THE VESTIBULAR SYSTEM: ITS ROLE IN POSTURAL CONTROL AND ITS FUNCTIONAL ASSESSMENT USING SPATIAL ORIENTATION

by

Fang Zhang

A thesis submitted to the Graduate Program in the School of Rehabilitation Therapy in conformity with the requirements for the

Degree of Doctor of Philosophy

Queen’s University

Kingston, Ontario, Canada

September, 2015

Copyright © Fang Zhang, 2015
Abstract

The vestibular system plays a role in postural control and spatial orientation. Ageing adversely affects vestibular function, postural control and the ability to maintain accurate spatial orientation. Study I investigated the interaction of vestibular input with lower limb somatosensory and visual inputs for head and trunk control during normal walking (NW) and narrow-based walking (NBW) and the effect of age on these interactions. The association of clinically measured functions of the vestibular system, lower limb somatosensation and vision with head/trunk control in the frontal plane during NW and NBW, and the impact of age were also examined. Study II evaluated the inter-trial reliability of three tools which can be used to screen for vestibular dysfunction via assessing spatial orientation, in young and older participants, and their sensitivity of these tools to age-related difference in vestibular function. In Study I, 15 young (25.40±3.56 years, 7 females and 8 males) and 15 older (72.60±5.33 years, 8 females and 7 males) were asked to perform NW and NBW. Vestibular, lower limb somatosensory and visual information was manipulated using galvanic vestibular stimulation, medium density foam and blurring goggles respectively; either concurrently or individually. The variables representing head control were more affected by visual and vestibular manipulation. The variables representing trunk control were more affected by lower limb somatosensory manipulation. Further, trunk roll angle during NW was significantly associated with lower limb vibration sensitivity, indicating the importance of lower limb somatosensory signals for trunk control. Age-related
difference was only reflected in head control. In Study II, 15 young (28.27±4.61 years, 7 females and 8 males) and 15 older (75.47±4.42 years, 7 females and 8 males) were asked to perform 6 trials of each of the Fukuda Stepping Test (FST), Triangle Walking Test and Straight Walking Test. Reliability and variability of all the relevant variables in the tests were evaluated. Distance of displacement (DD) in the FST was the only variable that exhibited moderate to high reliability and acceptable variability in both age groups. DD was also significantly higher in the older group, suggesting its sensitivity to potential age-related difference in vestibular function.
Co-Authorship

This thesis includes two main studies Study I (Chapter 3) and Study II (Chapter 4). Two manuscripts have been published and one manuscript has been prepared for submission, based on the work presented in Chapter 3. The authorship is as follows:


2. Zhang F, Deshpande N. Age-related differences in sensory interactions for head and trunk control in space during normal and narrow-based walking. Motor Control (in press). (The contribution of Fang Zhang: data collection, data analysis and manuscript writing)

3. Zhang F, Deshpande N. Association between Sensory Inputs and Head/Trunk Control: Effect of Aging (prepared for submission). (The contribution of Fang Zhang: study design, data collection, data analysis and manuscript writing)

One manuscript has been prepared for submission based on the work presented in Chapter 4. The authorship is as follows:

1. Zhang F, Culham E, Deshpande N. Assessing vestibular function via spatial orientation: test-retest reliability and sensitivity of 3 protocols (prepared for submission). (The contribution of Fang Zhang: study design, data collection, data analysis and manuscript writing)
Acknowledgements

First and foremost I would like to thank my supervisor Dr. Nandini Desphande for her time and dedication in helping me to achieve all the works included in this thesis. More importantly, it is she that leads me to the field of rehabilitation science research.

I would like to also thank the members of my advisory committee: Dr. Elsie Culham, who is my co-supervisor and Dr. Kathleen Norman. Your comments on my research works have been extremely important and helpful.

I would like to thank Debra Hamilton, Jean Jeffery and Sharon David for all the detailed things that you have done, ranging from academy to finance, to support all the graduate students. I am also grateful to Tessa Elliot, Katherine Lee and Sebastian Speers for their assistance in data collection. I also thank all the volunteers who participated in my studies especially the older participants. Your devotion is highly appreciated.

I am grateful to my parents in China for their love and unconditional support throughout my life. Also, thank you to my friends in both Canada and China for your encouragement.

The first three studies included in this thesis were supported by the Senate Advisory Research Committee, Queen’s University.
# Table of Contents

Abstract ................................................................................................................................. ii

Co-authorship ........................................................................................................................ iv

Acknowledgements ............................................................................................................... v

Table of Contents ............................................................................................................... vi

List of Tables ..................................................................................................................... x

List of Figures ................................................................................................................... xi

List of Abbreviations ....................................................................................................... xiii

Chapter 1 Introduction ...................................................................................................... 1

1.1 Outline of the Thesis ................................................................................................. 8

1.2 References ................................................................................................................ 11

Chapter 2 Literature Review ..................................................................................... 15

2.1 Introduction ............................................................................................................... 15

2.2 Investigation of Sensory Function for Postural Control ........................................ 15

2.2.1 Manipulation of Vestibular Signals .................................................................. 15

2.2.2 Manipulation of Visual Information ............................................................... 18

2.2.3 Manipulation of Lower Limb Somatosensory Information ............................... 19

2.3 Sensory Information and Interactions for Postural Control .................................... 21

2.3.1 The Role of the Vestibular System in Postural Control .................................... 23

2.3.2 The Role of the Visual System in Postural Control ......................................... 26

2.3.3 The Role of the Lower Limb Somatosensory System in Postural Control .......... 27

2.3.4 The Role of Sensory Interaction in Postural Control ....................................... 27

2.4 Effects of Age on Sensory Inputs and Sensory Interactions ................................... 32
Chapter 4 Inter-trial Reliability and Sensitivity of 3 Protocols Designed to Screen for Vestibular System Function via Spatial Orientation

4.1 Abstract

4.2 Introduction

4.3 Methods

4.3.1 Participants

4.3.2 Procedures and Outcome Measures

4.3.3 Statistical Analysis

4.4 Results

4.4.1 Fukuda Stepping Test

4.4.2 Triangle Walking Test

4.4.3 Straight Walking Test

4.5 Discussion

4.5.1 Reliability and Variability of the Three Tools

4.5.2 Sensitivity to Age-related Differences

4.6 Limitations

4.7 Conclusion

4.8 Reference

Chapter 5 General Discussion

5.1 Introduction

5.2 Role of Sensory Signals/Interactions in Head Control

5.3 Role of Sensory Signals/Interactions in Trunk Control

5.4 Screening for Vestibular Function via Spatial Orientation
5.5 Future Directions........................................................................................................157
5.6 Summary.....................................................................................................................159
5.7 Reference....................................................................................................................160

Appendix A Curriculum Vitae of the Author....................................................................163
Appendix B Ethics Approval for Study I (Chapter 3)..........................................................166
Appendix C Ethics Approval for Study II (Chapter 4)..........................................................168
Appendix D Letter of Information and Consent for Study I (Chapter 3)..............................171
Appendix E Brief Medical/Clinical Information Form for Study I (Chapter 3)......................174
Appendix F Letter of Information and Consent for Study II (Chapter 4)...............................175
Appendix G Brief Medical/Clinical Information Form for Study II (Chapter 4).....................178
Appendix H Waterloo Footedness Questionnaire...............................................................179
Appendix I Head roll angle, head pitch angle, trunk roll angle and trunk pitch angle in normal walking condition with GVS from one trial in one older participant.................................180
Appendix J Head roll angle, head pitch angle, trunk roll angle and trunk pitch angle in normal walking condition with GVS from one trial in one young participant.................................181
Appendix K Results of paired t test between two trials in the young and older group...........182
Appendix L Results of bivariate correlation analysis between head roll angle/trunk roll angle/head-trunk correlation in normal (NB) and narrow-based walking condition (NBW) (without any manipulation) and all the sensory functions in Study I (Chapter 3).....................................................183
List of Tables

Table 3.1 Sensory function assessments.................................................................................................................66
Table 3.2 The table shows the adjusted significance level for each variable.........................................................78
Table 3.3 The table shows the average age, height and weight of the young and older participants............................................................79
Table 3.4 Correlation coefficient and the corresponding p value for each sensory measure associated with head control, trunk control or head-trunk coordination during both normal walking and narrow-based walking.................................................................94
Table 4.1 Intra-class correlation coefficients (ICC), coefficients of variability (CV) and means and ranges of all the variables included in the Fukuda Stepping Test in both young and older participants................................................................................................................135
Table 4.2 The result of t test on distance of displacement between young and older group........................136
Table 4.3 Intra-class correlation coefficients (ICC), coefficients of variability (CV) and means and ranges of all the variables included in the Triangle Walking Test in both young and older participants................................................................................................................137
Table 4.4 Intra-class correlation coefficients (ICC), coefficients of variability (CV) and means and ranges of angle of deviation included in the Straight Walking Test in both young and older participants................................................................................................................140
List of Figures

Figure 3.1 The setup of the ten infrared emitting diodes.................................................................67

Figure 3.2 The position of the two Optotrak cameras with respect to the walking path. ..........67

Figure 3.3 The figure displays the direction of trunk and head movements: a: pitch (sagittal plane) and b: roll (frontal plane).............................................................................................................................................76

Figure 3.4 Average gait speed (m/s) (mean ± SD) increased with GVS (p<0.001) but decreased with narrow-based walking (p=0.03)..................................................................................................................................................81

Figure 3.5 Average head roll (degrees) (mean ± SD) increased with GVS on the foam (p=0.006) (d) but not firm surface (p=0.26) (c) in the older but not in the young group (a and b)......................83

Figure 3.6 Line graphs of head roll angle. (a) and (b) display head roll angle in no GVS and GVS condition on the foam surface in one young participant, respectively. (c) and (d) demonstrate head roll angle in no GVS and GVS condition on the foam surface in one older participant, respectively..................................................................................................................................................83

Figure 3.7 Data of average head roll angle for each participant in GVS condition compared to no GVS condition on firm and foam surface in young and older participants.................................84

Figure 3.8 Line graphs of head pitch angle. (a) and (b) display head pitch angle in narrow-based walking condition one young participant and one older participant, respectively......................85

Figure 3.9 Average trunk roll (degrees) (mean ± SD) increased with GVS (p=0.004) and narrow-based walking (p=0.001) on the foam (b and d) but not on the firm surface (a and c)..................................................................................................................................................86

Figure 3.10 Average trunk pitch (degrees) (mean ± SD) increased on the foam surface (p<0.001) (a) and with GVS (p=0.02) (b)..................................................................................................................................................87
Figure 3.11 Line graphs of trunk pitch angle. (a) and (b) display trunk pitch angle in GVS and on the foam surface in one young participant, respectively. (c) and (d) demonstrate trunk pitch angle in GVS and on the foam surface in one older participant, respectively.

Figure 3.12 Average head roll velocity (degree/s) (mean ± SD) decreased with goggles (p=0.016) and narrow-based walking (p=0.012).

Figure 3.13 Average trunk pitch velocity (degree/s) (mean ± SD) increased with GVS (p=0.002) (a) but decreased with narrow-based walking (p=0.002) (b).

Figure 3.14 Line graphs of trunk pitch velocity. (a) and (b) display trunk pitch velocity in GVS condition in one young participant and one older participant, respectively.

Figure 4.1 This figure shows where the markers were on the shoes, and how the variables were calculated for the Fukuda Stepping Test.

Figure 4.2 This figure shows how the triangle walking test was performed.

Figure 4.3 This figure shows how the straight walking test was performed and how the variable (angle of deviation) included in the test were calculated.
List of Abbreviations

- **GVS**: galvanic vestibular stimulation
- **M-L**: medio-lateral (direction)
- **A-P**: anterio-posterior (direction)
- **NB**: normal walking
- **NBW**: narrow-based walking
- **CNS**: central nervous system
- **PIVC**: parieto-insular vestibular cortex
- **VIP**: ventral intraparietal cortex
- **MSTd**: dorsal medial superior temporal extrastriate cortex
- **TPJ**: temporo-parietal junction
- **VNG**: Videonystagmography
- **VOR**: vestibulo-ocular reflex
- **UVD**: unilateral vestibular deficit
- **CPAT**: cerebellar-pontine-angle-tumour
- **FST**: Fukuda Stepping Test
- **TWT**: Triangle Walking Test
- **SWT**: Straight Walking Test
- **DD (in FST)**: distance of displacement
- **AS (in FST)**: angle of self-rotation
- **AD (in FST)**: angle of displacement
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DE (in FST)</td>
<td>distance error</td>
</tr>
<tr>
<td>DiE (in FST)</td>
<td>directional error</td>
</tr>
<tr>
<td>AE (in FST)</td>
<td>arrival error</td>
</tr>
<tr>
<td>AD (in SWT)</td>
<td>angle of deviation</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

The vestibular system plays an important role in both postural control and spatial orientation (1-3). Postural control is defined as the control of the body segments in space, and has been described as having two components: postural orientation and postural equilibrium (1;4). Postural orientation involves the active control of body alignment with respect to gravity, support surface, visual environment and internal references (1;4). Postural equilibrium involves the coordination of sensorimotor strategies to stabilize the body’s center of mass (COM) with respect to base of support (BOS) during both self-initiated and externally triggered disturbances (1;4). Postural equilibrium has also been referred to as postural stability, or balance which is a generic term describing the dynamics of body posture to prevent falling (1;5). Postural control is required during both standing and locomotion. During standing on both feet, the projection of the COM needs to be controlled within the BOS as defined by the position of the feet (1;6). During locomotion, the COM falls outside the BOS approximately 80% of one stride cycle and has to be recaptured by the precise placement of the swinging leg (1;5). Therefore, postural control during locomotion could be more challenging compared to that during standing (1;5).

Postural control requires sensory inputs primarily from the vestibular, visual and somatosensory systems. The vestibular system detects linear as well as angular
acceleration of the head around the anterio-posterior (A-P), medio-lateral (M-L) and vertical axes (1;2;7). It is also influenced by gravity and provides the CNS with a vertical reference with regard to gravity (1;2;7). Further, it directly contributes to postural control by aligning the head and trunk to the gravitational vertical reference through the vestibulo-colic reflex and vestibulo-spinal reflex, respectively (1;2). The visual system provides the central nervous system (CNS) with information of position and motion of the body with regard to the surrounding environment (1;8). Somatosensory information, especially lower limb somatosensory input, is also important for postural control as it conveys information of the motion and position of body segments with respect to each other and the supporting surface (1;9;10). For example, muscle spindles and the golgi tendon organs provide the CNS with information about the muscle’s length and contraction, articular receptors detect joint movement, and cutaneous mechanoreceptors on the soles of the feet respond to mechanical stimuli (1;9;10).

The CNS weighs and integrates sensory inputs from the three systems (11-15). Both patients with vestibular deficits and healthy people with manipulated vestibular signals have the ability to override the lost or impaired vestibular input using accurate visual and/or lower limb somatosensory inputs (11-15). For example, little or no difference was found between healthy participants and patients with vestibular dysfunction in terms of postural control during simple activities such as standing when visual and lower limb somatosensory inputs were accurate (15). However, when visual and/or lower limb somatosensory input were manipulated, significant differences were found in trunk roll
or pitch angle (15). Similarly, manipulated vestibular signals have been reported to have a significantly lesser impact on postural control, as measured by lower head roll and/or trunk roll angle in healthy persons when visual and lower limb somatosensory inputs were accurate, compared to when visual or lower limb somatosensory input was manipulated (11;13;14).

Postural control during standing and locomotion is commonly measured in the sagittal and frontal planes (13-15). Postural control in the frontal plane deserves special attention because of its faster and earlier age-related deterioration compared to that in the sagittal plane (16;17), and its close association with hip fracture in older adults (18;19). Accurate vestibular input is important for postural control in the frontal plane. When vision was occluded, patients with impaired vestibular function have been reported to exhibit worse postural control ability in the frontal plane compared to healthy persons during both standing and locomotion (12;15). Due to its importance, postural control ability in the frontal plane during locomotion is commonly included as a component of motor performance assessment especially for older people (20;21). For this purpose, narrow-based walking is oftentimes used whereby individuals are asked to walk on a narrow path that imposes constraints to foot placement in the frontal plane; therefore reducing the BOS in M-L direction.

The head and trunk are possibly the most important body segments for overall postural control during both standing and locomotion (1;12;22;23). The head contains both the
visual and vestibular sensory receptors. The control of both angular displacement and velocity of head movement is important to provide a stable platform for these two systems (1;22). The trunk has the largest body mass compared to any other body segments, and this mass must be controlled for efficient progression during locomotion (23). A large deviation of the trunk from the vertical position and/or trunk movement at high velocity that increases momentum may impose challenge for postural control (23). During standing, accurate visual and/or lower limb somatosensory information can compensate for vestibular deficit or manipulation for the control of head and trunk displacement and/or movement velocity (14;15). During locomotion, accurate visual information can be used to override the impact of vestibular deficit or manipulation for the control of head and trunk angular displacement (11-13). However, it is not known whether lower limb somatosensory input can be used to down-regulate inaccurate vestibular inputs for head and trunk control during locomotion. Similarly, whether visual input can be used to override inaccurate vestibular inputs for the control of head and trunk angular velocity during locomotion has not been investigated.

Changing gait speed and step characteristics are also strategies for achieving postural control during locomotion (24;25). For example, decreasing gait speed, adopting shorter step length and greater step width are regarded as conservative strategies for postural control during locomotion (24;25). Further, increased step-to-step variability in step length and step width has been found to relate to gait unsteadiness or fall risk (26-28).
However, the significance of specific changes in the magnitude of step variability has been debatable in the scientific literature (29;30).

Age-related deterioration in sensory function is well known (10;31-35). Additionally, age-related deterioration of the CNS has been reported to adversely affect the ability of the CNS to integrate multiple sensory inputs and compensate for unreliable or discordant sensory information (13;32). However, the impact of age on how the vestibular system interacts with lower limb somatosensory or visual input for head and trunk control during both normal and narrow-based walking is largely unknown. Therefore, the first study in this thesis investigated the impact of vestibular-lower limb somatosensory and vestibular-visual interaction on head and trunk control during both normal and narrow-based walking and the impact of age as the main objective. The secondary objective was to investigate the association of head and trunk control in the frontal plane during normal and narrow-based walking (without any sensory manipulation) with clinically measured sensory function of the three systems and possible age-related differences in these associations. The secondary objective serves as a supplemental analysis to further confirm the findings from the main objective/analysis. The results from this study could help us better understand the mechanism of head and trunk control during locomotion, and develop rehabilitation interventions, including patient education, to increase postural control ability and therefore mobility and promote safety especially in patients with sensory deficits or older people.
The vestibular system plays an important role in not only postural control, but also in spatial orientation. Spatial orientation addresses the questions of "Which way am I facing" or "Where am I going". It is generally defined as the sense/ability to keep track of the relationship of the body to a place/target in space (36;37). During walking, especially linear walking, spatial orientation is about planning and maintaining a walking orientation for efficient progression (38). Spatial orientation is also required in the task of non-linear path completion (39) or stepping-in-place (40). Larger linear and/or angular deviation from the designated target/path are considered as lower ability to maintain spatial orientation. Spatial orientation is not a component of postural control, but could be related to it (38;41). For example, larger trunk roll, triggered by galvanic vestibular stimulation (GVS), during linear walking was associated with larger deviation in the same direction from the linear path (38). Furthermore, the ability to maintain spatial orientation is largely dependent on visual and vestibular signals, which are also required for postural control (3;38;39).

It is obvious that the effect of vision on spatial orientation is dominant. Patients with vestibular deficits or healthy adults with manipulated vestibular input are able to maintain accurate spatial orientation with visual information available (3;39;41). Without visual input, vestibular deficit or experimental manipulation of vestibular information significantly decreases the accuracy of spatial orientation during both locomotion and stepping-in-place despite normal somatosensation (3;39;41).
Based on the role of the vestibular information in spatial orientation, several simple clinical/experimental spatial orientation tests have been developed to screen for vestibular deficits. These tests include the Fukuda Stepping Test, the Triangle Walking Test and the Straight Walking Test (39;41;42). In the Fukuda Stepping Test, blind-folded participants are asked to step in place for 50 or 100 steps and deviation from the original standing point is recorded (42). In the Triangle Walking Test, blindfolded participants are instructed to complete a triangular path (39). The Straight Walking Test requires blindfolded participants to walk straight to a previously seen target (41). The deviation from the designated path/target is measured. Previous studies (39;41;42) have shown that without visual input, compared to healthy participants, patients with vestibular deficits exhibit greater deviations from the intended target or path in all three tests, which suggests decreased ability to maintain accurate spatial orientation due to impaired vestibular function.

As previously noted, the vestibular system suffers from age-related deterioration, possibly contributing to impaired postural control in older adults (33;43). It is possible that the spatial orientation tests could be used to detect age-related differences in the vestibular function. Prior to the investigation of the sensitivity of these tests to age-related differences, the reliability and variability of the measures obtained using these tests need to be assessed. Therefore, in Study II the reliability and variability of the Fukuda Stepping Test, Triangle Walking Test and Straight Walking Test were assessed in
both young and older participants. The sensitivity of these tests to age-related differences was also investigated.

