal, there will be a delay of between one and two seconds, after which the surface will shift. After the first three familiarization trials, there will be larger shifts of the platform (large amplitude). You will perform ten trials with vibration either turned on or off (five on/five off), and you will be given a break after five trials. After ten total trials of platform shifts, the experimental session will be finished. We expect a time commitment of about 1.5-2 hours for the whole laboratory session including initial interview, testing and the experimental trials.

CONFIDENTIALITY

Every effort will be made to maintain the confidentiality of your participation in this project. Confidentiality will be maintained within legal limits.

RISKS/DISCOMFORTS

The experiments we are planning to conduct involve balancing tasks. Balancing tasks always involve the risk of falling. We will address this issue in several ways. First, you will be wearing a harness during all experimental trials. This will prevent any potential falls. Additionally, you will be instructed to take a step forward or backwards whenever you feel that you are losing balance. Third, there will be a spotter behind you who will stabilize you in case you are losing balance.

A possible discomfort includes fatigue. To prevent this discomfort, you will be allowed a rest of 30 seconds between trials. After a set of three trials, you will have a break of about two minutes. During all breaks, you will be able to rest in an armchair. We will ask you if you feel any fatigue, so if you need longer breaks, we will accommodate you.

In the unlikely event of unexpected events/problems during data collection, the principal investigator will immediately stop the protocol, assess the need for medical attention and if determined necessary notify emergency medical services (EMS) and remain with you until arrival of EMS. In the event you will not need medical attention, the principal investigator will assist you to recover and exit the study. The principal investigator will immediately report the incident to the appropriate University of Houston authorities. In the event of any harm resulting from your participation in this study, the University of Houston does not provide any financial compensation including costs for medical treatment

BENEFITS

There will not be any direct benefits associated with this study. However, your participation will not only allow you to gain insight into motor control research, but you will also help investigators to better understand how sensory information enhancement could help to improve postural control and balance. This could ultimately help to develop new technologies that may assist older adults to prevent falls

ALTERNATIVES

Participation in this project is voluntary and the only alternative to this project is non-participation.

INCENTIVES/REMUNERATION

There will not be any incentives associated with this study. You will be reimbursed for parking at the Texas Medical Center.

PUBLICATION STATEMENT

The results of this study may be published in professional and/or scientific journals. It may also be used for educational purposes or for professional presentations. However, no individual subject will be identified.

If you have any questions, you may contact Marius Dettmer at 713-743-9840. You may also contact Dr. Charles Layne, faculty sponsor, at 713-743-9840.

ANY QUESTIONS REGARDING YOUR RIGHTS AS A RESEARCH SUBJECT MAY BE ADDRESSED TO THE UNIVERSITY OF HOUSTON COMMITTEE FOR THE PROTECTION OF HUMAN SUBJECTS (713-743-9204).

Study Subject (print name): ____

Signature of Study Subject: ____

Date: ____

Principal Investigator (print name and title): ____

Signature of Principal Investigator: ____

Date: ____

Appendix B

Participant ID:

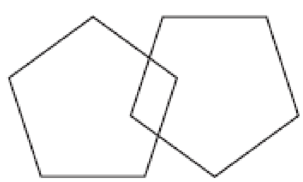
Date:

Used by permission of the Hartford Institute for Geriatric Nursing, Division of Nursing, New York University; available at: www.hartfording.org

The Mini-Mental State Exam

Patient____________________________ Examiner ________________________ Date__________

Maximum	Score	
		Orientation
5	( )	What is the (year) (season) (date) (day) (month)?
5	( )	Where are we (state) (country) (town) (hospital) (floor)?
		Registration
3	( )	Name 3 objects: 1 second to say each. Then ask the patient all 3 after you have said them. Give 1 point for each correct answer. Then repeat them until he/she learns all 3. Count trials and record. Trials __________
		Attention and Calculation
5	( )	Serial 7's. 1 point for each correct answer. Stop after 5 answers. Alternatively spell "world" backward.
		Recall
3	( )	Ask for the 3 objects repeated above. Give 1 point for each correct answer.
		Language
2	( )	Name a pencil and watch.
1	( )	Repeat the following "No ifs, ands, or buts"
3	( )	Follow a 3-stage command: "Take a paper in your hand, fold it in half, and put it on the floor."
1	( )	Read and obey the following: CLOSE YOUR EYES
1	( )	Write a sentence.
1	( )	Copy the design shown.