1.1 Outline of the Thesis

This thesis contains four chapters in addition to the introduction. Chapter 2 of the thesis provides a review of the literature on the role of sensory inputs and sensory interactions in postural control and age-related differences. The review also outlines the methods of sensory manipulation commonly used to investigate the impact of sensory information on postural control. The tests used to screen for vestibular deficits based on the role of the vestibular system in spatial orientation, including the Fukuda Stepping Test, Triangle Walking Test and Straight Walking Test, are also described in the review of literature.

The major purpose of Study I (Chapter 3) was to investigate the role of vestibular input and sensory interactions in head and trunk control during the normal and narrow-based walking conditions and possible impact of age on such role. The first main objective was to study vestibular-lower limb somatosensory interaction for head and trunk control in both the normal and narrow-based walking condition in young and older persons. The second main objective was to study vestibular-visual interaction for head and trunk control in both the normal and narrow-based walking condition in young and older persons. The secondary purpose of Study I was to investigate the association of head/trunk control in the frontal plane during normal and narrow-based walking (without any sensory manipulation) with sensory function in both young and older
persons. Fifteen healthy young and 15 older healthy participants were recruited, and their sensory function of the visual, vestibular and somatosensory systems was assessed. Head and trunk control were examined under the normal walking and narrow-based walking conditions with various sensory manipulations. Visual, vestibular and lower limb somatosensory inputs were manipulated using blurring goggles, galvanic vestibular stimulation (GVS) and foam, respectively; either individually or concurrently. The two walking conditions were performed under eight sensory manipulations: visual input (normal/goggles) X vestibular input (normal/GVS) X lower limb somatosensory input (normal/foam). Repeated measure ANOVA was used to understand the effect of sensory inputs and interactions on head and trunk control during both normal and narrow-based walking.

The specific objectives of Study II (Chapter 4) were 1) to assess the inter-trial reliability of three vestibular deficit screening tools in young and older persons; and 2) to investigate the sensitivity of the three tools to age-related difference in vestibular function. Fifteen healthy young and 15 healthy older participants were recruited, and were asked to perform 6 trials of each of the Fukuda Stepping Test, the Triangle Walking Test and the Straight Walking Test, respectively. The inter-trial reliability and variability of all the variables included in the three tests were assessed. The variables that demonstrated moderate to high reliability and acceptable variability were selected and compared between the two age groups in order to understand the sensitivity of the tests to age-related differences in the vestibular function. Intra-class coefficient (ICC)
and coefficient of variation (CV) were selected to assess reliability and variability of all the variables, respectively. Independent t test was used to investigate the sensitivity of the tools to age.

Lastly, Chapter 5 provides an overview of the new and important findings from the two studies in the context of the previous research along with their clinical relevance. Alternative explanations for the new and important findings are provided along with future research directions.
1.2 Reference


Chapter 2

Literature Review

2.1 Introduction

This review of the literature includes a description of common methods used to manipulate the vestibular, visual and lower limb somatosensory inputs. This is followed by knowledge about the role of these sensory systems and sensory interactions in head and trunk control, as well as age-related differences. The role of the vestibular system in spatial orientation and the vestibular dysfunction screening tools based on spatial orientation are also described.

2.2 Investigation of Sensory Function for Postural Control

The role of sensory inputs and sensory interaction in postural control is investigated using patients with sensory deficit usually in one system (1-3). Alternatively, experimental manipulation of sensory information from one or more systems has offered another way to assess the role of sensory inputs and sensory interactions (4-6).

2.2.1 Manipulation of Vestibular Signals

Postural control has been measured in both healthy participants and patients with diseases which impair the vestibular system, for example cerebellar-pontine-angle-tumour (CPAT) and unilateral and bilateral vestibular disorders, in tasks such as standing
and locomotion (1;7;8). The patients exhibited decreased trunk control ability compared to healthy participants, as measured by velocity and/or angle of trunk roll and/or pitch, during difficult tasks without any manipulation (e.g. standing on one leg) and standing and walking when other sensory system(s) are manipulated (1;7;8).

Aural irrigation (also called caloric vestibular stimulation) with cold or hot water and use of galvanic vestibular stimulation (GVS) are methods of vestibular manipulation (6;9-11). Aural irrigation with cold or hot water leads to a temperature gradient across the labyrinth which changes endolymph density. This generates forces which displace the endolymph-cupula system thereby stimulating the vestibular receptors (9). Caloric vestibular stimulation is performed by alternate irrigation of the external meatus using cold and hot water. After the irrigation, the function of vestibular reflex (e.g. vestibulo-ocular reflex (12)) or the muscle nerve activity (e.g. muscle sympathetic nerve activity (10)) is measured. Therefore, caloric stimulation is usually used to examine the function of the vestibular system to screen for vestibular neuropathy or to assess the impact of vestibular stimulation on muscle nerve activity. Caloric stimulation has been reported to alter muscle sympathetic nerve activity responses (10), and has been included in vestibular deficit diagnostic tests such as videonystagmography (13;14). However, it is rarely used to investigate the role of vestibular input in postural control.

Galvanic vestibular stimulation (GVS) is a common way to manipulate vestibular information in order to investigate its role in postural control (6;11;15;16). By applying
the anode of GVS on the mastoid process on one side and cathode on the other, a mild galvanic current brings about increased transmission rate of the vestibular nerve under the cathode and decreased transmission rate of the vestibular nerve under the anode (16). The impact of GVS on anterior and posterior semicircular canals is strong while its effect on the horizontal canal and otolith is weaker (16). Therefore, GVS mainly signals a head roll to the cathodal side when applied (16;17). As a result, participants will roll both head and trunk to the anodal side to compensate for the GVS-induced head roll during both standing and locomotion (6;16;17).

GVS is delivered by a stimulator through a constant current stimulus isolation unit (6;18). Each individual’s threshold for GVS varies and is determined prior to data collection (6;18). Participants are asked to stand with their feet together while the stimulus intensity is gradually increased by an investigator. Threshold is determined when upper body movement is observed by the investigator or the participant reports any sensations of dizziness or disorientation (6;18). Deshpande and Patla (6) showed that GVS at an intensity of 2 times the healthy participants’ threshold could induce significant increase in average trunk roll angle to the anodal side compared to the condition without GVS during locomotion; while 4 times threshold did not induce significant increase in average head roll angle. Bent et al. (18) applied GVS at heel contact, or mid-stance, or toe-off to healthy young participants at three times the individual threshold with intensities ranging from 1.0 mA to 1.5 mA. In all the conditions,
GVS induced significant head roll and trunk roll compared to the condition without manipulation.

2.2.2 Manipulation of Visual Information

There are a limited number of studies which investigated differences in postural control between patients with visual disorders and healthy participants (19;20). Portfors-Yeomans and Riach (19) measured standing postural control of healthy children with normal vision (aged 4 to 12) and patients (aged 5 to 12) with impaired vision. The results showed higher total power, a measure of sway magnitude, in the patients compared to the healthy participants (19). Epidemiological studies have also identified decreased visual acuity and visual contrast sensitivity as fall risk factors in older people (21;22).

The Sensory Organization Test (SOT) is a method used to investigate the effect of visual and lower limb somatosensory input on postural control during standing. The test includes six sensory conditions which become progressively more difficult (23;24). In the 6 conditions, visual input and lower limb somatosensory input are manipulated either concurrently or individually (23;24). Visual manipulation is achieved by closing eyes or through use of a visual surround in which the screen surrounding the subject sways with the participants’ anterio-posterior (A-P) sway (sway-referenced), therefore maintaining the visual field a constant distance from the participants’ eyes (23;24). Three visual manipulations are included in SOT: no manipulation, eyes closed and sway-referenced vision. Manipulation of visual input alone in SOT has been reported to significantly
increase displacement of center of pressure (COP) in A-P direction and the standard deviation of the displacement during standing in young healthy participants (23).

Blurring goggles have been used in order to understand the role of visual input in postural control during locomotion (6;25;26). The goggles simulate severe cataract, which reduce contrast sensitivity by up to 50% (6;25;26). Participants are asked to perform different locomotion tasks, such as stepping up or down and walking straight with and without wearing blurring goggles (25;26). Wearing goggles leads to worse postural control during single limb support as measured by larger fluctuation of root mean square of the COP position in M-L direction during stepping up and down (25;26). Wearing goggles also impaired the ability to use visual input to compensate for manipulated vestibular signals for trunk roll angle during locomotion (6).

2.2.3 Manipulation of Lower Limb Somatosensory Information

Patients with peripheral neuropathy and decreased lower limb somatosensory sensitivity have been compared to healthy participants in terms of postural control in different tasks (3;27;28;29). Previous studies have reported worse postural control in the patients compared to healthy participants as measured by significantly higher COP displacement in both A-P and M-L direction during standing and significantly higher pelvis and head acceleration during locomotion (27;28;29).
In the SOT somatosensation manipulation is achieved using a sway referenced platform (23). In the sway-referenced surface condition, the surface rotates in a toes-down or toes-up orientation as the participant sways forward and backward, respectively, so that a relatively constant ankle angle with respect to the surface is maintained. The sway-reference surface condition has been reported to increase the COP path length in A-P direction and the standard deviation of COP displacement in A-P direction compared to the fix surface condition in healthy young participants (23).

Application of vibrator to calf muscles or Achilles tendon and anaesthesia using hypothermia are two other methods used to manipulate lower limb somatosensation (30-36). Previous investigators applied vibrators to calf muscles or Achilles tendon to manipulate ankle proprioception during standing (30;31;36). Although different frequencies of vibration were used the results were similar. Vibration induced worse postural control during standing as measured by increased COP displacement, velocity of COP displacement and variance of the body mass torque (m x g x COP) in healthy young and middle-aged participants (30;31). Cold water applied to the plantar aspect of the foot decreases plantar sensitivity as confirmed by Semmes–Weinstein monofilaments (34;35). Decreased plantar sensitivity by hypothermia has been found to lead to cautious walking strategy, marked by smaller joint angles and lower muscle EMG during locomotion in healthy young participants (34). Impaired ability to use lower limb somatosensory input (due to hypothermia) to compensate for manipulated vestibular...
signals for the variance of COP displacement during standing has also been reported in healthy young and middle aged participants (33).

A compliant walking surface has also been used to manipulate lower limb somatosensory input (1;5;37-39). When participants stand or walk on a compliant surface (e.g. foam), lower limb somatosensory input, especially ankle proprioceptive information, becomes erroneous, thereby, being unusable to provide the CNS with a stable vertical reference with respect to the supporting surface for postural control (38;39). Standing and walking on foam have been reported to impair postural control as measured by increased trunk roll and pitch angle during standing and increased trunk pitch angle and/or displacement of center-of-mass (COM) in M-L direction during locomotion in healthy participants (5;38). Manipulation of lower limb somatosensory input is not the only effect of standing or walking on foam. Standing on a foam increases the contact area between the sole and the support surface (40). Walking on a foam has also been found to increase toe clearance compared to walking on firm surface (38). Therefore, changes in postural control during walking on foam may not be solely due to impaired somatosensation.

2.3 Sensory Information and Interactions for Postural Control

Outcome measures representing postural control during standing and locomotion can generally be divided into two categories: global responses and segmental responses. During standing, the movement of center of pressure (COP) is often measured as an
important global response. Measures include but are not limited to sway area, velocity of COP displacement, total distance of COP displacement over a defined period of time, displacement in the AP and ML direction, 95% ellipse area as well as the relationship (e.g. distance) between center of mass (COM) and COP (41;42;43). Head and trunk movement are critical segmental responses. Measures including angular displacement and velocity in both A-P and M-L directions of both segments are included as outcome measures in previous studies on postural control (1;5;44). Variability of head or trunk movement and head or trunk acceleration in either direction are sometimes taken into consideration as segmental responses (45;46).

During locomotion, important global responses include but are not limited to gait speed, movement of center of mass (COM) as well as step characteristics (6;47;48). Similar to postural control during standing, angular displacement and/or velocity of head and/or trunk in both A-P and M-L direction are also measured as critical segmental responses during locomotion (6;15;18;49). Head or trunk acceleration and variability of head or trunk movement in either direction are also sometimes measured as segmental responses during locomotion (7;37;50). In addition, muscle activity, joint movement or joint kinematics, joint moments and power during both standing and locomotion are sometimes recorded to reflect strategies used for postural control (52;53).
2.3.1 The Role of the Vestibular System in Postural Control

The vestibular system senses the acceleration of the head and controls the movement of the head and trunk through several important reflexes (16;54;55). The peripheral vestibular organs consist of semicircular canals and otoliths (16;55). The semicircular canals update the CNS with information of angular acceleration of the head around vertical, horizontal and antero-posterior (A-P) axes (16;55). The otoliths detect linear acceleration of the head and are influenced by gravity (16;55). The basic function of the vestibular system is to convey information of head motion and position to the CNS (16;55). The CNS uses such information, together with other sensory inputs, to construct an internal map of body motion and position with regard to the surrounding environment, including gravity (16;55).

The vestibular system is also directly associated with head and trunk control through the vestibulo-colic reflex (VCR) and vestibulo-spinal reflex (VSR), respectively (55;56;57). The VCR induces neck muscle contractions and stabilizes the head in space, thereby providing a stable platform for visual input and a stable vertical reference for overall postural control. When a perturbation occurs to the head, vestibular signals are produced. The VCR will then act on neck muscles to stabilize the head by generating motor responses opposing the perturbing head movement (55;57;58). Therefore, the VCR functions as an error-activated negative feedback system (55;57;58). The VSR contributes to trunk control by collaborating with the cervicospinal reflex (CSR) and controlling leg movements (55;56;58). The CSR involves the activation of trunk muscles...
in response to stimulation of neck sensory receptors, and the receptors are particularly represented by muscle spindle afferents in deep, intervertebral muscles (56;58). For example, when both the head and the trunk passively rotate to the left (no relative movement of the head with regard to the trunk), the VSR will be activated and lead to left leg extension and right leg flexion. When the head is rotated relative to both gravity and the stationary trunk, the VSR and CSR oppose one another and limb extension remains balanced. The VSR also acts on the muscles of the trunk, thus additionally aiding in trunk control (56;58). The vestibular system also contributes to visual image stabilization during locomotion though the vestibulo-ocular reflex (VOR) by moving the eyes contrary to the head motion (60).

The vestibular system may not be critical for postural control in easy tasks, such as walking when accurate visual and lower limb somatosensory inputs are available (6;15). However, accurate vestibular signals are required for postural control in tasks with greater challenges (1;6;15). For example, Allum et al. (1) asked 15 patients with unilateral vestibular deficit (UVD), 26 patients with cerebellar-pontine-angle-tumour (CPAT) which impairs vestibular signals, and 88 healthy participants to perform a series of tasks (1). The differences among the three groups were significant in trunk roll and pitch velocity during standing on one leg on firm surface and with eyes open for 20s, and trunk roll and pitch angle during walking up a set of stairs (1). The importance of vestibular signals for postural control in difficult tasks may be ascribed to the fact that
the vertical reference provided by this system is based on the most “robust” vertical reference frame (gravitational vertical reference) (61;62).

Vestibular input is important for postural control in the frontal plane during standing and locomotion (1;63). Postural control in the frontal plane deserves special attention because of its faster and earlier age-related deterioration, compared to that in the sagittal plane (64;65), and its close association with hip fracture in older adults (66). Hegeman et al. (63) recruited 6 patients with bilateral vestibular loss (average age: 47.2 years) and 76 healthy participants (average age: 47.3 years) to perform several tasks, such as standing with eyes open and closed on firm and foam surface for 20 seconds. In the tasks of standing with eyes open + firm surface and standing with eyes close + firm surface, the patients revealed higher trunk roll angle and roll velocity compared to healthy participants. However, no difference was found in trunk pitch angle or trunk pitch velocity (63). Glasauer et al. (7) asked 10 healthy participants (aged 20 to 45) and 7 patients with bilateral vestibular deficits (aged 26 to 68) to walk straight to a target 4m away from the starting point with eyes open and closed. Variability of trunk roll angle in the eyes closed condition was significantly higher compared to that in the eyes open condition in the patients but not in the healthy participants. In the eyes closed condition, variability of trunk roll angle of the patients was also significantly higher than that of the healthy participants (7).
2.3.2 The Role of the Vision in Postural Control

Postural control depends on not only the vestibular system, but also on vision and lower limb somatosensation (2;23;27;28;55;67). Unlike the vestibular system, visual input contributes to the alignment of the body by providing a reference frame with respect to the visual environment (55;67). The results from previous studies using the SOT and blurring goggles have shown the importance of visual input for postural control during both standing and locomotion (23;25;26). For example, Riley and Clark (23) recruited 15 college volunteers (age 20 to 22) and asked them to perform six 20s trials in each of the six SOT conditions. COP path length in the A-P direction was significantly longer in condition 2 (eyes closed and surface fixed) compared to condition 1 (eyes open and surface fixed). COP path length standard variation in A-P direction was significantly larger in Condition 6 (visual sway-referenced and surface sway-referenced) compared to condition 4 (eyes open/visual fixed and surface sway-referenced). Moreover, Buckley et al. (25) asked 12 older participants (average: 72.3 years) to step up to a higher level and down to a lower level with 3 different heights: 7.2cm, 14.4cm and 21.6cm, with and without wearing blurring goggles. Wearing blurring goggles resulted in worse postural control, represented by higher (by an average of 29.7%) root mean square changes in position of the COP in the M-L direction during the single limb support phase of stepping, compared to no goggles (25).
2.3.3 The Role of the Lower Limb Somatosensory Input in Postural Control

Lower limb somatosensation provides the CNS with information of the motion and position of body segments and the supporting surface (55;68). When lower limb somatosensory input is manipulated or inaccurate, postural control in both A-P and M-L direction decreases, as measured by head or trunk angular displacement, velocity, acceleration and/or variance of movement (27;37;39). For example, Fransson et al. (39) asked 12 young healthy participants (aged 18 to 37) to perform static standing for 120s in 4 different sensory conditions: firm surface + eyes open, firm surface + eyes closed, foam surface + eyes open and foam surface + eyes closed. The variance of movement in all directions (M-L, A-P and vertical) in the four body segments (knee, hip, shoulder and head) showed higher values in condition 3 (foam surface + eyes open) compared to condition 1 (firm surface + eyes open). Similarly, Menz et al. (37) asked 30 healthy young (aged 22 to 39) and 30 healthy older participants (aged 75 to 85) to walk 15m on firm and compliant surfaces. The root mean square of head and pelvis acceleration was higher in compliant surface walking condition compared to firm surface walking condition in nearly all the directions (A-P, M-L and vertical direction), with the exception of head acceleration in A-P direction in both the young and older group.

2.3.4 The Role of Sensory Interaction in Postural Control

Sensory systems do not function independently. Rather, the CNS has to appropriately integrate and weigh sensory signals from different systems depending on the availability and reliability of each system, the task and the environment (6;15;55;69).
2.3.4.1 Vestibular-lower limb somatosensory interaction

Vestibular-lower limb somatosensory interaction has been studied during standing (1;11;60). Investigations have revealed that intact lower limb somatosensation can compensate for impaired vestibular signals in patients with vestibular deficits and healthy people for postural control in both A-P and M-L direction during both standing and locomotion tasks (1;11;60). For example Allum et al. (1) asked participants to perform a standing task for 20s in each of the four sensory conditions: firm surface + eyes open, firm surface + eyes closed, foam surface + eyes open and form surface + eyes closed. They found that when standing on a firm surface with eyes open, patients with cerebellar-pontine-angle-tumour (CPAT) exhibited higher trunk roll angle compared to healthy participants. When standing on foam with eyes open, the patients demonstrated significantly higher trunk roll angle, trunk roll velocity as well as trunk pitch angle compared to healthy participants in the same condition (1). Similarly, Wardman et al. (11), applied GVS (intensity: 1 mA) to 6 healthy participants (aged 8 to 57) when they stood on firm and foam surface. Participants exhibited lower GVS-induced head and trunk roll angle in the firm surface condition compared to the foam surface condition. The results from these studies have shown the role of the intact lower limb somatosensation in compensation for the loss or manipulation of normal vestibular signals during standing.
There are a limited number of investigations of the ability of accurate lower limb somatosensation to compensate for inaccurate/manipulated vestibular input during locomotion (1,63). Allum et al. (1) found that in the task of walking for 5 steps with eyes closed the differences among the three groups (healthy participants, patients with UVD and patients with CPAT) were significant in trunk pitch angle and velocity as well as trunk roll velocity despite accurate lower limb somatosensation. However, there was no comparison between walking on a firm and foam surface in the study (1). Hegeman et al. (63) also asked 6 people with bilateral vestibular loss (BVL) and 76 healthy participants to perform 3m-walking (approximately 5 steps) at self-selected pace. The patients exhibited significantly higher trunk pitch velocity compared to healthy participants. However, there was no comparison of postural control between walking on foam and firm condition (63). Therefore there is little information on whether accurate lower limb somatosensation can be used to compensate for inaccurate vestibular signals during locomotion.

The neural substrates for vestibular-somatosensory interaction have been investigated (71-75). Grüsser et al. (71) reported that monkeys’ neurons in the parieto-insular vestibular cortex (PIVC) responded to both vestibular stimulation (horizontal chair rotation in darkness) and somatosensory stimulation (trunk rotations under a stable head), and PIVC is a potential area for vestibular-somatosensory integration in the monkey. Previous studies have also reported that the posterior insula and temporo-parietal junction (TPJ) could represent the human homologue of the monkey PIVC,
which could also be considered as a potential area for vestibular-somatosensory integration in human beings (72-75). However, previous studies have used a large variety of neuroimaging methods and vestibular stimulation techniques. Therefore, the exact location of human PIVC remains to be determined.

According to previous studies, intact lower limb somatosensory input could largely override the impact of loss or manipulation of normal vestibular information during standing (1;11;16). However, it is unknown if this holds true during locomotion. Therefore, the first primary goal of Study I (Chapter 3) was to understand the role of vestibular-lower limb somatosensation interaction in the control of head and trunk angular displacement and velocity during locomotion.

2.3.4.2 Vestibular-visual interaction

Accurate visual input has also been shown to compensate for vestibular loss or manipulation (1;7;8;15). With accurate visual input, patients with vestibular deficits maintain the ability for postural control; however, when vision is inaccurate postural control is affected (1;7;8;15). Such compensation has been observed in both standing and locomotion tasks (1;7;8;15).

During standing for 10s in four conditions (eye open + firm surface, eye open + foam surface, eye closed + firm surface and eye closed + foam surface), Baloh et al. (8) reported that in the eye open + foam surface condition patients with bilateral vestibular
loss (n=10, average age 45.6) demonstrated higher but not significantly higher average COP sway amplitude and COP sway velocity in both A-P and M-L direction compared to the healthy participants (n=10, average age 46.1). In the eyes closed + foam surface condition, the patients revealed significantly higher values in the two variables in both directions (8).

During locomotion with and without crossing an obstacle, McFadyen et al. (15) reported that 6 healthy participants (average age: 26.5) had the ability to use accurate visual input to override the impact of GVS on the control of head and trunk roll angular displacement. However, when visual input was manipulated using goggles, GVS-induced head and trunk roll angle were higher compared to those with accurate visual input (15).

The dorsal medial superior temporal extrastriate cortex (area MSTd) and ventral intraparietal cortex (area VIP) are two potential areas for visual-vestibular integration (76-78). Previous studies have focused on the activity of the neurons in these two area in macaque monkeys (76-78). Available evidence shows that neurons in both MSTd and VIP respond to both visual and vestibular stimuli, achieved by self-motion in macaque monkeys (76-78). The neurons in VIP were particularly sensitive to the stimuli of head horizontal rotation to the right with eyes open, which could be regarded as both visual and vestibular stimulation (76); while most neurons in MSTd tended to respond to lateral motion both to the left and right (77).
Previous studies on the impact of vestibular-visual interaction on postural control mainly focused on the head and trunk angular displacement but not the angular velocity, particularly studies on postural control during locomotion (6;15). However, fast movement of head and trunk could pose a threat to postural control during locomotion. Therefore, the second primary goal of Study I (Chapter 3) was to investigate the vestibular-visual interaction for the control of head and trunk angular displacement and velocity during locomotion.

2.4 Effects of Age on Sensory Inputs and Sensory Interactions

The vestibular, visual and somatosensory systems suffer from age-related morphological, physiological and functional deterioration (79-86). Ageing of the vestibular system is reflected by loss of hair cells, intracellular anatomic changes and synaptic alterations (87-90). Hair cells (sensory cells) are highly differentiated cells which cannot be reproduced during adulthood (87). Hair cells have been found to degenerate with age in both the crista of the semicircular canals and the macules of the saccule and utricle (88). Studies using light and electron microscopy have revealed intracellular anatomic changes, including cell shrinkage, changes in stereocilia and kinocilia, vesicle formation and degeneration of otoconia (90-92). Available evidence also shows changes in the microenvironment in the vestibular system, such as decrease in the ampullary nerve branches, which contain fibers from the semicircular canals (92). There is also evidence showing age-related deterioration in function of the reflexes associated with the system such as VCR and VOR (80;93). For example, Deshpande et al. (93) asked three groups of
participants to participate in a dynamic visual acuity test which was used to examine the function of VOR. DVA was measured while the participants walked on a treadmill at 0.75 and 1.5 m/s and were asked to identify the direction of the opening of letter "C" on a screen. The screen was placed at 0.5 m for near DVA and at 3.0 m for far DVA. For near DVA at 1.5 m/s, the differences between the young (n=10, 20–33 years) and the older (n=10, 75–85 years) group were significant, showing age-related changes in the function of VOR.

The visual system experiences age-related structural changes including a loss of photoreceptors, bipolar cells, and ganglion cells and changes in the connections among these cells in the retina as well as deterioration in the geniculo-striate pathway (85;86). Decreased lens opacity with aging and light scattering of the aging lens have also been reported (94;95). In accordance with the age-related changes in the visual system, visual function including visual acuity and visual contrast sensitivity have been reported to deteriorate with age (85;96;97). For example, Mantyjarvi and Laitinen (96) measured contrast sensitivity using the Pelli-Robson chart in 7 age groups, ranging from 6-9, 10-19, 20-29 to 60 and older. The sample size in each group varied to a small extent with the smallest of 10 persons in the 40-49 group and the largest of 15 participants in the group 6-9 years of age. Contrast sensitivity was examined in 6 conditions: reading the chart with the right eye and left eye and both eyes from 1 and 3 m away from the chart. The results from all the conditions showed a similar trend. Contrast sensitivity increased from the 6-9 age group or the 10-19 age group depending on the condition, reached a
peak in the 30-39 age group and started to decrease from the 30-39 age group in all the conditions. In 4 out of the 6 conditions, the 60-75 age group showed the lowest value among all the groups (96).

In the somatosensory system, the important receptors, including muscle spindles, Golgi tendon organs, articular receptors and cutaneous receptors, have been found to deteriorate with age in terms of morphological, physiological and functional changes (83;84;98). Muscle spindles exhibit increased spindle capsule thickness and a loss of intra-fusal fibers per spindle (82;84). Spherical axonal swellings and expanded motor end plates have also been observed (82;84). Golgi tendon organs, articular receptors and cutaneous receptors all undergo age-related decline in number (83;98). In addition, the sensitivity of muscle spindles, Golgi tendon organs, articular receptors and cutaneous receptors all decrease with age (84;98). Accordingly, proprioception, cutaneous pressure sensitivity and vibration sensitivity have been reported to decrease with age (84;99;100). For example, Verschueren et al. (99) tested proprioception for passive ankle plantar flexion in 102 healthy older (average age 62.5) and 24 healthy young (average age 21.7) participants. They were asked to open their hand when the ipsilateral ankle reached the prescribed target angle. The deviation from the specific target angle increased with age, and the oldest group (aged 70 to 75) showed significantly greater deviation compared to the other groups.
In addition to age-related deterioration in sensory systems, older people have decreased ability of the CNS to integrate sensory information from different systems and alter the weighting of each of them according to their accuracy, task or environment for postural control (5;6;37;101). Such age-related difference has been reported in both standing and locomotion tasks (5;6;37;101). Benjuya et al. (101) recruited 20 healthy young (average age: 26.6) and 32 healthy older (average age: 77.8) and instructed them to stand with eyes open and closed for 20s with feet 17 cm apart and close together. In the feet together condition with eyes open, the older participants exhibited significantly higher values compared to the young participants only in COP path length and the elliptical area that covers 95% of the sampled COPs. In the condition of feet together with eyes closed, the older participants showed higher values in the two variables mentioned above as well as for COP sway amplitude in A-P and M-L direction and COP sway velocity (101).

Deshpande and Patla (6) asked 9 healthy young (aged 20 to 35) and 9 healthy older participants (aged 65 to 85) to walk straight to a target 6.5m away from the start point to the beat of a metronome (80 steps/min) with 4 different sensory manipulations [2 (no GVS/GVS) X 2 (normal vision/blurring goggles)]. They found that GVS-induced trunk tilt to the anodal side was significant in both young and older people in the blurred vision condition during walking. However, in the normal vision condition, older participants but not young people had significant GVS-induced trunk roll during locomotion. It is possible that young participants used the available visual input to
reduce the weighting of the discordant vestibular system, preventing trunk roll to the anodal side. In contrast, a proposed age-related decline in central integrative mechanisms of the CNS may have the affected integrative ability of the CNS to re-weigh the vestibular system, resulting in significant trunk roll to the anodal side in the older adults (6). The difference between healthy young and older adults in terms of vestibular-visual interaction for the control of head and trunk angular velocity during locomotion as well as vestibular-lower limb somatosensory interaction for postural control (angular displacement and velocity) during locomotion is still unclear.

2.5 Narrow-based Walking

The ability to control postural stability in the M-L direction during locomotion is of great importance in older persons as this ability deteriorates faster and earlier with increasing age, compared to that in the A-P direction (64;65). Additionally, M-L stability has been reported to be associated with fall-related fracture in older adults (66;102;103). In older persons, the risk for a hip fracture has been found to increase by six fold when the fall occurs in the frontal plane (102). Hayes et al. (103), reported that out of 82 participants who fell and sustained a hip fracture, 60% fell to the side, whereas 23% of 313 participants who fell but did not sustain a hip fracture, fell to the side.

Narrow-based walking has been used to assess the ability to control M-L stability during locomotion (104-106). Participants are required to walk with a narrow base, between two lines on the floor (104-106). The distance between the lines was fixed [e.g. 25cm
or standardized to the body size [e.g. 25cm 50% of the distance between the subject’s anterior superior iliac spines (104)]. Despite the importance of M-L stability to older people, only one study was found (104) which specifically investigated age-related difference in postural control during narrow-based walking. Schrager et al. (104) asked 34 healthy participants (aged 54 to 92) to walk with a normal base and standardized narrow base for 6m. In the narrow-based walking condition, age-associated increases in COM peak velocity and COM displacement in M-L direction and decreases in gait speed were observed (104). However, the sensory strategies that young and older people use for M-L postural control during narrow-based walking are unknown.

As a result, Study I investigated of the impact of age on vestibular-lower limb somatosensory and vestibular-visual interaction during normal and narrow-based walking, respectively.

2.6 Vestibular Dysfunction Screening via Spatial Orientation

Spatial orientation is generally defined as the sense/ability to keep track of the relationship of the body to a place/target in space, which answers questions such as "Which way am I facing" or "Where am I going" (107;108). Spatial orientation is required in tasks, ranging from straight walking and completion of a designated path to stepping-in-place (109-111). Despite the difference among the tasks, the standard to measure the ability to maintain spatial orientation is similar: larger linear and angular deviations from the designated target/path are regarded as lower ability to maintain spatial orientation.
Spatial orientation largely depends on sensory inputs from the visual and vestibular systems (109-111). It is obvious that vision plays a dominant role in spatial orientation regardless of the availability of other sensory signals; while the importance of the vestibular system in spatial orientation greatly increases when vision is not available (109-111). The importance of the visual and vestibular systems for spatial orientation is reflected by the results from previous studies which used the Fukuda Stepping Test (FST), Triangle Walking Test (TWT) and Straight Walking Test (SWT) to assess the ability to maintain spatial orientation and the function of the vestibular system (109-111).

During the FST, participants are asked to stand on one spot with eyes blinded-folded, and then to step in place for 50 or 100 steps (111;112). Both linear and angular deviation from the original spot are recorded to reflect the ability to maintain spatial orientation (111;112). Fukuda found that after 50 steps, forward progression of the body by up to 50 cm, and self-rotation up to 30° was observed in healthy persons. After 100 steps, there was progression up to 100 cm, and self-rotation up to 45° in healthy persons (111). In contrast, one patient with inner ear disease (right otalgia and otorrhea which impairs vestibular signals) demonstrated progression of the body of 75 cm to the right and self-rotation to the right of 120° after 50 steps, and displacement of the body backward for 35 cm (which was very rare) to the right and self-rotation of 350° to the right after 100 steps (111).
During the SWT participants are asked to walk as straight as possible for a certain distance from the original spot to the final spot (109). Angular deviation from the straight direction/path as well as distance traveled before deviation from the path is recorded. Cohen and Sangi-Haghpeykar (109) included 3 groups of participants: 20 healthy volunteers (average age 52.5), 20 patients with unilateral benign paroxysmal positional vertigo (BPPV) (average age 58.0), and 20 patients with unilateral vestibular weakness (average age 53.9). Participants were instructed to walk straight for 7.62m with eyes open and closed at three speeds to a metronome: 60 beats/min (slow), 120 beats/min (medium), 176 beats/min (fast). In the eyes-open condition, no difference was found among the groups in any of the speed conditions. In the eyes-closed condition, healthy participants deviated significantly less than the patients with BPPV and unilateral vestibular weakness in terms of angular deviation from the path in slow and fast conditions. Healthy persons also walked farther before deviation than the group with unilateral vestibular weakness in all speed conditions. The BPPV group did not differ significantly from the other groups in terms of the distance walked before deviation.

During the TWT, participants were required to complete a right triangular path (with two right-angle segments of the same length) as accurately as possible in terms of both distance and direction in each segment (110). Angular deviation from the designate segments (directional error), linear deviation from each corner of the path (arrival error) and the difference between the distance completed by the participants and the length
of each segment (distance error) are measured to represent the ability to maintain spatial orientation (110). Glasauer et al. (110) studied seven young subjects (aged 18 to 36), five patients with vestibular deficits (aged 27 to 65) and a control group of five age- and gender-matched healthy subjects. Participants were required to complete the TWT with eyes open and closed in clockwise (CW) and counter-clockwise (CCW) directions. With eyes open, no difference was found between the groups. In the eyes-closed condition, the patients showed much larger arrival errors at all the corners of the designated path, and directional errors at segments 2 and 3 than the other two groups in both CW and CCW conditions (110).

There are other spatial orientation tasks and vestibular deficit screening tools. Particularly, spatial orientation tasks designed to navigate in a virtual environment are based on ability to develop spatial maps using hippocampal circuitry (113;114) such as the virtual Morris water task (114). The virtual Morris water task consists of a virtual circular pool with water located in the center of a virtual square room. A virtual hidden platform is in the pool and the room has four virtual walls around it. One distal cue is placed on each wall. The aim of the task is accurate navigation from a random position on the edge of the pool to the hidden platform based on the cues on the walls using a keyboard. Brandt et al. (114) found that the patients with vestibular loss took more time to navigate to the platform than the controls, suggesting decreased ability to achieve accurate spatial orientation. However, performance in these tasks is assessed in a sitting position with eyes open using virtual images and some form of a hand operated tool to
navigate. Therefore, it does not require refined body alignment potentially integrating vestibular signals. As a result, authors suggest the differences in performance of the vestibular deficit patients may be ascribed to the hippocampal atrophy observed in these patients rather than the difference in vestibular function (114).

Vestibular deficit screening tools based on vestibular functions other than spatial orientation have also been reported in literature. These tools include but are not limited to dynamic visual acuity (DVA) (115), trunk sway measure (1), tandem walking test (116) and head impulse test (117). The DVA test consists of presentation of slides on a computer screen (115). Each slide presents a string of 5 numbers (integers from 0 to 9). Font sizes range from 12 to 20, in increments of 2 points. The computer is placed 2 meters away from the participants, and they are asked to identify the numbers during both standing and walking on a treadmill. The percentage of correct responses are measured. Hillman et al. (115) asked 10 healthy participants and 5 patients with vestibular deficits to perform the DVA test for 5 trials in standing and walking conditions, and each trial consisted of 10 slides. The patients showed significantly worse overall performance during both standing and walking compared to that of the controls (115).

A series of standing and locomotion tests were used to distinguish healthy participants from patients with vestibular deficits. During these tests, trunk roll angle, trunk pitch angle, trunk roll velocity and trunk pitch velocity were measured using digitally-based angular-velocity transducers (1). Patients (n=15) with unilateral vestibular deficits
showed significantly higher values of all the four variables compared to healthy participants (n=88) during standing on foam surface with eyes closed for 20s and walking over a set of four low barriers placed 1-m apart (1).

In the tandem walking test, participants are asked to walk for 10 consecutive heel-to-toe steps with the arms crossed in 2 conditions: eyes open and eyes closed (116). The performance is evaluated by the number of steps taken without stepping out of line, moving the arms, or opening the eyes in the eyes-closed condition. Cohen et al. (116) asked 60 healthy participants and 60 patients with vestibular deficits to perform the tandem walking test. The performance of the control group was significantly better than that of the patients in both conditions.

In the head impulse test, participants are instructed to fixate on a target 4 feet in front of them while sitting in a chair (117). The examiner turns the participants head briskly 3 times to the left and 3 times to the right for 20 to 30°. Positive response (presence of vestibular deficit) is determined as a drift in the direction of gaze followed by a saccadic recovery in at least two out of three turns. Beynon et al. (117) performed the head impulse test and caloric test on 150 participants. The caloric test indicated that 76 participants had normal vestibular function, 23 had mild vestibular paresis, 21 had moderate vestibular paresis and 30 had severe vestibular paresis. The participants who had positive response in the head impulse test had significantly more severe paresis than those who had negative response. However, the sensitivity of the head impulse
test in the mild vestibular paresis group (0%) and moderate vestibular paresis group (9.5%) was very low. Conversely, Fukuda walking Test, Triangle Walking Test and Straight Walking Test are unique in that they are designed to screen for vestibular function based on the role of the vestibular system in spatial orientation.

As previously discussed, the function of the vestibular system decreases with aging. The prevalence of vestibular dysfunction has also been shown to increase markedly with age, and has been identified by one study as a potential fall risk factor (118). Based on a survey conducted by Agrawal et al. (118) in 6270 participants in the US, the prevalence of overt vestibular dysfunction increased from 18.5% in the group of 40 to 49 year old to 84.8% in the group of 80 and older. In the study, vestibular dysfunction was determined by failure to stand on foam with eyes closed for 30 seconds, during which the participants need to primarily rely on vestibular signals. The prevalence of vestibular dysfunction and falling were highly associated. The prevalence of falling (in the past 12 months) increased from 2.0% in the group without vestibular dysfunction to 6.9% in the group with vestibular dysfunction, while the unadjusted odd ratio was 3.6 (119).

It is unknown whether the stepping test or locomotion tests (walking straight and triangular walking), which assess the ability to maintain spatial orientation, are sensitive to age-related differences in the vestibular system. However, prior to determining if these tests could be used to detect age-related difference in vestibular function, the
inter-trial reliability and variability must be determined in both young and older adults in order to ensure consistency of the tools to reflect vestibular function in both groups.

Therefore, Study II (Chapter 4) focused on the reliability and variability of the three tests in both young and older adults, and whether they could be used to detect age-related differences in vestibular function via assessing the ability of the participants to achieve accurate spatial orientation in different conditions.
2.7 Reference


40. Wu G, Chiang JH. Reduced the amplitude of the maximal plantar pressures and increased the contact area between the sole and the support. Exp Brain Res 1997; 114:163–169.


Chapter 3

Head and Trunk Control during Normal and Narrow-Based Walking: Impact of Sensory Manipulations and Age

3.1 Abstract

Fifteen young (20-30 years) and 15 older (>65 years) healthy participants were recruited to investigate the effect of aging on head and trunk control during normal and narrow-based walking (NBW) with visual, vestibular and/or lower limb somatosensory manipulations. Visual, vestibular and lower limb somatosensory inputs were manipulated, either concurrently or individually, using blurring goggles, galvanic vestibular stimulation (GVS) and medium density foam, respectively. Head roll angle increased with GVS on the foam surface only in the older group. Head roll velocity decreased with goggles, but increased with GVS in the older group with large effect size but not in young. Trunk roll angle increased with GVS and in NBW on the foam but not the firm surface irrespective of age groups. Trunk roll velocity and trunk pitch angle and velocity increased on the foam surface irrespective of other conditions or manipulations. The results show that head control depends more on visual and vestibular signals, suggesting a “top-down” model for head control. Trunk control relies more on lower limb somatosensory inputs, suggesting a “bottom-up” model for trunk control. Age-related differences were only reflected in head control with vestibular and/or lower limb somatosensory manipulation.
3.2 Introduction

The precise control of angular displacement and velocity of both the head and trunk during dynamic tasks is important for postural control (1;2). The head contains the sensory receptors of both the visual and vestibular system. Therefore, the head needs to be controlled, in terms of both angular displacement and velocity, in order to provide a stable platform for the two sensory systems (1;3). Larger deviation from the vertical position or faster movement of the head makes the vestibulo-ocular reflex (VOR) less robust for foveating visual images (4), which can lead to an unstable platform for visual input. Faster movement of the head may also result in higher ambiguities of the otolithic signal, thereby making the interpretation of vestibular information more difficult (3). Finally, head control is critical because the central nervous system (CNS) uses the head position as a reference for the planning of overall postural control (5).