	_____	Total Score
		ASSESS level of consciousness along a continuum __________
		Alert Drowsy Stupor Coma

"MINI-MENTAL STATE." A PRACTICAL METHOD FOR GRADING THE COGNITIVE STATE OF PATIENTS FOR THE CLINICIAN. *Journal of Psychiatric Research*, 12(3): 189-198, 1975. Used by permission.

Appendix C

Modified Physical Activity Readiness Questionnaire (PAR-Q)

For most people physical activity should not pose any problem or hazard. PAR-Q has been designed to identify the small number of adults for whom physical activity might be inappropriate or those who should have medical advice concerning the type of activity most suitable for them. Common sense is your best guide in answering these few questions. Please read them carefully and mark the yes or no opposite the question as it applies to you.

Yes	No	1) Has a physician ever said you have a heart condition <u>and</u> you should only do physical activity recommended by a physician?
Yes	No	2) When you do physical activity, do you feel pain in your chest?
Yes	No	3) in the past month have you had chest pain when you were not doing physical activity?
Yes	No	4) Do you lose your balance because of dizziness or do you ever lose consciousness?
Yes	No	5) Do you have a joint or a bone condition or problems with your feet? If so, specify:
Yes	No	6) Do you have insulin dependent diabetes or related conditions? If so, specify:
Yes	No	7) Do you have any breathing difficulties or suffer from asthma?
Yes	No	8) Do you suffer from epilepsy?
Yes	No	9) Do you have any neurological conditions? If so, specify:
Yes	No	10) Have you had a major operation? If so, specify (what, when):
Yes	No	11) Do you suffer from any other medical conditions? If so, specify:
Yes	No	12) Do you know of any other reason you should not exercise or increase your physical activity?
Yes	No	13) Are you using any medication currently or have been using any in the last week? If so, what kind of medication did you use?
Yes	No	13) Are you able to stand upright for four to five minutes?

Appendix D

PARTICIPANT RECRUITMENT SCRIPT

The initial interview for recruitment for the older age group will be conducted by the principal investigator. During the initial interview, the prospective participant will be given an overview of the study. The prospective participants will then be interviewed to determine eligibility to participate based on the PAR-Q and other information (age, height, weight). If the answer to any question will indicate breach of inclusion / exclusion criteria, the prospective participant will be informed that they are not eligible to participate. They will be thanked for their time commitment. They will be encouraged to ask any unanswered questions associated with the study. In case all inclusion criteria are met, the prospective participant will be offered to make an appointment to come to the laboratory and to participate in the study.

Activity	Detail & Purpose	Stop/Go
Introduction of the PI	Position: PhD-candidate at UH/HHP/CNBR with a research interest in Neuromotor Control, aging, prevention of falls, Background in Exercise Science	
Prospective participant prompted for questions they may have	Address potential concerns	
PI provides overview of the study	Background: Vibration of the foot sole as a technique to increase sensory functioning Significance: Understanding of control mechanisms of postural balance, improvement of balance Methodology: Standing on foam soles with embedded vibrating chips while performing different tasks Expected time commitment: 1.5-2 hours Potential discomforts: mild fatigue Participant rights: terminate participation at any time Benefits: participation in novel research	
Prospective participant prompted for questions they may have	Inform participant about the study; address potential concerns	
PI asks the participant to state their age, height and weight	Determine eligibility to participate in the study based on age (70 -85 years of age eligible to participate)	
PI administers PAR-Q (reads instructions, marks answers)	Determine eligibility to participate in the study based on general health status and potential injuries or medical diagnoses	
Prospective participant prompted for questions	Inform participant about the PAR-Q; address any concerns	
PI proposes scheduling data collection appointments	PI informs participant about the data collection	
Exchange of contact information with the participant	Ability to contact the participant (reminders, scheduling changes, etc.)	

Appendix E

CENTER for NEUROMOTOR and BIOMECHANICS RESEARCH CNBR

UNIVERSITY of HOUSTON
A CARNEGIE-DESIGNATED TIER ONE PUBLIC RESEARCH UNIVERSITY

Health & Human Performance

The National Center for Human Performance — Texas Medical Center

Does foot sole vibration improve your balance?

Healthy adults needed for sensory enhancement study

- You should be healthy and between 20-35 years or 70-85 years old
- You should be able to stand upright for periods of 4-5 minutes
- Be part of an investigation of state of the art sensory enhancement technology
- Participate in a study that may help to improve older adults' balance
- The test session will be performed at the Texas Medical Center in Houston
- The test session will take approximately 100-110 minutes

For information on participating in this study, please contact us at
(713) 743-9272 or madettmer@uh.edu
This project has been reviewed by the University of Houston Committee for the Protection of Human Subjects (713)743-9204