The trunk bears the largest body mass compared to other body segments. Larger deviation from the vertical position or faster movement of the trunk could increase momentum, and therefore the challenge to postural control (6). In addition, movement of the trunk at higher velocity may limit the allowable time for neuromuscular corrections if instability is experienced during standing or locomotion (6). Overall, large deviation and fast movement of both head and trunk may pose a threat to the precision of postural control. Therefore, angular displacement and/or velocity of both head and trunk are often included as important outcome measures for postural control in different tasks, such as standing and locomotion (7-9).
The control of head and trunk largely depends on sensory inputs from the visual, vestibular and lower limb somatosensory systems (9-13). In particular, vestibular inputs play an important role (9;10). The basic function of the vestibular system is to convey information of head motion and position to the CNS, and the system is influenced by the direction of gravity (14;15). The CNS uses such vestibular information, together with other sensory inputs, to establish an internal map of body motion and position with regard to the surrounding environment, including gravity. The vestibular system operates with the most “robust” vertical reference frame (gravitational vertical reference). As a result, vestibular information can be used to resolve sensory conflicts arising from other sensory systems (16;17). The vestibular system can contribute to the control of head and trunk movement through the vestibulo-colic reflex (VCR) and vestibulo-spinal reflex (VSR), respectively (11;14;16). Further, the weighting of vestibular signal is higher in difficult tasks, such as standing on one foot, compared to easy tasks, such as standing on both feet (9;18). In addition to the vestibular system input, visual input provides the CNS with a vertical reference with regard to surrounding environment (14;19). Lower limb somatosensory information provides the CNS with information of the motion and position of the whole body with respect to the supporting surface during different tasks including standing and locomotion (13;14).

Although the three sensory systems function independently at the periphery, the CNS integrates these sensory signals and increases the weighting of dependence on the
accurate sensory inputs and decreases the weighting of/dependence on the inaccurate sensory inputs for postural control depending on the accuracy of sensory signals, task and the environment in which the task is performed (20-22). Previous studies have shown that accurate visual inputs can be used to override the impact of inaccurate vestibular information for the control of angular displacement of the head and trunk during locomotion (20;21). However, less is known about visual-vestibular interaction for the control of the angular velocity of the head and trunk displacement during locomotion. Further, there is evidence that accurate lower limb somatosensory inputs can be used to down-regulate the weighting of the perturbed vestibular inputs for the control of the displacement and/or angular velocity of the head and/or trunk during standing (9;22). However, little is known about the role of lower limb somatosensory-vestibular interaction in the control of the head and trunk during locomotion.

Age-related deterioration in function of the three sensory systems has been well documented (23-28). Visual acuity and visual contrast sensitivity have been reported to deteriorate with age (23;24). There is also evidence showing age-related deterioration in function of the reflexes associated with the vestibular system such as VCR and vestibule-ocular reflex (VOR) (27;28). Further, for the somatosensory system, joint proprioception, cutaneous pressure and vibration sensitivity all decrease with age (25;26). Additionally, age-related deterioration has been reported to negatively influence the ability of the CNS to integrate sensory inputs from multiple systems and override the impact of inaccurate sensory signals using accurate sensory information (20;29).
Postural control in the M-L direction in older persons deserves particular attention because of its faster and earlier deterioration with increasing age compared to that in the A-P direction (30;31). In the older population poorer postural control in the M-L direction is also associated with higher rate of fall-related hip fractures (32). Moreover, according to previous studies, accurate vestibular input is important for postural control in the M-L direction during both standing and locomotion (9;33).

In order to assess M-L postural control, especially in older people, the challenge is increased in M-L direction by asking the individuals to walk on a narrow path that constraints foot placement and reduces base of support. This method is commonly referred to as narrow-based walking (34). Schrager et al. (34) reported that COM peak velocity and displacement in M-L direction and step width increased with ageing, and gait velocity and step length decreased with ageing during both normal and narrow-based walking. These age-related changes were more pronounced during narrow-based walking compared to those during normal walking (34). However, little is known about the role of vestibular-lower limb somatosensory and vestibular-visual interaction in postural control during narrow-based walking and the effect of age on this role.

In addition to head and trunk control, global measures such as gait speed and step characteristics could be considered as global strategies/responses for postural control during locomotion (20;21). For example, decreasing gait speed, adopting shorter step
length and/or greater step width are regarded as conservative strategies for postural control during locomotion (20;21). Further, older persons and fallers have been reported to exhibit higher step-to-step variability in step length and step width compared to young people and non-fallers (35-37).

The primary objectives of this study were to investigate the interaction of vestibular input with lower limb somatosensory input and visual input for head and trunk control during normal and narrow-based walking in both young and older persons. Further, the effect of such interactions on global measures of gait speed and step characteristics was also evaluated. The sensory interactions were examined by controlled perturbation of sensory systems. The secondary objective was to explore the relationship of head/trunk control in the frontal plane with measured functions of the three sensory systems (visual, vestibular and lower limb somatosensory system) during both normal and narrow-based walking in young and older persons. These relationships were examined under normal sensory conditions (i.e. without any sensory perturbation).

We hypothesized that compared to young persons, older participants would exhibit less ability to use the available lower limb somatosensory input and/or visual information to reduce the weighting of the discordant/manipulated vestibular signal for the control of displacement and/or velocity of both head and trunk. The narrow-based walking condition would further exaggerate such age-related differences, as with increased challenge to postural control older participants may have more difficulty in down-
regulating the manipulated vestibular input. This study could help us to better understand the role of sensory inputs and interactions for head and trunk control during locomotion, and develop rehabilitation intervention to improve postural control in older people and/or patients with vestibular deficits.

3.3 Method

3.3.1 Participants

Fifteen young (age range = 20–35 years, seven women, eight men) and 18 older (age range = 65–85 years, ten women, eight men) healthy adults were initially recruited.

The young participants were students at Queen’s University or their friends or colleagues from the Kingston, Ontario community. They were recruited through personal contact by investigators in this study. The older participants were recruited from the Kingston, Ontario community by putting posters in the Senior Center and retirement homes (St. Lawrence Place Retirement Residence and Rideaucrest Home) as well as putting newspaper advertisements in Kingston This Week. Those interested in the study responded to the information by calling or emailing the investigators and expressing their willingness to participate in the study. Before arranging for appointments in the laboratory, potential participants were asked about their medical history by phone or email. Those who used walking aids or those who reported a history of neuromuscular disorder, diabetes, dizziness or >1 falls in the past year were excluded. Additionally, those with lower limb pain while walking (e.g., due to recent injury,
symptomatic lower limb arthritis, peripheral vascular disease) were also excluded as the study involved repeated walking trials. The medical information form is found in Appendix E.

The data of 3 older participants were excluded after they came to the laboratory because they voluntarily chose to withdraw from the study without completing data collection. Two of these 3 participants withdrew as they felt unstable when walking on the foam surface, and the third person withdrew as he felt uncomfortable with galvanic vestibular stimulation. Therefore, 3 additional participants were recruited in the older group. As a result, the data of 15 healthy young and 15 healthy older participants were included for the analysis.

3.3.2 Procedures

This study was performed in the Motor Performance Laboratory at the Queen’s University. After arrival in the laboratory, participants read the information form about the study and signed an informed consent form (Appendix D) approved by the Queen's University Health Sciences and Affiliated Teaching Hospitals Research Ethics Board. Their age was recorded and their height and weight were measured. Participants were also asked to report the number of hours that they were physically active and the physical activities that they were involved in routinely. Their dominant foot was determined using Waterloo Footedness Questionnaire for the purpose of lower limb somatosensory assessment (38).
Twenty-eight of the 30 participants had their sensory function assessed prior to the walking trials, while two participants completed sensory function assessment after completing the walking trial procedures. This strategy was adopted when two participants chose to come to the laboratory at the same time.

3.3.2.1 Sensory Function Assessment

Table 3.1 shows the sensory function tests used in this study. Sensory function of the visual, vestibular and lower limb somatosensory systems was tested. The order of all the tests was randomized. For vision tests the participants were allowed to wear lenses or glasses if they wore them routinely. Binocular visual acuity was assessed at the distance of 3 m using the standard Snellen eye chart (39). Binocular visual contrast sensitivity was assessed using the standard Pelli-Robson chart procedure (40). The log contrast sensitivity score was determined by the last group of three letters in which two or three out of the three letters were correctly identified. Higher value in the result of both visual acuity test and contrast sensitivity test indicates better visual acuity and contrast sensitivity, respectively.

Vestibular function was examined using the subjective visual vertical (SVV) test (41) and the dynamic visual acuity test (DVA) (42). During the SVV test (F.O.B. Genie Audio Inc, ON, Canada), the participants used a controller to adjust an illuminated marker line, which was projected by a projector onto a wall, to a straight vertical direction in a dark
room (based on their perception without any physical vertical reference). The angular difference between the marker line adjusted by the participants and the physical vertical line and was recorded. The angular difference was used to represent the function of the vestibular system, the function of the otoliths to be specific (41). Higher value in the result of the SVV test indicates poorer otolith function.

During the DVA test (Johnson Space Center, NASA, USA), participants were asked to stand and walk at 1m/s and 1.5m/s on a treadmill (42). A reading screen (of a laptop) was put at 3m away from the participants for far DVA and at 0.5m for near DVA. The Landolt “C” optotypes (letter “C”) were displayed on the reading screen, and during both standing and walking the participants were required to verbally identify the direction of the opening of the “C” optotypes: up, down, left or right. The order of the direction was randomized. Fifteen optotype sizes were used, which ranged from 1.0 to −0.4 logMAR (1.0 is equivalent to a 20/200 ratio in Snellen Chart, while 0.0 is equivalent to a ratio of 20/20 in Snellen Chart). The reading screen of the laptop (for both far DVA and near DVA) exhibited each optotype for 0.5 seconds, and 28 presentations of the optotypes were used to establish the DVA threshold for both walking and standing condition and for both near DVA and far DVA. The DVA threshold for all the conditions was estimated as the optotype size in which half of the responses were correctly identified. The final DVA score for both far DVA and near DVA was calculated as (DVA threshold during walking – DVA threshold during standing) (42). Higher value in the result of the DVA test indicates poorer vestibular function.
Lower limb somatosensory assessment included the vibration sensitivity test, cutaneous pressure sensitivity test and ankle proprioception test. Lower limb cutaneous pressure sensitivity was examined using Semmes-Weinstein Monofilament (43). With the participants in the supine position on a plinth, Semmes-Weinstein Monofilaments (North Coast Medical Inc., CA, USA) were applied by one investigator from the one with the lowest force to the one with the highest force (0.07, 0.4, 2, 4, 10, 300 gram) to the plantar surface of the first metatarsal head of the dominant foot. The participants were asked to say "Now" if they could sense the force. The cutaneous pressure sensitivity was determined by the lowest force that the participants could sense. Higher value in the result of the cutaneous pressure sensitivity test indicates poorer cutaneous pressure sensitivity.

Lower limb vibration sensitivity threshold was tested using a hand-held electromagnetic vibrator (Bio-Medical Instrument Co. Ohio, USA) (44). With the participants in the supine position on a plinth, an investigator applied the head of the vibrator to the plantar surface of the first metatarsal head of the dominant foot. The investigator increased the vibration intensity very slowly from 0, and the participants were asked to say "Now" if they could perceive the vibration. The vibration sensitivity was determined by the voltage corresponding to lowest vibration intensity (i.e. vibration amplitude) that the participants could sense. The first metatarsal on the foot sole was selected for both the cutaneous pressure sensitivity test and the vibration sensitivity test, because the
sensitivity of the first metatarsal ranks in the middle of all the sites of the foot sole (45). Higher value/threshold in the result of the lower limb vibration sensitivity test indicates poorer vibration sensitivity.

Ankle proprioception was measured using a custom made potentiometer (Department of Mechanical Engineering, Queen's University, Canada) (46). With the participants in sitting position, their dominant foot was attached to a footplate without hip abduction or hip adduction. The participants were asked to wear a head-phon and were blindfolded, so that they could not hear or see the movement of the footplate. The footplate rotated at 0.25°/s, 3 times in a dorsiflexion and 3 times in a plantar-flexion direction (6 trials in total), and the order was randomized. The participants were required to press a switch as soon as they perceived the rotation and its direction (either dorsiflexion or plantar-flexion) of the footplate. The degree of angular displacement of the footplate required for each participant to perceive the rotation and its direction were recorded. The final ankle proprioception score was calculated as the average degrees of the correctly identified trials. Twenty eight of 30 participants correctly identified all 6 trials, while the other two correctly identified 4 and 5 trials, respectively. Higher value in the result of the ankle proprioception test indicates poorer ankle proprioception.
Table 3.1 Sensory function assessments

<table>
<thead>
<tr>
<th>Sensory System</th>
<th>Sensory Function Assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vision</td>
<td>Visual acuity</td>
</tr>
<tr>
<td></td>
<td>Visual contrast sensitivity</td>
</tr>
<tr>
<td>Vestibular System</td>
<td>Subjective visual vertical</td>
</tr>
<tr>
<td></td>
<td>Dynamic visual acuity</td>
</tr>
<tr>
<td>Lower limb somatosensory system</td>
<td>Cutaneous pressure sensitivity</td>
</tr>
<tr>
<td></td>
<td>Cutaneous vibration sensitivity</td>
</tr>
<tr>
<td></td>
<td>Ankle proprioception</td>
</tr>
</tbody>
</table>

3.3.2.2 Experimental Setup

Ten infrared emitting diodes (IREDs) were attached to the following ten anatomical landmarks on the participant’s body (Fig 3.1): cranial vertex; above the ears (left and right); acromion processes (left and right); the seventh cervical, 12th thoracic, and the second sacral vertebra; and left and right lateral malleoli. During all walking trials, two OPTOTRAK camera banks (Northern Digital, Waterloo, Canada) placed with one at each end of the walking path (Fig 3.2) were used to track the movement of the IREDs, and the data were captured at a sampling rate of 100 Hz (0.01s in each time frame).
Fig 3.1 The setup of the ten infrared emitting diodes

Fig 3.2 The position of the two Optotrak cameras with respect to the walking path.
3.3.2.3 Walking Conditions

Participants were asked to wear running shoes and their normal corrective glasses/lenses, if they wore them routinely. They were instructed to stand at the start of the walking path in the relaxed manner looking straight ahead with hands by their side. Data collection began once this position was achieved. After standing for 4 seconds in this position, participants were asked to proceed using a verbal 'go' signal. They initiated walking using their preferred foot and walked straight ahead on a 6 m path at the pace that they were comfortable with. The data from 1s to 1.5s from the initial 4s standing data were used to calculate the vertical reference for head and trunk control (as introduced subsequently), while the data of the 4 seconds during standing were excluded for subsequent analysis.

This study was performed as a component of a more comprehensive, larger research study. Therefore, a total of four walking conditions were performed in a random order: (a) unconstrained normal walking; (b) walking with a narrow base, between lines of tape placed 25 cm apart; (c) walking while counting backwards from a given number <100 by 3 and (d) walking while crossing two obstacles in the path. Two trials were performed in each walking condition. Only conditions (a) and (b) were analyzed for the purpose of this chapter.

In the narrow-based walking condition, the participants were instructed to keep their feet between two lines 25cm apart on the floor. The narrow-based walking condition
successfully decreased step width compared to normal walking condition (p<0.001, details stated subsequently). Only 9 trials (from two young and one older participant) out of 480 trials in the narrow-based condition (480=32 trials X 30 participants/2) had average step width wider than 25cm. Exclusion of those trials did not change the impact of sensory manipulations or walking conditions.

3.3.2.4 Sensory Manipulations

The 64 walking trials (in each participant) were divided into two blocks according to lower limb somatosensory manipulation: walking on the firm surface or foam surface. Visual and vestibular inputs were manipulated in a random order, either individually or concurrently in each block.

Visual input was manipulated using custom made blurring goggles (Optometry Laboratory, University of Waterloo, Waterloo, ON, Canada). Visual contrast sensitivity is significantly reduced to the level of dense cataract by the goggles (20).

Vestibular information was manipulated using bipolar galvanic vestibular stimulation (GVS; S48, Grass Medical Instruments, MA). GVS increases firing rate of the vestibular nerve on the cathodal side and decreases the firing rate on the anodal side. In this way an experimentally induced imbalanced impulse transmission rate of the vestibular nerves is created from the two sides (47). The threshold GVS intensity of each participant was determined by asking him/her to stand with eyes closed and feet close
together. GVS intensity was increased slowly until the investigator could visibly perceive the postural sway of the participant in the anodal direction (47). The anode was randomly placed either on the right (R) or the left (L) side as Deshpande and Patla (20) reported no differences between the effect of GVS on head and trunk control with the anode placed on the left and that on the right side. GVS was applied at two times (2t) threshold intensity throughout the walking process. This intensity was selected because Deshpande and Patla (20) showed that during locomotion GVS intensity of 2 times the healthy participants’ threshold provided sufficient vestibular manipulation to safely increase average trunk roll angle compared to no GVS. GVS was initiated two seconds prior to the verbal “go” signal so that the initial sudden GVS-induced instability could be eliminated.

Lower limb somatosensory input was manipulated using a compliant walking surface (6 m long medium-density foam mat), which had a stiffness of 13.13 kN/m and provided a linear relationship between weight applied and surface compression [$R^2=0.95$; (48)]. The foam was 12.5 cm thick, and the density and thickness prevented the foot from contacting the floor (bottoming out) during walking. For both standing and walking tasks, medium-density foam is commonly used to manipulate lower limb somatosensory information, especially the ankle proprioceptive signal (9;49). During standing or walking on a hard/firm support surface, the support surface provides a stable reference frame so that accurate lower limb somatosensory information is conveyed to the CNS (50). However, when the support surface is compliant, the lower limb somatosensory signal,
especially ankle proprioceptive input becomes erroneous and is inaccurate for providing a vertical reference frame for postural control (50;51). Foam surface has also been found to reduce the amplitude of the maximal plantar pressures, increase the contact area between the sole and the support foam surface during standing and increase minimum toe clearance compared to walking on firm surface (48;52).

3.3.2.5 Protocol for Walking Trials

There were 8 sensory manipulations [2 visual conditions (normal/goggles) X 2 vestibular manipulations (no GVS/GVS) X 2 lower limb somatosensory manipulations (firm/foam)] combined with 4 walking conditions. All participants performed 64 walking trials (4 walking conditions X 8 sensory manipulations X 2 trials in each condition). The 64 trials were divided into two blocks according to lower limb somatosensory manipulation (firm vs foam). Twenty-seven of the 30 participants performed the block of 32 walking trials on the firm surface first. Three participants performed the foam surface trials first, because they were the second participant on the days when we collected data back-to-back for 2 participants. The 3 participants include the 2 who participated in walking trials prior to the sensory assessment as mentioned above (Page 61). The third person participated in the sensory assessment prior to the walking trials because he came to the laboratory after another participant on the same day but not at the same time. When data were reanalysed excluding the data of these three participants, the impact of walking conditions/sensory manipulations did not differ from the results presented in
this chapter. Within each block of lower limb somatosensation, the order of the conditions (walking conditions combined with sensory manipulations) was randomized.

3.3.3 Outcome Measures

OPTOTRAK data were filtered at 5 Hz using a single, low-pass Butterworth filter. The filtered data were used to compute all the variables related to head and trunk control and global responses in this study. The frequency (5 Hz) was calculated and determined as the point where the amount of signal distortion is equal to the amount of noise allowed through (53).

3.3.3.1 Vestibular-lower limb somatosensory and vestibular-visual interaction for head and trunk control

For the primary goal of the study, two trials were performed in each of the 16 conditions [2 (normal/narrow-based walking) X 2 (No GVS/GVS) X 2 (firm/foam) X 2 (normal vision/goggles)]. Two trials were performed based on the evidence of the Balance Evaluation Systems Test (BESTest) in which two trials of the Sensory Orientation Session (visual and lower limb somatosensation manipulation involved) exhibited a high ICC (0.96) (54). The reliability of whole BESTest was 0.91 (54). Two trials of BESTest was also sufficient to differentiate between people with and without balance deficits (54). Paired t tests showed no difference between the two trials except for two variables: gait speed and average step length (Appendix K). Each variable included in the statistical analysis was averaged over the two trials including these two variables. This was done
because the absolute differences between the two trials for these variables were small (gait speed: 4.30% in the young groups, 5.47% in the older group; average step length: 4.13% in the young groups, 4.69% in the older group), and the impact of the sensory manipulations and walking conditions did not differ whether values of the first trial, the values of the second trial or the average values were used in the analyses.

*Global Locomotor Responses*

The displacement of the second sacral vertebral IRED during the middle 2 m (between 2 and 4m) of the walking path was used to calculate the average gait speed so that the acceleration and deceleration phases during the walking trial were excluded.

The data from the IREDs on the left and right lateral malleoli were used for the calculation of average step length, step width and the variability of step length and step width. Average step length and width were calculated for each trial as the root mean square of the step length and width of all the steps captured with exclusion of the first step. Coefficients of variation (CV) were calculated to represent the variability of step length and step width. CV of step length and width were also based on all the steps captured with exclusion of the first step.

*Segmental Responses*

The data from the IREDs on the cranial vertex and the seventh cervical vertebrae were used to calculate head position and determine the head angular displacement. The
average head position from 1.0s to 1.5s (during standing) was used as the reference/original head position. The data of head angular displacement in each time frame were used to calculate the head angular velocity in each time frame. Average head pitch angle, head pitch velocity (head movement in the sagittal plane, Figure 3.3a), head roll angle and head roll velocity (head movement in the frontal plane; Figure 3.3b) were calculated as the root mean square of respective variable in each time frame for the first 5m of the 6m walking path to represent head control in space (3;20). The right and anterior directions were positive while left and posterior directions were negative for the head control variables (Figure 3.3). However, the average values of head pitch angle, head roll angle, head pitch velocity and head roll velocity included in statistical analysis were positive because the averages were computed as the root mean squares rather than mathematic means. Therefore, the absolute values of head movement and velocity were taken into consideration rather than direction. The last 1m of the walk was excluded while computing the variables because no data were captured from the IREDs on left and right malleoli in this 1m segment. Therefore, no step was captured over the last 1m. Additionally, there were also missing data (large gaps) from the other IREDs over this 1m segment. The data of IREDs on left and right malleoli were captured by Optottrak camera 2, and the data of other IREDs were captured by Optottrak camera 1 (Figure 3.2). Being too close or too far away from the camera made data capture difficult, which resulted in missing data over the last 1m. For all participants, except the one mentioned subsequently (Page 80), there was no missing data from the IREDs over the first 5m for all the variables related to head and trunk control. However, there were
some other trials with missing data only from the IREDs on the left and right malleoli over the first 5m as mentioned subsequently (Page 80).

The data from the IREDs on the seventh cervical and the 12th vertebrae thoracic were used to calculate trunk position and determine trunk angular displacement during walking. The average trunk position from 1.0s to 1.5s during standing was used as the reference/original trunk position. The data of trunk angular displacement in each time frame were used to calculate the trunk angular velocity in each time frame. Average trunk pitch angle, trunk pitch velocity (Figure 3.3a), trunk roll angle and trunk roll velocity (Figure 3.3b) were calculated as the root mean square of the respective variable in each time frame for the first 5m of the 6m walking path to represent the trunk control (9;20). The right and anterior direction were positive while left and posterior direction were negative for the trunk control variables (Figure 3.3). However, the average values of trunk roll angle, trunk pitch angle, trunk roll velocity and trunk pitch velocity included in statistical analysis were positive because the averages were computed as the root mean squares rather than mathematic means. Therefore, the absolute values of trunk movement and velocity were taken into consideration rather than direction.
3.3.4 Statistical Analysis

3.3.4.1 Vestibular-lower limb somatosensory and vestibular-visual interaction for head and trunk control and global responses (primary objective)

The vestibular-lower limb somatosensory interaction and vestibular-visual interaction for head and trunk control as well as global responses (gait speed and step characteristics) and age-related differences were investigated linearly. For the vestibular-lower limb somatosensory interaction only the trials with normal vision were included. A repeated measure analysis of variance (ANOVA; 2 age groups × 2 walking conditions × 2 vestibular manipulations × 2 lower limb somatosensory manipulations) was separately performed for each outcome measure. For the vestibular-visual interaction only the trials on the firm surface were included. A repeated measure analysis of variance (ANOVA; 2 age groups × 2 walking conditions × 2 vestibular manipulations × 2 visual manipulations) was separately performed for each outcome measure. For both ANOVA, walking conditions and sensory manipulations were regarded as within-subject factors, while age group was included in the ANOVA model.
as a between-subject factor. The SPSS 21.0 for Windows statistical package was used for data analysis.

The data were tested for normal distribution. The data for gait speed, average step length and width were normally distributed. The data of all the other variables were ln-transformed (natural logarithm) so that normal distribution was achieved. The data transformation did not change the impact of sensory manipulations and walking conditions when compared to the results based on non-transformed data.

Statistical significance level was adjusted for the main effects using Bonferroni correction considering the number of related variables. For example, participants may adopt a stiffening strategy (the coupling between head and trunk) during the difficult tasks such as narrow-based walking as the challenge to postural control increases compared to normal-based walking (55). As a result, head and trunk movement in the same plane were considered as related variables. For example, the significance level was adjusted for head roll angle and trunk roll angle (two variables) in the two ANOVA analyses resulting in the adjusted significance level as 0.05/(2X2)=0.013. The adjusted significance level for each variable is presented in Table 3.2. When the p values of interactions in the primary analysis were lower than 0.1 (marginal result), further analysis/post hoc analysis was performed. For example, if a marginal (p<0.1) or significant (p<0.05) interaction was observed in the primary analysis between walking condition (normal/narrow-based walking) and walking surface (firm/foam), the ANOVA
was performed separately in trials on the foam and firm surface, in order to identify if the impact of narrow-based walking was different on different walking surface. Furthermore, partial eta squared, which represents effect size, for each condition/manipulation was calculated. Norms for partial eta-squared are: < 0.06 as small; 0.06 to 0.13 as medium; > 0.13 as large (56).

Table 3.2 The table shows the adjusted significance level for each variable.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Significance Level</th>
<th>Marginal level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gait Speed (1 variable)</td>
<td>0.05/(1X2)=0.025</td>
<td>0.1/(1X2)=0.05</td>
</tr>
<tr>
<td>Average head roll angle, average trunk roll angle (2 variables)</td>
<td>0.05/(2X2)=0.013</td>
<td>0.1/(2X2)=0.025</td>
</tr>
<tr>
<td>Average head roll velocity, average trunk roll velocity (2 variables)</td>
<td>0.05/(2X2)=0.013</td>
<td>0.1/(2X2)= 0.025</td>
</tr>
<tr>
<td>Average head pitch angle, average trunk pitch angle (2 variables)</td>
<td>0.05/(2X2)=0.013</td>
<td>0.1/(2X2)= 0.025</td>
</tr>
<tr>
<td>Average head pitch velocity, average trunk pitch velocity (2 variable)</td>
<td>0.05/(2X2)=0.013</td>
<td>0.1/(2X2)= 0.025</td>
</tr>
<tr>
<td>Step length, step width (2 variables)</td>
<td>0.05/(2X2)=0.013</td>
<td>0.1/(2X2)= 0.025</td>
</tr>
<tr>
<td>Step length variability, step width variability (2 variables)</td>
<td>0.05/(2X2)=0.013</td>
<td>0.1/(2X2)= 0.025</td>
</tr>
</tbody>
</table>

3.3.4.2 Relationship of Head/Trunk Control in the Frontal Plane with Sensory Functions (secondary objective)

The associations of the variables representing head and trunk control (average head roll angle, average trunk roll angle and head-trunk cross-correlation coefficient; a total of 3 dependent variables) with sensory function measures (visual acuity, visual contrast sensitivity, lower limb vibration sensitivity, lower limb cutaneous pressure sensitivity,
ankle proprioception, subjective visual vertical, dynamic visual acuity) were explored using separate linear regression analyses for each dependent variable in the normal walking and narrow-based walking condition. These associations were examined only under normal sensory conditions i.e. for walking trials without any sensory manipulation. First, bivariate correlation (Appendix L) was performed between the dependent variable and each sensory function test, and only the sensory functions that were at least marginally correlated \((p<0.1 \text{ and } r>0.2)\) with the dependent variable were included in the regression model (57). Linear regression was performed with and without age adjusted (with or without adding age as an independent variable). Non-normal distributed dependent variables were ln-transformed and outliers of independent variables (values higher or lower than mean\(\pm 4\text{SD}\)) were excluded (58). Only one value of one independent variable (SVV) was excluded. SPSS 21.0 was used and the significance level was set at \(p=0.05\).

### 3.4 Results

The demographic information of participants is displayed in Table 3.3.

**Table 3.3** The table shows the average age, height and weight of the young and older participants.

<table>
<thead>
<tr>
<th></th>
<th>Age (SD) (year)</th>
<th>Height (SD) (cm)</th>
<th>Weight (SD) (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young Group (n=15)</td>
<td>25.40 (3.56)</td>
<td>167.27 (7.88)</td>
<td>62.75 (11.38)</td>
</tr>
<tr>
<td>Older Group (n=15)</td>
<td>72.60 (5.33)</td>
<td>165.27 (12.20)</td>
<td>67.37 (13.07)</td>
</tr>
</tbody>
</table>
3.4.1 Vestibular-Lower Limb Somatosensory Interaction for Head and Trunk Control and Global Responses

The statistical results (F values, p values and partial eta squared) were based on the transformed data. The reported values of all the variables (both in numbers and in the figures) are based on untransformed data. The data of 8 trials of one young participant in this analysis were corrupted because of missing data from the IREDs which were used to calculate gait speed and head and trunk-related variables. Therefore, the data of 14 young and 15 older participants were included in this analysis (except for the analysis of step characteristics). The data from the IREDs on the left and/or right lateral malleoli of three young participants (including the one mentioned above, Page 74) and one older participant (28 trials in total) were missing. Therefore, the data of 26 participants were included for the analysis of step characteristics.

3.4.1.1 Global Locomotor Responses

Gait Speed

Gait speed marginally decreased in the narrow-based walking condition compared to normal walking condition ($F_{(1,27)}=5.28$, $p=0.03$, partial eta squared=0.16), but significantly increased with GVS compared to no GVS ($F_{(1,27)}=32.48$, $p<0.001$, partial eta squared=0.55) (Figure 3.4) irrespective of other conditions/manipulations. There was no significant effect of foam and no age-related difference was observed.
Figure 3.4 Average gait speed (m/s) (mean ± SD) increased with GVS (p<0.001) but decreased with narrow-based walking (p=0.03). The ** denotes a significant effect on gait speed (p<0.013), while the * denotes a marginal effect (p≤0.025).

Step Characteristics

Overall, the average step length (the root mean square) significantly decreased in the narrow-based walking condition (0.64m±0.11 (SD)) compared to normal walking condition (0.67m±0.10) (F(1, 24)=8.57, p=0.007, partial eta squared=0.26), but increased on the foam surface (0.67m±0.09) (F(1,24)=21.52, p<0.001, partial eta squared=0.47) compared to the firm surface (0.63m±0.09), and marginally increased with GVS compared to no GVS (F(1,24)=6.43, p=0.018, partial eta squared=0.21). The average step width (the root mean square) significantly decreased in the narrow-based walking condition (0.19m±0.04) compared to normal walking condition (0.23m±0.04) (F(1,24)=33.54, p<0.001, partial eta squared=0.58), but increased on the foam surface (0.22m±0.05) compared to firm surface (0.20m±0.04) (F(1,24)=10.84, p=0.003, partial eta squared=0.31). Step width increased with GVS only on the firm (F(1,25)=11.19, p=0.003, partial eta squared=0.31) but not foam surface (F(1, 26)=0.06, p=0.81, partial eta squared=0.02). No significant age-related difference on step length or width was found.
Overall, step length variability increased on the foam surface compared to firm surface with large effect size but the difference was not statistically significant ($F_{(1,24)}=5.76$, $p=0.02$, partial eta squared=0.19). No significant effect of GVS and narrow-based walking was observed on step length variability. No significant effect of any manipulation or walking condition was observed on step width variability. No significant age-related difference was observed for step length and step width variability.

3.4.1.2 Segmental Responses

The analysis for average head roll angle (the root mean square) demonstrated a significant lower limb somatosensory manipulation X vestibular manipulation X age interaction ($F_{(1,27)}=5.80$, $p=0.02$, partial eta squared=0.18). Further analysis was performed in the young and older group separately. In the young group, no significant effect of GVS or the foam walking surface was found (Figures 3.5a and 3.5b). In the older group, head roll angle increased with GVS compared to no GVS condition on the foam surface ($F_{(1,14)}=10.45$, $p=0.006$, partial eta squared=0.43); however, no effect of GVS was found on a firm surface ($F_{(1,14)}=1.40$, $p=0.26$, partial eta squared=0.09) (Figures 3.5c and 3.5d). Line graphs of the data of average head roll angle in one young and one older participant are presented in Fig 3.6. The average head roll angle data of each participant are presented in Fig 3.7 as an example of data of each participant in this study. No significant effect of the narrow-based walking condition was observed on average head roll angle.
Figure 3.5 Average head roll (degrees) (mean ± SD) increased with GVS on the foam (p=0.006) (d) but not firm surface (p=0.26) (c) in the older but not in the young group (a and b). The ** denotes a significant effect on average head roll angle, while the * denotes a marginal effect.

Figure 3.6 Line graphs of head roll angle. (a) and (b) display head roll angle in no GVS and GVS condition on the foam surface in one young participant, respectively. (c) and (d) demonstrate head roll angle in no GVS and GVS condition on the foam surface in one older participant, respectively.
Figure 3.7 Data of average head roll angle for each participant in GVS condition compared to no GVS condition on firm and foam surface in young and older participants.

Average head roll velocity decreased in the narrow-based walking condition (5.90°/s±2.37) compared to normal walking condition (6.85°/s±2.92) (F(1,27)=8.66, p=0.007, partial eta squared=0.24), but increased on the foam surface (6.86°/s±2.57) compared to that on firm surface (5.87°/s±2.74) (F(1,27)=21.04 p<0.001, partial eta squared=0.44). A GVS X age interaction (F(1,27)=6.08 p=0.02, partial eta squared=0.18) was observed. Further analysis showed head roll velocity increased but not significantly in either age group. However, the effect size was larger in the older (F(1,14)=4.38 p=0.06, partial eta squared=0.24) than that in the young persons (F(1,13)=2.51 p=0.14, partial eta squared=0.16).
Average head pitch angle significantly increased in the narrow-based walking condition (9.78°±6.29) compared to normal-based walking (6.76°±4.11) \((F_{(1,27)}=16.43, p<0.001, \text{ partial eta squared}=0.38)\). When line graphs of the data were inspected for head pitch angle, it was observed that head pitch increased in positive/anterior direction as shown in Fig 3.8a and b. No significant effect of GVS, foam or age was observed on the average head pitch angle.

![Figure 3.8 Line graphs of head pitch angle. (a) and (b) display head pitch angle in narrow-based walking condition in one young participant and one older participant, respectively.](image)

A significant walking condition X vestibular manipulation X age interaction was observed for average head pitch velocity \((F_{(1,27)}=3.11, p=0.09, \text{ partial eta squared}=0.10)\). However, further analysis performed separately for young and older participants showed no significant effect of the narrow-based walking condition or GVS on average head pitch velocity in either the young or the older group.

The analysis for average trunk roll angle demonstrated a significant walking condition X lower limb somatosensory manipulation interaction \((F_{(1,27)}=6.59, p=0.02, \text{ partial eta squared}=0.20)\). Further analysis showed that average trunk roll angle increased in the
narrow-based walking condition on the foam surface ($F_{(1,28)}=13.94, \ p=0.001$, partial eta squared=0.33) but not on the firm surface ($F_{(1,27)}=1.37, \ p=0.25$, partial eta squared=0.05) (Figures 3.9a and 3.9b). A marginal lower limb somatosensory manipulation X vestibular manipulation interaction was also present ($F_{(1,27)}=3.28, \ p=0.082$, partial eta squared=0.11) for average trunk roll angle. Further analysis showed that trunk roll angle increased with GVS on the foam surface ($F_{(1,28)}=10.11, \ p=0.004$, partial eta squared=0.27) but not on the firm surface ($F_{(1,27)}=2.56, \ p=0.12$, partial eta squared=0.07) (Figures 3.9c and 3.9d). No age-related difference was found for trunk roll angle.

Figure 3.9 Average trunk roll (degrees) (mean ± SD) increased with GVS ($p=0.004$) and narrow-based walking ($p=0.001$) on the foam (b and d) but not on the firm surface (a and c). The ** denotes a significant effect on trunk roll and pitch angle, while the * denotes a marginal effect.

Average trunk roll velocity increased on the foam surface (6.33°/s±2.09) compared to firm surface (4.53°/s±1.57) ($F_{(1,27)}=92.41, \ p<0.001$, partial eta squared=0.77). No
significant effect of GVS, the narrow-based walking condition or age was found on trunk roll velocity.

The analysis for average trunk pitch angle demonstrated a significant increase when walking on foam ($F_{(1,27)}=124.83$, $p<0.001$, partial eta squared=$0.82$) and a marginal increase with GVS ($F_{(1,27)}=5.73$, $p=0.02$, partial eta squared=$0.18$) compared to firm surface and no GVS, respectively (Figures 3.10a and 3.10b). When line graphs of the data were inspected for trunk pitch angle, it was observed that trunk pitch angle increased in positive/anterior direction as shown in Fig 3.11a to d. A marginal four-way age group X walking conditions X vestibular manipulation X lower limb somatosensory manipulation interaction ($F_{(1,27)}=4.11$, $p=0.053$, partial eta squared=$0.13$) was present. However, further analysis showed that the impact of GVS and the foam surface did not differ between the two age groups.

![Figure 3.10](image)

**Figure 3.10** Average trunk pitch (degrees) (mean ± SD) increased on the foam surface ($p<0.001$) (a) and with GVS ($p=0.02$) (b). The ** denotes a significant effect on trunk roll and pitch angle, while the * denotes a marginal effect.
Average trunk pitch velocity decreased in the narrow-based walking condition (5.12°/s±1.41) compared to the normal condition (6.06°/s±1.75) ($F_{(1,27)}=9.62$, $p=0.004$, partial eta squared=0.26), but increased with GVS (6.18°/s±1.73) compared to no GVS (5.69°/s±1.43) ($F_{(1,27)}=7.29$, $p=0.012$, partial eta squared=0.21) and on the foam surface (6.58°/s±1.35) compared to the firm surface (5.27°/s±1.57) ($F_{(1,27)}=74.21$, $p<0.001$, partial eta squared=0.73). No significant effect of age was observed on average trunk pitch velocity.

3.4.2 Vestibular-visual Interaction for Head and Trunk Control and Global Responses

The data of 16 trials of the same young participant mentioned above (Page 80) were corrupted because of missing data from IREDs which were used to calculate gait speed and head and trunk-related variables. Therefore, the data of 14 young and 15 older
participants were included in this analysis (except for the analysis of step characteristics). The data from the IREDs on the left and/or right lateral malleoli of the same three young participants mentioned above (Page 80) (34 trials in total) were missing. Therefore, the data of 27 participants were included for the analysis of step characteristics.

3.4.2.1 Global locomotor responses

_Gait Speed_

Gait speed decreased in the narrow-based walking condition (1.08°/s±0.21) compared to the normal condition (1.14°/s±0.17) \((F_{(1,27)}=8.00, p=0.009, \text{partial eta squared}=0.23)\), but increased with GVS (1.15°/s±0.19) compared to no GVS (1.09°/s±0.20) \((F_{(1,27)}=16.66, p<0.001, \text{partial eta squared}=0.38)\). A walking condition X vision interaction was observed \((F_{(1,27)}=6.08, p=0.02, \text{partial eta squared}=0.18)\). Further analysis showed that gait speed decreased with narrow-based walking in normal vision but not significantly \((F_{(1,27)}=2.33, p=0.14, \text{partial eta squared}=0.08)\); while the decrease was significant with goggles \((F_{(1,27)}=16.07, p<0.001, \text{partial eta squared}=0.37)\). No main effect of goggles was observed. No age-related difference was found.

_Step Characteristics_

Overall, average step length decreased in the narrow-based walking condition (0.61m±0.10) compared to the normal walking condition (0.64m±0.08) \((F_{(1,25)}=14.97, p=0.001, \text{partial eta squared}=0.38)\), while it increased with GVS (0.64m±0.09) compared to no GVS (0.62m±0.09) \((F_{(1,25)}=12.91, p=0.001, \text{partial eta squared}=0.34)\). No significant
effect of goggles was observed on average step length. Average step width decreased in the narrow-based walking condition (0.19m±0.04) compared to the normal condition (0.22m±0.03) ($F_{(1,25)}=21.06$, $p<0.001$, partial eta squared=0.46), while it increased with GVS (0.21m±0.04) compared to no GVS (0.19m±0.04) ($F_{(1,25)}=10.08$, $p=0.004$, partial eta squared=0.29). No significant effect of goggles was observed on step width. No age-related difference was found for step length and width.

Overall, no significant effect of any condition/manipulation on step length variability was found. Step width variability increased with blurred vision (goggles) (0.14±0.06) compared to normal vision (0.11±0.05) ($F_{(1,25)}=11.72$, $p=0.002$, partial eta squared=0.32). No significant effect of GVS and narrow-based walking was found on step width variability. No significant age-related difference was observed for the variability of step length and step width.

3.4.2.2 Segmental responses

No significant effect of any manipulation/condition was observed on average head roll angle. Average head roll velocity marginally decreased with blurred vision compared to normal vision with large effect size ($F_{(1,27)}=6.54$, $p=0.016$, partial eta squared=0.20) (Figure 3.12a) and decreased in the narrow-based walking condition compared to normal walking condition ($F_{(1,27)}=7.17$, $p=0.012$, partial eta squared=0.21) (Figure 3.12b). A walking condition X GVS interaction was observed ($F_{(1,27)}=5.29$, $p=0.03$, partial eta squared=0.16). Further analysis showed head roll velocity decreased in narrow-based
walking without GVS ($F_{(1,27)}=12.82$, $p=0.001$, partial eta squared=0.32); while the
decrease was not significant with GVS ($F_{(1,27)}=1.76$, $p=0.20$, partial eta squared=0.06). A
marginal vestibular manipulation X age interaction was observed ($F_{(1,27)}=3.92$, $p=0.06,$
partial eta squared=0.13). Further analysis showed that in the young persons head roll
velocity was not affected by GVS ($F_{(1,13)}=1.99$, $p=0.18$, partial eta squared=0.12); while in
the older group it increased with GVS, not significantly but with large effect size
($F_{(1,14)}=3.87$, $p=0.07$, partial eta squared=0.14).

Figure 3.12 Average head roll velocity (degree/s) (mean ± SD) decreased with goggles ($p=0.016$)
and narrow-based walking ($p=0.012$). The ** denotes a significant effect on head roll velocity,
while the * denotes a marginal effect.

Average head pitch angle significantly increased in the narrow-based walking condition
(9.20°±6.25) compared to normal walking condition (6.11°±3.61) ($F_{(1,27)}=23.94$, $p<0.001$,
partial eta squared=0.47). No significant effect of GVS or goggles was observed on head
pitch angle. No significant effect of any manipulation or condition was observed on
average head pitch velocity. No age related difference was observed for either head
pitch angle or head pitch velocity.
No significant effect of any condition/manipulation or age was found on average trunk roll angle or average trunk roll velocity.

Average trunk pitch angle marginally increased with GVS \(5.50^\circ \pm 1.61\) compared to no GVS \(4.67^\circ \pm 1.64\) \(F(1,27)=6.62, p=0.016, \text{partial eta squared}=0.20\). No significant effect of walking condition or goggles was found on trunk pitch angle. No age related difference was observed for trunk pitch angle. Average trunk pitch velocity increased with GVS \(F(1,27)=12.15, p=0.002, \text{partial eta squared}=0.31\) but decreased with narrow-based walking \(F(1,27)=11.83, p=0.002, \text{partial eta squared}=0.31\), compared to no GVS and normal walking, respectively (Figure 3.13a and b). When line graphs of the data were inspected for trunk pitch velocity, it was observed that trunk pitch velocity increased with GVS in positive/anterior direction as shown in Fig 3.14a to b. No significant effect of goggles and age was observed on trunk pitch velocity.

![Figure 3.13](image)

Figure 3.13 Average trunk pitch velocity (degree/s) (mean ± SD) increased with GVS \(p=0.002\) (a) but decreased with narrow-based walking \(p=0.002\) (b). The ** denotes a significant effect on trunk pitch velocity, while the * denotes a marginal effect.
Figure 3.14 Line graphs of trunk pitch velocity. (a) and (b) display trunk pitch velocity in GVS condition in one young participant and one older participant, respectively.

3.4.3 Relationship between Frontal Plane Head/Trunk Control and Sensory Function

In the normal walking condition (Table 3.4), average trunk roll angle was significantly and positively associated with lower limb vibration sensitivity threshold, and the significance did not change after adjusting for age. Average head roll angle and head-trunk coordination were not significantly associated with any sensory function.

In the narrow-based walking condition (Table 3.4), head-trunk coordination (head-trunk cross-correlation coefficient) was negatively associated with SVV. Adjusting for age made the association between head-trunk coordination and SVV marginal. Average head roll angle and average trunk roll angle were not associated with any sensory inputs.
Table 3.4 Correlation coefficient and the corresponding p value for each sensory measure associated with head control, trunk control or head-trunk coordination during both normal walking and narrow-based walking.

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>dependent Variable (s)</th>
<th>β±SE (without adjusting for age)</th>
<th>P value (without adjusting for age)</th>
<th>β±SE (adjusting for age)</th>
<th>P value (adjusting for age)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hd Roll NW</td>
<td>Cutaneous pressure sensitivity</td>
<td>0.33±0.77</td>
<td>0.16</td>
<td>0.23±0.94</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>Vibration sensitivity</td>
<td>0.08±0.14</td>
<td>0.77</td>
<td>0.03±0.15</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>Far DVA (1m/s)</td>
<td>-0.24±3.58</td>
<td>0.25</td>
<td>-0.27±3.71</td>
<td>0.22</td>
</tr>
<tr>
<td>TrRoll NW</td>
<td>Vibration sensitivity</td>
<td>0.36±0.02</td>
<td>0.05</td>
<td>0.51±0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>H-T Corr NW</td>
<td>N.C.</td>
<td>N.C.</td>
<td>N.C.</td>
<td>N.C.</td>
<td>N.C.</td>
</tr>
<tr>
<td>Hd Roll NBW</td>
<td>N.C.</td>
<td>N.C.</td>
<td>N.C.</td>
<td>N.C.</td>
<td>N.C.</td>
</tr>
<tr>
<td>TrRoll NBW</td>
<td>N.C.</td>
<td>N.C.</td>
<td>N.C.</td>
<td>N.C.</td>
<td>N.C.</td>
</tr>
<tr>
<td>H-T Corr NBW</td>
<td>SVV</td>
<td>-0.39±0.05</td>
<td>0.05</td>
<td>-0.38±0.06</td>
<td>0.06</td>
</tr>
</tbody>
</table>

Hd Roll/TrRoll = average head/trunk roll angle, H-T Corr = cross-correlation between average head and trunk roll angle, NW = normal walking, NBW = narrow-based walking, N.C. = no sensory input was correlated with the dependent variable so no independent variable was included.
3.5 Discussion

This study investigated how vestibular input is used and how it interacts with lower limb somatosensory and visual input for head and trunk control during normal and narrow-based walking in healthy young and older adults. The effect of sensory interactions and manipulations on global postural responses were also assessed. Gait speed increased with manipulation of the vestibular system but decreased in the narrow-based walking condition. Head roll velocity decreased in the narrow-based walking condition and with visual manipulation. Trunk roll angle increased with GVS on the foam surface but not on the firm surface. Trunk pitch angle and velocity and trunk roll velocity increased with manipulation of lower limb somatosensory input alone. The difference between young and older participants was reflected by increased head roll angle with GVS on the foam surface in older but not in young persons. Head roll velocity also increased with GVS in the older group as shown by the large effect size; however, this difference did not reach statistical significance.

3.5.1 Impact of Sensory Manipulations and Walking Conditions on Global Responses

Gait speed decreased in the narrow-based walking condition in both groups (Figure 3.4). The decrease in gait speed in narrow-based walking is consistent with the findings of Schrager et al. (34). This suggests that the participants from both groups may have used a cautious strategy in order to adapt to the constraints of the narrow path. The difference between the two groups in gait speed in the narrow based walking condition was not statistically significant. This may be ascribed to the fact that the majority (12
out 15) of the older participants were young old i.e. 75 years old or younger, and all were very healthy and active. All older participants could walk independently. Further, 11 out of the 15 older participants regularly performed physical exercises for at least 5 hours per week, with activities including jogging and cycling.

Overall, gait speed increased with GVS, and this is the first study to report this finding. Increasing gait speed may be a strategy to counteract the M-L perturbation induced by GVS by generating momentum of the body in A-P direction. Orendurff et al. (59) measured the displacement of the COM when participants walked at 4 designated speeds (0.7, 1.0, 1.2 and 1.6 m/s) and self-selected gait speed (1.61m/s). They found that displacement of COM in M-L direction was smaller when participants walked at a faster speed, and this trend remained consistent for all the gait speeds. The results suggest this strategy may be at least partially useful, as head and trunk roll angle did not increase with GVS when walking on the firm surface. However, when lower limb somatosensation was disrupted, head roll angle increased with GVS in older participants and GVS had a main effect on trunk roll angle.

Both the narrow-based walking condition and GVS pose challenges to postural control in M-L direction. However, participants adopted different strategies by increasing gait speed with GVS and decreasing gait speed in the narrow-based walking condition. Challenge in M-L direction to postural control is possibly the only challenge that GVS poses. Therefore, maintaining stability in M-L direction might be the priority, which may
be achieved by increasing gait speed. However, in the narrow-based walking condition the participants had to maintain stability in M-L direction as well as secure appropriate foot placement within the lines demarcating the path. This possibly requires additional attention which may have resulted in the cautious strategy as suggested by the slower gait speed (60). Although slower gait speed has been reported to be associated with larger COM displacement in M-L direction (59), which could negatively impact M-L stability during narrow-based walking, slower gait speed may also allow longer double-support phase time to compensate for unexpected perturbations (61) thus, improving stability. The reduction in gait speed was perhaps at least effective on the firm surface, as neither trunk roll angle nor velocity increased in the narrow-based walking condition compared to normal walking condition when walking on the firm surface.

The foam walking surface did not influence gait speed. These findings are consistent with those reported by Menz et al. (62). No main effect of goggles was observed. When vision was blurred, participants only adopted a more cautious strategy by further decreasing gait speed in narrow-based walking, which was not observed in the normal vision condition. The finding is to some extent contrary to the findings of McFadyen et al. (21) who found that gait speed decreased when the participants walked with goggles compared to normal vision. However, in their study the goggles did not allow detection of any objects from the surrounding environment. In contrast, the goggles used in this study are known to significantly reduce contrast sensitivity (20) but they allow some identification of objects in the surrounding environment. Therefore, it is possible that
participants did not feel the need to reduce gait speed in the static environment of the laboratory.

Consistent with previous findings (20), step width variability was affected only by the quality of visual information, which suggests that optimum visual information may be required to control step-to-step rhythm in the M-L direction. The effects of visual manipulation on head control (decrease in head roll velocity) and step variability were both in M-L direction. These findings suggest the importance of accurate visual input for postural control in M-L direction with less importance in the A-P direction. GVS had no impact on step length or width variability. These findings are consistent with those reported by Deshpande and Patla (20). In addition, in this study the foam surface did not influence step width or length variability. These findings are different from the findings of MacLellan and Patla (48). However, the significant effect of the foam surface on step length variability in their study was possibly due to the use of less stringent p value (<0.05). On the other hand, we used Bonferroni correction and a p value of <0.013 to indicate significance.

Average step length and width increased on the foam walking surface and with GVS but decreased in the narrow-based walking condition. It is possible that the increase and decrease in step length with GVS and in narrow-based walking, respectively, were in accordance with the respective changes in gait speed. Adjusting for gait speed, the impact of GVS on step length became insignificant (p=0.11), and the impact of narrow-
based walking was significant under unadjusted significance level but became insignificant under the adjusted significance level \( p=0.027 \), while the effect of foam remained significant \( p<0.001 \). Gait speed was a significant covariate for step length \( p<0.001 \). It is also quite understandable that step width decreased with narrow-based walking due to the restrictions on foot placement. Increase in step length and width when walking on the foam surface is consistent with findings of MacLellan and Patla (48). Increase in step length on the foam surface may assist in reducing number of steps in an attempt to reduce contact with the surface that provides erroneous information. Increase in step width on the foam surface and with GVS probably ensured a larger BOS in which the COM can be controlled (48) for improving stability. Despite this strategy, trunk roll velocity, trunk pitch angle and velocity all increased on foam irrespective of other manipulations or conditions. In contrast, increased step length and width with GVS may be partially effective for trunk control, as trunk roll and trunk roll velocity did not increase with GVS on the firm surface.

### 3.5.2 Impact of Sensory Manipulations and Walking Conditions on Head Control

Head roll velocity decreased with blurred vision and in the narrow-based walking condition (Figure 3.12), but increased on the foam surface compared to firm surface. Age-related differences in head control were reflected by the finding that head roll velocity increased with GVS in older persons (not statistically significant but with large effect size), and head roll angle increased with GVS on the foam surface in older but not
in young participants (Figure 3.5). Head pitch angle increased in the narrow-based walking condition.

Head roll velocity decreased with both blurred vision and the narrow-based walking condition. Decreased head roll velocity with blurred vision reached the adjusted marginal p level (0.025) but not the adjusted significance p level (0.013). However, there was a large effect size, which was shown by large partial eta squared (partial eta squared=0.20) calculated by SPSS. Partial eta squared is calculated as $SS_{effect}/(SS_{effect}+SS_{error})$, where $SS_{effect}$ is the sum of square for the effect of interest and $SS_{error}$ is the sum of square for error term associated with that effect. A marginal result with a large effect size means that increasing sample size would lead to a significant result under the adjusted significant level. Sample size calculation using statistical software G*Power (64) showed that the decrease in head roll velocity with blurred vision would become significant if the overall sample size increased to 36. Decreased head roll velocity with blurred vision could possibly be considered as a strategy to adapt to this suboptimal vision condition and reduce image motion. It is possible that the compensation of the vestibulo-ocular reflex (VOR) was not sufficient to maintain image clarity with blurred vision, and decreased head roll velocity was adopted perhaps in an attempt to improve clarity under suboptimal vision conditions during walking.

The decreased head roll velocity observed in the narrow-based walking condition has not been reported before. This strategy may be associated with increased weighting of
the vestibular signal for postural control in the difficult task of narrow-based walking. Decreasing head roll velocity may simplify the interpretation of vestibular input, and improve accuracy of the vestibular signal during narrow-based walking (3). This strategy suggests the importance of accurate vestibular information for postural control during this task. A GVS X narrow-based walking interaction on head roll velocity was observed in the vestibular-visual analysis but not in the vestibular-lower limb somatosensory analysis. Combined analysis (walking condition X walking surface X GVS X vision X age) showed no significant GVS X narrow-based walking interaction (p=0.36). That means in this study for either head control or trunk control, vestibular manipulation did not specifically impact postural control during narrow-based walking. It is possible that applying GVS intensity at 2 times threshold may not be enough to evoke differential responses.

Head roll angle of the older persons increased when GVS was applied, only when walking on the compliant surface. This was not observed in young persons. Healthy older adults exhibited increased head roll velocity with GVS non-significantly but with larger effect size. The head roll velocity non-significantly increased with GVS in young persons with large effect size in the vestibular-lower limb somatosensory analysis but not in the vestibular-visual analysis. Combined analysis (walking condition X walking surface X GVS X vision) showed head roll velocity increased non-significantly with GVS with large effect size only in the older group (partial eta squared=0.25) but not in the young group (partial eta squared=0.09). Sample size calculation using statistical
software G*Power (64) showed that the increase in head roll velocity with GVS in the older group would become significant under the adjusted significance level of 0.013 if the sample size of the older group increased to 24. Such age-related difference has not been reported but could be supported by previous studies. In older people, the weighting of the vestibular input for head control may be higher compared to that in young people, especially when lower limb somatosensory input was manipulated. In other words, even with normal vision the CNS of older people was probably unable to down-regulate/decrease the weighting of the manipulated vestibular signal for the M-L head control, particularly when the walking surface became compliant. The decreased CNS integrative ability might be ascribed to age-related deterioration of the brain, particularly the age-related neuronal loss in the vestibular nuclei in the brainstem (65) as well as the age-related atrophy of the posterior multimodal sensory area in the association cortex (66). These areas are closely related to integrating sensory inputs from different systems (including vestibular signal) and directing motor behaviour (65-67).

Increased weighting of vestibular afferents or higher sensitivity to vestibular perturbation in older people compared to young people could possibly be considered as a strategy to compensate for age-related deterioration in both the peripheral vestibular receptors (68) and/or the vestibular nuclei in the brain stem (65). Available evidence suggests that increased sensitivity could possibly maintain normal function despite reduced peripheral input (69). Jahn et al. (69) applied GVS to 57 healthy participants (20
to 69 years old) and measured torsional eye movement responses. Results showed higher nystagmus slow phase velocity and higher nystagmus frequency in the group 60-69 compared to those in the 20-29 group. Alternatively, it is also possible that the increased vestibular weighting in older people would stem from the age-related deterioration of other sensory systems, such as the somatosensory system (70). To examine whether the age-related difference was due to the ageing of the vestibular system or the ageing of other systems such as the visual or lower limb somatosensory system, we compared the function of the three systems between the young and older group. The results showed no difference in the visual system, but significantly worse function of the other two systems in the older group: sole cutaneous pressure sensitivity ($t_{(28)}=5.17$, $p<0.01$), sole vibration sensitivity ($t_{(28)}=4.05$, $p=0.001$), ankle proprioception ($t_{(28)}=5.46$, $p<0.001$) and near DVA at 1.5m/s ($t_{(24)}=2.44$, $p=0.02$). Therefore, increased weighting of vestibular input in the older group may result from either the deterioration of other systems, such as somatosensory system, or be considered as a compensation for the deterioration of the vestibular system or both.

Age-related difference was only reflected in head control but not in trunk control in this study. During locomotion, direct and effective reflexes are responsible for stabilizing the head, such as cervico-collic reflex (71;72). Lack of such direct and effective reflex, combined with much larger body mass of the trunk, possibly made trunk control more difficult than head control even for young persons, especially when sensory signals were discordant. Therefore, young persons, with intact neurological function, may have the
ability to achieve relatively robust head control even when both the vestibular and lower limb somatosensory inputs are manipulated.

Head roll velocity increased on the foam surface, which was the only variable representing head control that was affected by lower limb somatosensory manipulation alone. However, this impact was possibly due to the concurrent increase in trunk roll velocity on the foam surface, as adjusting for trunk roll velocity made the increase in head roll velocity on foam insignificant (p=0.55). When walking on foam, the participants may have adopted a stiffening strategy by the coupling the head and trunk in order to decrease the controlled degrees of freedom during this difficult task (55).

Head pitch increased in the narrow-based walking condition, which has not been reported before. When line graphs of the data were inspected for head pitch angle, it was observed that head pitch increased in positive/anterior direction (Figure 3.8). A simple explanation could be the requirement to ensure the foot placement between the tapes on the floor which delineated the narrow base using visual input. Alternatively, it is possible that the increased head pitch was a method to increase the sensitivity of the vestibular system, the otoliths to be specific. With increased head pitch angle, the utricle is closer to the horizontal plane, so that the change in the shear force applied on the otoconial membrane is maximal, which leads to higher sensitivity of the otolith as well as better detection of head movement and the direction of gravity (3). However, it is not clear why some participants adopted an oscillating pattern for head pitch in the
narrow-based walking condition, in which their head pitch angle fluctuated throughout the walking process (Appendix I and J).

3.5.3 Impact of Sensory Manipulations and Walking Conditions on Trunk Control

Trunk roll angle increased with GVS and in the narrow-based walking condition only on the foam walking surface (Figure 3.9). Truck pitch angle increased on the foam walking surface (Figure 3.10), while trunk pitch velocity increased with GVS but decreased in the narrow-based walking condition (Figure 3.13).

The trunk roll angle increased in the narrow-based walking condition and with GVS only when walking on the foam surface. The findings were consistent with findings by Allum et al. (9) and Gill et al. (73). Allum et al. (9) asked healthy participants and patients with unilateral vestibular deficits (UVD) and those with cerebellar-pontine-angle-tumour (CPAT) to perform a series of tasks, including standing on one leg for 20s and walking for 8 tandem steps on firm and foam surfaces. The difference in trunk roll angle among the three groups was significant for both tasks on the foam surface but not on firm surface (9). Gill et al. (73) asked the healthy young and older participants to perform a series of tasks, including standing on one leg (narrow base) and two legs (wide base) on a firm and a foam surface for 20s. Both groups showed higher trunk roll angle and trunk roll velocity during standing on one leg compared to standing on two leg on both surfaces. However, the absolute differences between standing on two legs and standing on one leg were much larger on the foam surface compared to those on the firm surface for
both variables. The results from both this study and previous studies (9;73) suggest that trunk control especially that in the M-L direction may require accuracy of lower limb sensory inputs during standing and locomotion with challenges. This is possibly because postural control during tasks with challenges may require precision in execution of balance-recovery reactions. According to Thoumie et al. (74), intact lower limb somatosensory inputs, especially ankle proprioception, play an important role in such balance-recovery reactions. Manipulation of lower limb somatosensory input may have limited the recovery reactions during walking on foam with GVS or a narrow base, possibly leading to the increase in trunk roll angle. However, average trunk roll angle increased with GVS and in the narrow-based walking condition on the foam surface only to a small extent (less than 1°) despite the significant results. Such a small increase may be significant for investigation of the effect of sensory interactions on trunk control but may not be clinically critical. Future study using a narrower base of support and/or higher GVS intensity may present greater challenge and possibly reveal a scaling effect.

No age-related difference in trunk control was observed in this study. This is contrary to findings of Deshpande and Patla (20) who asked 9 healthy young (20-35 years) and 9 older participants (65-85 years) to walk straight to a target 6.5m away to the beat of a metronome (80 steps/min) with GVS and/or blurring goggles. With normal vision, trunk roll angle in the young group was not influenced by GVS while the trunk tilted in the anodal direction in the older group. The difference in findings between this study and Deshpande and Patla (20) may be related to the different walking tasks. Walking to a
target to the beat of a metronome adds a cognitive challenge to the task, which is probably more difficult especially for the older participants compared to walking straight at self-selected pace in this study (75;76).

The average trunk pitch angle marginally increased with GVS, and trunk pitch velocity increased with GVS but decreased in the narrow-based walking condition. Sample size calculation using G*Power (64) shows that an overall sample size of 36 is needed to demonstrate a significant increase in trunk pitch angle with GVS with a significance level of 0.013. The impact of both GVS and narrow-based walking on head and trunk is mainly in M-L direction; therefore, the impact of GVS or narrow-based walking on trunk control in A-P direction may not reflect their direct impact on trunk control. These changes could possibly be attributed to similar changes in gait speed in the respective conditions. When line graphs of the data were inspected for trunk pitch angle and velocity, it was observed that trunk pitch angle and velocity increased with GVS in positive/anterior direction (Figure 3.11 and 3.14). Therefore, increased trunk pitch angle or velocity could possibly be regarded as a strategy to bring the center of mass (COM) of the whole body forward to achieve forward momentum and increased gait speed, so that the GVS-induced M-L perturbation could be counteracted (59). In order to support this inference, we re-analyzed the impact of sensory manipulations and walking conditions on trunk pitch velocity including gait speed as a covariate. The results show that after adjusting for gait speed, trunk pitch velocity marginally decreased in narrow-based walking (p=0.02) while the increase with GVS became insignificant (p=0.06), while the impact of
foam on trunk pitch velocity remained significant (p<0.001). The gait speed was a significant covariate (p<0.001).

In this study, neither trunk roll angle nor velocity was affected by GVS or the narrow-based walking condition on firm walking surface. However, increased gait speed with GVS and increased step width with GVS were both observed. Possibly a higher momentum in the A-P direction combined with a wider base of support have largely maintained trunk control in M-L direction. Therefore, GVS alone did not induce increased trunk roll velocity or angle. Conversely, despite significantly decreased step width in the narrow-based walking condition, trunk roll angle and velocity were also not affected by the narrow-based walking condition alone. Possibly the decreased gait speed in narrow-based walking has led to longer double support phase in response to the increased M-L challenge to postural control as mentioned above (Page 97). In response to M-L challenges imposed by GVS and narrow-based walking, different but possibly successful strategies have been adopted. The results may suggest a complex mechanism of trunk control in M-L direction, and seemingly higher priority of postural control in M-L direction compared to that in A-P direction.

Overall even with intact lower limb somatosensory input, blurred vision had a marginal effect on head control with large effect size, and vestibular stimulation increased head roll velocity in older people. Manipulation of lower limb somatosensory input alone exhibited significant influence on only one variable related to head control: head roll
velocity. Further, the increased head roll velocity on foam may not reflect the direct impact of the foam surface on head control as mentioned above (Page 104). In contrast, vestibular or visual manipulation alone had a significant impact on neither trunk roll angle nor trunk roll velocity. Manipulation of lower limb somatosensory input alone had a significant effect on trunk roll velocity, trunk pitch and trunk pitch velocity. The subtle differences between the impact of sensory manipulations on head and trunk control may support differential segmental control (77;78). It is suggested that head control may rely more on reflexes in which the visual and/or vestibular system are directly involved, such as opto-kinetic cervical reflex and/or the vestibulo-cervical reflex (50). Such reliance may suggest the importance of "top-down" model* for head control, which means head control may be organized in relation to visual and/or vestibular input (50;79;80). In contrast, trunk control may depend more on accurate lower limb somatosensory information. This suggests the importance of the “bottom-up” model* for trunk control, which means trunk control may be organized from the support surface upward (79;80).

3.5.4 Relationship between Frontal Plane Head/Trunk Control and Sensory Function

The results have shown the linear relationship between trunk control in M-L direction and lower limb vibration sensitivity during normal walking. This relationship may further suggest higher weighting of lower limb somatosensory inputs for trunk control in M-L direction compared with other sensory systems. This finding may further support that a "bottom-up" model could be used for trunk stability (79;80).

*The meaning of the “top-down” and “bottom-up” model is different from that in other fields in neuroscience (81;82).
A linear relationship was found between head-trunk coordination in M-L direction and vestibular function during narrow-based walking. During narrow-based walking, the participants may have adopted a "top-down" strategy, using the vestibular system as the vertical reference. It is surprising that head-trunk coordination was linearly related to vestibular signal (SVV) but not lower limb somatosensory information when challenges were imposed in the frontal plane. This seemingly is contradictory to the contribution of lower limb somatosensation to trunk stability in M-L direction during narrow-based walking that we found in this study. The role of vestibular input in narrow-based walking may be explained by its high weighting for postural control especially in M-L direction during locomotion tasks with challenges, such as stepping up stairs (9,18). Adjusting for age did not greatly change the results, which may suggest similar sensory strategies were used in young and older people for head and trunk control.

The findings in this study were to some extent different from the hypothesis. Compared to young persons, older participants were only less able to decrease the weighting of the discordant vestibular input for head control but not trunk control. Even with sensory manipulations no significant difference was observed between young and older participants in terms of head and trunk control during narrow-based walking.
3.6 Limitations

This study has several limitations. For example, this study was unable to compare the extent of the impact of manipulation of the vestibular system and that of the lower somatosensory system. The manipulation of vestibular input was quantified in this study. However, it is difficult to quantify the effect of lower limb somatosensory manipulation by using a foam mat. As a result, the impact of the foam walking surface on the lower limb somatosensory system and the impact of GVS on the vestibular system may not be comparable with respect to intensity of the perturbation. It is also possible that applying GVS intensity at 2 times threshold may not be high enough to trigger differential responses with intact lower limb somatosensory input and some visual information.

3.7 Conclusion

In conclusion, this study examined lower limb somatosensory-vestibular and visual-vestibular interactions during narrow-based walking in young and older adults on head and trunk control. The results have shown the importance of lower limb somatosensory inputs for trunk control and visual and vestibular inputs for head control. The results have also suggested the possibility of higher reliance on vestibular information to control head angle and velocity in older people compared to young adults. Further, the complexity of trunk control in M-L direction in different conditions was observed. Moreover, the findings may lay a foundation for the development of rehabilitation interventions to improve postural control, especially in older persons and/or patients with vestibular deficits. For example, patients with vestibular deficits could be trained to
rely upon lower limb somatosensory information as their primary postural sensory system, because intact lower limb somatosensory input could largely override inaccurate vestibular information during locomotion as suggested by our results. Potential rehabilitation implications of this study are included in General Discussion in this thesis.
3.8 Reference


Chapter 4

Inter-trial Reliability and Sensitivity of 3 Protocols Designed to Screen for Vestibular System Function via Spatial Orientation

4.1 Abstract:

Vestibular information is significantly integrated for maintaining spatial orientation. Therefore, tasks requiring accurate spatial orientation have been used as tools to screen for vestibular dysfunction. This study evaluated the inter-trial reliability of three tools that are used to screen for vestibular dysfunction by testing the ability to maintain spatial orientation, and the sensitivity of these tools to potential age-related difference in vestibular function. Fifteen young and 15 older healthy adults were asked to complete 6 trials of each of the Fukuda Stepping Test, Triangle Walking Test and Straight Walking Test. The outcome measures reflecting distance and rotational errors in spatial orientation were computed using foot position. Distance of displacement (DD) from the initial position in the Fukuda Stepping Test exhibited high reliability and acceptable variability in both young and older persons. DD was also sensitive to age-related differences between the two groups. Distance of displacement in the Fukuda Stepping Test is a reliable and sensitive measure to screen for vestibular system function. Results suggest the need for age-dependent normative baseline data for identifying age-appropriate cut off levels.
4.2 Introduction

Spatial orientation describes the sense of heading and self-motion during locomotion, which is used to plan precise motor commands for progressing to a target (1). The ability to maintain accurate spatial orientation is dependent on vision, vestibular and somatosensory inputs (2-5). Undoubtedly, the effect of vision on spatial orientation is dominant. When visual information is available, patients with vestibular deficits and healthy adults with manipulated vestibular input can maintain accurate spatial orientation (4;5). However, when vision is occluded, vestibular deficits and experimental manipulation of vestibular information significantly decrease the accuracy of spatial orientation during walking and stepping-in-place (4-6). The vestibular system updates the central nervous system (CNS) with information about both linear and angular acceleration of the head, which is used to derive information of the distance and direction of locomotion (7;8). Further, the vestibular projections to parietal and temporal cortical areas and hippocampus may underlie vestibular impact on perceived orientation and self-motion (9;10).

Lower limb somatosensory input may play a much less important role in spatial orientation compared to the vestibular signal (4). Fitzpatrick et al. (4) guided blindfolded participants from a starting position to an end position along one of four curved paths in a random order. In some trials the participants walked with guidance, which was an intermittent touch on the top of the participants’ shoulders as an indication of the direction of turn. In other trials they were pushed in a wheelchair with and without
GVS. The use of wheelchair negated the potential contribution of lower limb somatosensory input on spatial orientation. On reaching the end position, the participants removed the blindfold and were asked to indicate where they perceived the start position was. The estimation of the direction from the designated start to the perceived start were measured. The results showed no difference in estimation of the direction between the walking trials and wheelchair trials without GVS. Further, in wheelchair trials, GVS significantly altered participants’ perceptions of the direction of the start position (4). Their results suggest that perception of direction of progression required for spatial orientation is related to the vestibular input rather than the lower limb somatosensation.

Tools such as Fukuda Stepping Test (6) have been used to screen for vestibular deficits by testing the ability to maintain accurate spatial orientation. In the Fukuda Stepping Test, participants are required to step in place with arms stretched forward and eyes blind-folded for 50 or 100 steps. Previous studies (6;11) showed that patients with vestibular deficits and healthy people with experimental imbalance in vestibular information demonstrate displacement and self-rotation in the direction of the affected side, after stepping for 50 or 100 steps.

Walking on a triangular path (5) and walking straight ahead (12) without visual information have also been used to assess spatial orientation in both healthy persons and patients with vestibular deficits. In the triangle walking test (5), participants are
asked to complete a previously seen triangular path as accurately as they can with eyes blindfolded. Glasauer et al. (5) found larger deviations from the designated path in patients with vestibular dysfunction compared to healthy participants. Similarly, in the straight walking test, participants are asked to walk to a target located straight ahead with eyes blindfolded. Cohen and Sangi-Haghpeykar (12) demonstrated significantly larger path deviation in the patients with vestibular deficit compared to healthy participants.

There are other spatial orientation tasks and vestibular deficit screening tools. Spatial orientation tasks designed to navigate in a virtual environment are based on ability to develop spatial maps using hippocampal circuitry rather than the vestibular input (13). For example, in the virtual Morris water task, which is performed on a laptop, the participants are asked to navigate from a random location on the edge of a virtual pool to a hidden platform in the pool using a keyboard (13). Other vestibular deficit screening tools include but are not limited to dynamic visual acuity (DVA) (14), tandem walking test (15) and head impulse test (16). However, they are based on vestibular functions other than spatial orientation. Conversely, Fukuda Walking Test, Triangle Walking Test and Straight Walking Test are unique in that they are designed to screen for vestibular function based on the role of the vestibular system in spatial orientation.

It is evident that simple screening tools may distinguish individuals with vestibular deficits from healthy persons based on errors in spatial orientation. However, before
determining if these tools could be used to detect age related impairment in spatial orientation, it is first necessary to assess the inter-trial reliability of the three tools in order to test whether the variables included in the tools consistently reflect the ability of the participants to maintain spatial orientation in the same condition.

With increasing age the vestibular system experiences loss of vestibular hair cells, vestibular neurons and nerve axons (17;18). Hair cell reduction begins as early as 40 years of age (18). Further, age-related deterioration in the ability to maintain accurate spatial orientation has been reported (19;20). Using complex tasks, previous research has shown that older adults have larger deviations compared to younger adults in a variety of spatial orientation tasks requiring visualization abilities and memory for object locations (19;20) or tasks with clear implications for way-finding, such as selecting and remembering landmarks (21;22). However, no study has shown whether the abovementioned simple clinical and experimental tools used to screen for vestibular deficits based on the role of the vestibular system in spatial orientation (5;6;12), are sensitive to age-related difference in vestibular function.

Therefore, the first purpose of this study was to investigate the inter-trial reliability and variability of the outcome measures derived from the FST, TWT and SWT in both young and older adults. The secondary purpose was to test the sensitivity of the outcome measures with moderate to high reliability and acceptable variability to differences between young and older adults.
4.3 Methods

4.3.1 Participants

A total of fifteen young (age 20–35 years, 7 females and 8 males, height: 170.8±8.6cm, weight: 67.9±12.3 kg) and fifteen older adults (age 65–85 years, 7 females and 8 males, height: 167.7±12.7cm, weight: 74.5±16.0kg) were recruited. The young participants were students at Queen’s University or their friends or colleagues from the Kingston, Ontario community. They were recruited through personal contact by investigators in this study. The older participants were participants in two previous studies performed in the Motor Performance Laboratory; the study which Chapter 3 is based on and a study on vestibular system and diabetes (not included in this thesis). The older participants expressed their willingness to take part in new studies in the laboratory after they participated in the two studies mentioned above. The older participants were contacted by telephone by the investigators, and appointments were arranged if they reported no condition in the exclusion criteria and were willing to participate in this study. Participants were excluded if they reported a history of neuropathy or past diagnosis of overt vestibular pathology (e.g. benign paroxysmal positional vertigo or vestibular neuritis) or other major neurological/musculoskeletal condition (e.g. Parkinson’s disease, stroke, MS etc.). Those with painful lower limb arthritis or requiring an assistive device for walking were also excluded. One older participant was found to have diabetes (without neuropathy). However, the data for this participant was retained as the vestibular function of this participant was within normal limits in all items involved in Videonystagmography (VNG) test. Further, exclusion of the data of this participant did
not change the results (no ICC increased from low to moderate or decreased from moderate to low with the exclusion of the data). The Fukuda Stepping Test requires stepping with arms raised to the shoulder level. Therefore, participants who were unable to raise arms to shoulder level and hold this position for at least 30s were also excluded. All the 30 participants who came to the laboratory completed all trials of all the tests. Therefore, no additional participants were recruited.

4.3.2 Procedures and Outcome Measures

This study was performed in the Motor Performance Laboratory as well as in the clinical laboratory in the School of Rehabilitation Therapy (Louise D'Acton Building) at Queen's University. After arrival at the Motor Performance Laboratory, participants read the information form about the study and signed an informed consent form (Appendix F) approved by the Queen's University Health Sciences and Affiliated Teaching Hospitals Research Ethics Board. Their age was recorded and their height and weight were measured. The participants together with the investigators then went to the clinical laboratory to perform the tests because of the bigger area of this laboratory compared to that of the Motor Performance Laboratory.

Before the tests, four markers were attached to the participants' shoes, two at the level of toes (As1 and As2, Figure 4.1a) and two at the level of heels (Bs1 and Bs2, Figure 4.1a). At the end of each trial markings were placed on the floor corresponding to these markers. The outcome measures in each trial were calculated based on the markings on
the floor. The participants were asked to perform 6 trials of each of the following three tests with eyes blind-folded using an eye patch: Fukuda Stepping Test (FST), Triangle Walking Test (TWT) and Straight Walking Test (SWT). The order of the tests was randomized. Before each test, the investigators described the procedures of the test to the participants. Next, the participants practiced the test 2 to 3 times (with and without eyes closed) until they were familiar with the test and the laboratory environment as suggested by Glasauer et al. (5). The variables were calculated by the investigators after completing each trial. The participants were not given any feedback concerning their performance during the tests.

4.3.2.1 Fukuda Stepping Test

The participants were asked to stand on the center of the coordinate system with feet close together (shown in Figure 4.1), such that the mid-point of A's (the mid-point between As1 and As2) and B's (the mid-point between Bs1 and Bs2, Figure 4.1a) overlapped the original point of the coordinate (Point O, Figure 4.1a). They were then blind-folded and asked to step in place after the verbal instruction “go”. They stepped for 50 steps at their self-selected pace with both arms raised to 90° of shoulder flexion. When 50 steps were completed, the participants were asked to stand in their last position without moving, and 4 markings were placed on the floor corresponding to the markers on the shoes (Ae1, Ae2, Be1 and Be2, Figure 4.1b) to indicate the end position of the feet. After each trial, the participants were guided to a chair with their eyes closed to sit and rest for approximately 5 minutes during which the investigators
completed the measurements. The participants were not allowed to see the markers placed on the floor so that they had no feedback of their performance. After the rest, they were asked to perform the next trial. The process continued until the 6 trials were completed.

*Outcome measures:*

The outcome measures for the Fukuda Stepping Test were:

1. Distance of displacement (DD, OC in Figure 4.1b): After each trial the middle point between Ae1 and Ae2 (A'e), and the one between Be1 and Be2 (B'e) were marked on the floor. The center of segment A'eB'e was marked as point C. The distance between the original Point O and Point C was defined as the distance of displacement.

2. Angle of self-rotation (AS, thetic angle of turning of the body around its vertical axis. A line was drawn to intersect both A'e and B'e. The angle of self-rotation was defined as the angle between this line and the Y axis.

3. Angle of (angular) displacement (AD, 2 in Figure 4.1b): the angle the individual moves from the start position.
4.3.2.2 Triangle Walking Test

The protocol for this test was based on the description provided by Glasauer et al. (5). Before the test, the participants were shown the right isosceles triangle with three points/markers (X, Y and Z in Figure 4.2) placed on the floor. The length of XY and YZ was 3m and the length of XZ was 4.24m. The participants were then asked to complete the triangular path as accurately as possible at their normal pace with eyes blindfolded. They were informed that the accuracy was based on their arrivals/stops at each turning point but not the walking process/pattern. Participants always started walking from Point X to Y after the verbal instruction “go”, and they were asked to stop at the point which they perceived as the first correct turning point (the first designated turning point: Point Y). The investigators did not tell the participants when or where to stop; the participants stopped based on their own estimation/perception. At the first stop, two
markings were placed on the floor at the level of toes (as described in 4.3.2.1, Page 126) to indicate the position of the feet. The participants started to walk again after another "go" to complete the second segment (Segment YZ), and they stopped at the point which they perceived as the second turning point (Point Z). Again markings were placed on the floor. The same process described above was applied when they completed the last segment (Segment ZX). After each trial participants were guided to a chair with their eyes closed and were allowed to sit and rest for approximately 8 minutes, during which the investigators completed the measurements. The participants were not allowed to see the markers placed on the floor so that they had no feedback of their performance. Before the next trial the investigators asked participants to take a look at the path especially the turning points. However, further practice was not performed between trials. The process continued until the 6 trials were completed.

*Outcome measures:*

The mid-point of each pair of the markings at every stop/turning point was marked on the floor, and was regarded as the arrival/turning points of the participants: Point X', Y' and Z' (Figure 4.2). Three lines were drawn to join Points X and Y', Y' and Z', Z' and X'. Outcome measures were modified from those described by Glasauer et al. (5), because floor markings were used to compute outcome measures instead of a motion analysis system. The outcome measures were:

1. **Distance errors (DE):** the distance error was defined as the difference between required length of each segment/total triangular path and actual distance covered. In
Figure 4.2, distance errors in the first (DE1), second (DE2), third segment (DE3) and total length (DET) were calculated as: |XY'-XY (i.e. 3m)|, |Y'Z'-YZ (i.e. 3m)|, |Z'X'-ZX (i.e. 4.24m)| and |(XY'+YZ'+Z'X')-(XY+YZ+ZX) (i.e. 10.24m)|, respectively (Figure 4.2).

2. Directional errors: the directional error was the difference between the walking direction during one segment with respect to the previous segment and the angles required at each turning point. The directional errors in the first (DiE1) and second turning point (DiE2) were measured as: |∠XY'Z' -∠XYZ (i.e. 90°)| and |∠Y'Z'X' -∠YZX (i.e. 45°)|.

3. Arrival errors (AE): the arrival error described the distance of each participant's turning point to the required/designated turning point at the end of a segment. The arrival errors at three turning points were calculated as the distance between: Y and Y' (AE1), Z and Z' (AE2) and X and X' (AE3) (Figure 4.2).

Figure 4.2 This figure shows how the triangle walking test was performed. Point X, Y and Z are the turning points of the designated path, while Point X', Y' and Z' are the possible turning points of one of the participants who always started from Point X and walked in counter-clockwise direction. See the details in the section of Procedure and Outcome Measures.
4.3.2.3 Straight Walking Test

Before each trial, participants were asked to stand at Point Oₜ (Figure 4.3), and the direction of straight ahead was shown to them by the investigators by putting a reflector at the end point, Point Oₑ. The participants were then asked to walk forward as straight as possible with eyes blind-folded and without any feedback. When the participants crossed Line Z which was 6m away from the start point, they were asked to stop by the verbal instruction "Stop". Two markings (X and Y which corresponded with As₁ and As₂ in the Fukuda Stepping Test, Figure 4.3) were then placed on the floor at the level of toes. After each trial, the participants were asked to turn around with their eyes closed and were guided back to the start point (Point Oₜ). They were also not allowed to see the markers placed on the floor. There was nearly no rest time provided between trials, unless requested by the participant, as the measurement only took only approximately 30 seconds.

**Outcome measure:**

The outcome measure for the SWT was the angle of deviation. Two vertical lines were drawn to intersect Point X and Line Z (the final line which is 6m away from the starting point) and Y and Line Z, and the intersections were X' and Y'. Point C was the middle point of X' and Y', and the angle of deviation was ∠OₑOₜC (∠1 in Figure 4.3). The angle of deviation included in this study was different from that described by Cohen and Sangi-Haghpeykar's (12). They used the tiles on the floor to mark the point of deviation (the point that the participants started to deviate from the straight line, e.g. Point D in Figure
4.3) and $\angle O_eDC$ ($\angle 2$) was the angle of deviation in their study. In this study, the angle of deviation was calculated in the way described above in order to make it comparable to the variable of directional error in TWT.

Figure 4.3 This figure shows how the straight walking test was performed and how the variable (angle of deviation) included in the test were calculated. The participants always started walking from $O_s$ and were asked to walk as straight as possible to the $O_e$ and the $\angle O_eO_1C$ ($\angle 1$) is the angle of deviation. See the details in the section of Procedure and Outcome Measures.

4.3.3 Statistical Analysis:

For each outcome measure the intra-class correlation coefficient (ICC) and coefficient of variation (CV) were calculated to represent inter-trial reliability and variability, respectively. The ICC has been used as a standard coefficient to reflect the reliability of a variable. However, the major disadvantage concerning the interpretation of any ICC is that the estimates are dependent on the range of the measures: the wider the range, the higher the ICC (23). As a result, CV was calculated in addition to ICC in this study, as any variable with either low reliability or high variability is inappropriate in clinical and research environments. Using CV alone also has a disadvantage that CV tends to
exaggerate the variability when the mean is low especially when it is close to 0. Therefore, both ICCs and CVs were calculated based on the data from all 6 trials. The variables with moderate or high ICC [moderate: $0.5 < \text{ICC} \leq 0.7$, high: ICC $> 0.7$ (24)] and acceptable CV [CV $< 30\%$ (25)] in both young and older people were selected. Independent t tests were performed to assess the sensitivity of the selected variables to age-related difference between young and older participants. SPSS 21.0 was used to perform all the analysis and the significance level was set at $p=0.05$.

4.4 Results:

4.4.1 Fukuda Stepping Test

The ICC of distance of displacement (DD) was significant and high and the CV was within acceptable limits in both young and older groups (Table 4.1). Therefore, a t-test was performed using DD to determine if there were differences between young and older adults. The result of the t-test (Table 4.2) shows that DD was significantly higher in older adults compared to young participants ($p=0.02$). Angle of self-rotation ($A_{\theta}$) showed low ICC in both young and older participants; while angle of displacement (AD) had moderate ICC in young participants but low ICC in the older group. The CVs of both $A_{\theta}$ and AD were higher than 30% in both groups.

4.4.2 Triangle Walking Test

Five out of the 9 variables included in TWT had moderate and significant ICCs in young participants; however, the ICCs of only distance error for the third segment (DE3) and
total distance error (DET) were moderate and significant in older group. The ICCs of the other variables were low. The CVs of all the variables were higher than 30% (Table 4.3). As none of the measures met the selected criteria, the variables included in TWT could not be used to assess differences between young and older adults.

4.4.3 Straight Walking Test

The ICC of angle of deviation was moderate and significant (ICC=0.51) in the young group but low (ICC=0.18) in older participants. The CV of this variable was higher than 30% in both groups (Table 4.4). Therefore, angle of deviation was not selected to test age-related difference between the young and older group.
Table 4.1 Intra-class correlation coefficients (ICC), coefficients of variability (CV) and means and ranges of all the variables included in the Fukuda Stepping Test in both young and older participants.

<table>
<thead>
<tr>
<th>Group</th>
<th>ICC (p value)</th>
<th>CV</th>
<th>Mean (Range)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DD</td>
<td>AS(\theta)</td>
<td>AD</td>
</tr>
<tr>
<td>Young</td>
<td>0.80</td>
<td>0.39</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>(p&lt;0.001)</td>
<td>(p&lt;0.001)</td>
<td>(p&lt;0.001)</td>
</tr>
<tr>
<td>Older</td>
<td>0.90</td>
<td>0.25</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>(p&lt;0.001)</td>
<td>(p=0.001)</td>
<td>(p&lt;0.001)</td>
</tr>
</tbody>
</table>

DD=distance of displacement, AS\(\theta\)=angle of self-rotation, AD=angle of displacement.
Table 4.2 The result of t test on distance of displacement between young and older group

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean (SD)</th>
<th>t value</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Young</td>
<td>Older</td>
<td></td>
</tr>
<tr>
<td>Distance of displacement</td>
<td>86.48 (48.42)</td>
<td>131.08 (51.63)</td>
<td>(t_{28}=-2.44)</td>
</tr>
</tbody>
</table>
Table 4.3 Intra-class correlation coefficients (ICC), coefficients of variability (CV) and means and ranges of all the variables included in the Triangle Walking Test in both young and older participants.

<table>
<thead>
<tr>
<th>Group</th>
<th>ICC (p value)</th>
<th>CV</th>
<th>Mean (Range)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DE1</td>
<td>DE2</td>
<td>DE3</td>
</tr>
<tr>
<td>Young</td>
<td>0.60 (p&lt;0.001)</td>
<td>0.54 (p&lt;0.001)</td>
<td>0.42 (p&lt;0.001)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.48 to 106.07)</td>
<td>(0.38 to 91.26)</td>
</tr>
<tr>
<td>Older</td>
<td>0.37 (p&lt;0.001)</td>
<td>0.49 (p&lt;0.001)</td>
<td>0.63 (p&lt;0.001)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(0.55 to 164.73)</td>
<td>(0.76 to 128.95)</td>
</tr>
</tbody>
</table>

DE1 (distance error for the first segment) = |XY'-XY|, DE2 (distance error for the second segment) = |YZ'-YZ|, DE3 (distance error for the third segment) = |Z'X'-ZX|. 
<table>
<thead>
<tr>
<th>Group</th>
<th>DET (p value)</th>
<th>DiE1 (p value)</th>
<th>DiE2 (p value)</th>
<th>DET CV</th>
<th>DiE1 CV</th>
<th>DiE2 CV</th>
<th>Mean (Range)</th>
<th>DiE1 Mean</th>
<th>DiE2 Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young</td>
<td>0.56</td>
<td>0.53</td>
<td>0.38</td>
<td>46.81%</td>
<td>44.69%</td>
<td>62.95%</td>
<td>113.82</td>
<td>12.41</td>
<td>10.59</td>
</tr>
<tr>
<td></td>
<td>(p&lt;0.001)</td>
<td>(p&lt;0.001)</td>
<td>(p&lt;0.001)</td>
<td>(3.96 to 338.45)</td>
<td>(0.53 to 36.80)</td>
<td>(0.22 to 36.92)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Older</td>
<td>0.64</td>
<td>0.32</td>
<td>0.01</td>
<td>48.45%</td>
<td>68.06%</td>
<td>69.92%</td>
<td>150.28</td>
<td>11.89</td>
<td>13.17</td>
</tr>
<tr>
<td></td>
<td>(p&lt;0.001)</td>
<td>(p&lt;0.001)</td>
<td>(p=0.43)</td>
<td>(0.02 to 450.48)</td>
<td>(0.03 to 45.82)</td>
<td>(0.04 to 40.90)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

DET (Total distance error)=|\((XY' + Y'Z' + Z'X') - (XY + YZ + ZX)\)|, DiE1 (directional error for the first turning)=|\(\angle XY'Z' - \angle XYZ\)|, DiE2 (directional error for the second turning)= |\(\angle Y'Z'X' - \angle YZX\)|
<table>
<thead>
<tr>
<th>Group</th>
<th>ICC (p value)</th>
<th>CV</th>
<th>Mean (Range)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AE1</td>
<td>AE2</td>
<td>AE3</td>
</tr>
<tr>
<td>Young</td>
<td>0.57</td>
<td>0.39</td>
<td>0.44</td>
</tr>
<tr>
<td></td>
<td>(p&lt;0.001)</td>
<td>(p&lt;0.001)</td>
<td>(p&lt;0.001)</td>
</tr>
<tr>
<td>Older</td>
<td>0.28</td>
<td>0.42</td>
<td>-0.05</td>
</tr>
<tr>
<td></td>
<td>(p&lt;0.001)</td>
<td>(p&lt;0.001)</td>
<td>(p=0.71)</td>
</tr>
</tbody>
</table>

AE1= the distance between Y and Y', AE2= the distance between Z and Z', AE3= the distance between X and X'.
Table 4.4 Intra-class correlation coefficients (ICC), coefficients of variability (CV) and means and ranges of angle of deviation included in the Straight Walking Test in both young and older participants.

<table>
<thead>
<tr>
<th>Group</th>
<th>ICC</th>
<th>CV</th>
<th>Mean (Range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young</td>
<td>0.51 (p&lt;0.001)</td>
<td>49.37%</td>
<td>3.14 (0.21 to 10.21)</td>
</tr>
<tr>
<td>Older</td>
<td>0.18 (p=0.01)</td>
<td>70.65%</td>
<td>2.82 (0.11 to 9.66)</td>
</tr>
</tbody>
</table>
4.5 Discussion

In this study, we assessed the reliability of outcome measures obtained from the three assessment tools which could be used to screen for potential deficits in vestibular system. The results showed that only one outcome measure, the distance of displacement (DD) in the Fukuda Stepping Test, exhibited acceptable ICC and CV values in both young and older participants. Further, older persons had significantly higher DD compared to young participants, revealing the sensitivity of DD to age-related difference in the ability to achieve accurate spatial orientation; therefore, the age-related difference in the vestibular function.

4.5.1 Reliability and Variability of the Three Tools

The distance of displacement (DD) of Fukuda Stepping Test had high ICC and acceptable CV in both young and older participants. The results are consistent with those of Bonanni and Newton (26). However, Bonanni and Newton reported moderate and significant ICCs for angle of self-rotation (AS\(\varnothing\)) and angle of displacement (AD); while the current study showed low ICCs for AS\(\varnothing\) in both young and older participants and low ICC of AD in the older group. The higher ICC of AS\(\varnothing\) and AD reported by Bonanni and Newton (26) could possibly be attributed to the difference in the participants in two studies. In their study, only young and middle-aged participants (24 to 56 years old) were recruited; while in this study both young and older participants were included. Both AS\(\varnothing\) and AD exhibited low ICCs in the older group as shown in this study. Therefore, the exclusion of older participants may have led to moderate ICC of AS\(\varnothing\) and AD in the
study by Bonanni and Newton (26). Another possible reason for the difference in the findings from two studies might be the wider ranges of these two variables in the participants in the Bonanni and Newton study compared to ours; because they used negative values to indicate rotation to the left side (ASø: Day 1: –94° to +98°, Day 2: –89° to +90°; AD: Day 1: –70° to +86°, Day 2: –74° to +48°), whereas absolute values of both ASø and AD were used in previous studies (6;11). The resultant high ranges of the values possibly contributed to somewhat higher ICCs for ASø and AD, which is a limitation of using ICC alone to show the reliability of variables. We calculated CV for each variable as supplement to ICC due to the disadvantage of using ICC alone to reflect the reliability.

DD demonstrated higher reliability compared to ASø and AD in both this and Bonanni and Newton's study (26). This finding may partially be explained by the characteristics of the measures involved in the Fukuda Stepping Test. During the test, angular orientation, reflected by ASø and partially by AD, could be dependent on a reference frame established by either vestibular input or neck proprioception or both for an internal representation of spatial orientation (2;6;11). The CNS regulates the weighting of the sensory information from each system according to the instantaneous angular displacement, velocity and acceleration (2;27;28). It is possible that the use of different reference frames through the 6 trials complicated the estimation of angular orientation and led to moderate to low reliability of ASø and AD. Bove et al. (2) also showed that during stepping-in-place with eyes blind-folded, application of vibration to the neck
muscles (manipulation of neck proprioception) resulted in larger linear deviation as well as body rotation compared to the control (no vibration) condition. However, the impact of such vibration on body rotation was much larger than that on linear distance of displacement (2). Therefore, linear spatial orientation reflected by DD in FST, may heavily rely on the vestibular signal with less dependence on neck proprioception compared to ASθ and AD as the magnitude of linear displacement for short distances can be accurately estimated from otolith signals, the utricle signal to be specific (28). Therefore, the reference frames in all 6 trials might be more consistent for DD, which is perhaps the reason for a high reliability and acceptable variability.

Fukuda Stepping Test may largely show the function of the vestibular system, although the role of neck proprioception in spatial orientation during stepping-in-place cannot be excluded completely (2). During Fukuda Stepping Test, participants with impaired/manipulated vestibular input demonstrated larger values of angle of self-rotation and distance of displacement compared to healthy controls (6). This suggests that neck proprioception was not used to override the impact of manipulated/impaired vestibular signals to maintain spatial orientation during the test. Therefore, it would appear that the Fukuda Stepping Test reflects vestibular function.

The ICCs of most of the variables (6 out of 10) included in TWT and SWT were significant and moderate in young group, but most of them (8 out of 10) were low in older participants. Such contrasting finding in the young and older group may be ascribed to
the high requirement for spatial memory in these two tests. During the TWT and SWT in this study, the participants had to complete a previously seen path and walk to a previously seen target. It is possible that they established a pre-planned strategy or motor program when the path or the target was shown to them before each trial (4). Their performance of spatial orientation was possibly based on the established strategy or program, and sensory feedback needed to be compared to the expected inputs (4). However, as the participants had to remember the location of each turning point in TWT and the target in SWT, the accuracy of such pre-planned strategy or motor program may highly depend upon spatial memory. Especially in the TWT, the participants were asked to stop at each turning point (for approximately 3s), which lengthened the time to complete the task. Previous studies have reported diminished spatial memory in older people, which could be associated with age-related deterioration of the hippocampal formation that plays a unique role in spatial memory and is vulnerable to aging in human beings (29;30). Additionally, available evidence has shown a close association between hippocampal function of spatial representation and vestibular signal (10). Patients with vestibular loss may develop atrophy of the hippocampus (13). As a result, the performance of older people, with possibly deteriorated spatial memory, vestibular function and inaccurate pre-planned strategy or motor program could be unreliable over the 6 trials. In the Fukuda Stepping Test, spatial memory related to distance and rotation may not be relevant and spatial orientation may rely mostly on integration of sensory information.
4.5.2 Sensitivity to Age-related Differences

DD, included in FST, was sensitive to age-related difference in the ability to achieve accurate spatial orientation revealing the sensitivity of the FST to age-related difference in the vestibular system especially in otoliths which register linear acceleration. In contrast to semicircular canals, otoliths are sensitive to linear acceleration as small as 0.018m/s² (31), and the magnitude of linear displacement can be accurately detected over short distances from utricle information (28). However, age-related changes in otolith morphology (32) and otolith-related functions (33;34) have been reported. In particular, the adverse impact of age-related changes in the otoliths on detection of linear movement has been demonstrated (35). Together, these findings possibly suggest the need for age-specific guidelines for interpreting the results of performance in the Fukuda Stepping Test.

4.6 Limitations

This study has some limitations. Firstly, during TWT the participants were asked to stop at each turning point, which may further complicate the test and decrease the reliability especially in older people. However, we refrained from using motion analysis system for this study as such complex instrumentation is not available in clinical settings. A simpler form of TWT could be developed in the future with the aim of increasing the reliability of the measures.
4.7 Conclusion

Among several outcome measures included in this study, distance of displacement (DD) in the Fukuda Stepping Test was the outcome measure with the highest reliability and lowest variability. In addition, DD was sensitive to the differences between young and older people. In the future, normative/cut-off values of the variables included in the Fukuda Stepping Test could be established in order to screen for vestibular deficits or weakness.
4.8 Reference


Chapter 5

General Discussion

5.1 Introduction

The vestibular system plays a role in both postural control and spatial orientation (1-3). Ageing adversely affects vestibular function, postural control as well as the ability to maintain accurate spatial orientation (1;4-6). The two studies in this thesis were designed and conducted based on these roles and possible age-related differences. Study I (Chapter 3) investigated the impact of vestibular input and its sensory interactions with lower limb somatosensory and visual inputs on head and trunk control during normal and narrow-based walking in young and older persons. The study suggested the dependence of head control on a “top-down” model and the reliance of trunk control on a “bottom-up” model. Particularly, trunk control in the medio-lateral direction in narrow-based walking and with GVS may require accurate lower limb somatosensory information. Age-related difference was reflected only in head control. Study II (Chapter 4) focused on the reliability of three tools which have been used by previous investigators to screen for vestibular dysfunction using spatial orientation. The study demonstrated that distance of displacement (DD) in the Fukuda Step Test was the only variable that exhibited moderate to high reliability (ICC) and acceptable variability (CV) in both younger and older adults. DD was also sensitive to age-related difference in the vestibular function.
In this chapter, a summary of the findings of the two studies, and possible and alternative explanations, models and inference are proposed. In addition, the rehabilitation implications and future research based on the results are presented.

### 5.2 Role of Sensory Signals/Interactions in Head Control

Head control is critical for postural control as the head contains both the visual and vestibular sensory systems. Therefore, the head needs to be controlled, in terms of both angular displacement and velocity, in order to provide a stable platform for both systems (7-9). Very few studies have investigated the effect of vestibular input and its interactions with somatosensory and visual input on head control, in terms of both angular displacement and velocity, during locomotion.

Chapter 3 provides a comprehensive evaluation of vestibular-lower limb somatosensory and vestibular-visual interaction for head control during locomotion, in terms of both head angular displacement and velocity in both A-P and M-L direction. The results showed decrease in head roll velocity with blurred vision compared to normal vision. Head roll velocity increased with GVS, not significantly but with large effect size, in the older group. The findings highlighted dependence of head control more on visual input and relatively, less on vestibular information. Further, the higher importance of visual signals for head control in the M-L direction compared to that in A-P direction was also established.
Decreased head roll velocity with blurred vision was interpreted as a possible adaptation to this suboptimal vision condition for reducing image motion. Alternatively, decreased head roll velocity may also be regarded as a method to simplify the interpretation of vestibular input and ensure precision of estimation of linear motion of the head and gravity (9). With decreased head angular velocity, any change in the vestibular signal may be largely due to head linear acceleration, therefore decreasing the ambiguity of the vestibular information and simplifying the interpretation of vestibular signal (9). Thus, head control may rely on the accurate vestibular input when vision is blurred. In contrast, increase in head roll velocity of older participants may suggest not only the inability to adopt this strategy but also further worsening of head control with discordant vestibular signals.

Head control with manipulation of visual or vestibular inputs alone was associated with the adjustment of head movement velocity but not head displacement. This may be because head movement velocity is associated with both the visual system/gaze stabilization [e.g. the vestibulo-ocular reflex (VOR) (10)] as well as the vestibular system [e.g. the interpretation of vestibular information (9)]. Therefore, adjustment of head movement velocity may have been a strategy to adapt to inaccurate sensory signals from both systems. In contrast, head displacement may not be as highly dependent on the vestibular system when some visual information is available. It is possible that the
impact on head displacement may become more apparent when vision is occluded completely.

Dependence of head control more on visual input, and relatively less on vestibular information, may be explained by a model proposed by Mergner and Rosemeier (11). In their model, perceived head motion in space is expressed as the combination of information conveyed by both the vestibular and visual system. The model also shows that the vestibular system could yield a true value for head movement perception only if the frequency of head movement is very high (11). This is a potential reason why head control may not largely depend on the vestibular signal especially when some vision is available.

5.3 Role of Sensory Signals/Interactions in Trunk Control

The trunk bears the largest body mass compared to other body segments. Larger deviation from the vertical position or faster movement of the trunk increases the challenge to postural control (12). However, previous studies have mainly focused on the impact of the vestibular signal and vestibular-lower limb somatosensory interaction on trunk control during standing (13-16); its impact during locomotion is largely unknown. Chapter 3 investigated the impact of vestibular-lower limb somatosensory and vestibular-visual interaction on trunk control during normal and narrow-based walking conditions. Trunk roll velocity, and trunk pitch angle and velocity increased on the foam surface compared to on the firm surface. Trunk roll angle increased with GVS
and in narrow-based walking compared to no GVS and normal walking, respectively, only on the foam surface. The findings have underlined the importance of lower limb somatosensory input for trunk control during locomotion, and have shown that accurate lower limb somatosensory signals can override vestibular perturbation.

The importance of lower limb somatosensation for trunk control during locomotion is consistent with previous studies on trunk control during standing (16-18). The findings might be explained by the critical role of lower limb somatosensory input in automatic postural responses or balance recovery reactions (19;20). They might also be explained by a model proposed by Maurer et al. (21) based on trunk control during standing. In the model, an internal estimate of body-in-space angle could be derived from the ankle joint proprioceptive signal or vestibular signal. When the ankle joint proprioceptive signal is accurate, the estimate of body-in-space angle is determined by the accurate proprioceptive signal alone. When the ankle joint proprioceptive signal is inaccurate, sensory re-weighting occurs and the contribution of the vestibular signal increases. The model explains why an estimate of body-sway angle in space can be accurate even if vestibular input is inaccurate. In the study reported in Chapter 3 neither trunk roll angle nor trunk roll velocity increased with GVS when walking on the firm surface.

The findings have important rehabilitation implications. For patients with vestibular deficits, many areas at home can be made safer by removing carpets on the floor so that accurate lower limb somatosensory information is provided. Assistive devices such as
grab bars can be installed in the bathroom to assist the patients if a bath rug is needed. Moreover, patients with vestibular deficits could be trained to depend upon lower limb somatosensory information. For example, patients with vestibular deficits could practice balance with eyes closed during both standing and locomotion so that they would rely on lower limb somatosensory information as the primary sensory input in order to compensate for vestibular loss. Active motor experience and repeated practice are required for patients with vestibular deficits so that the nervous system can build appropriate sensory expectations for postural control and movement (22).

5.4 Screening for Vestibular Function via Spatial Orientation

The Fukuda Stepping Test, Triangle Walking Test and Straight Walking Test have been used to screen for vestibular dysfunction, based on the important impact of vestibular signal on spatial orientation (25-27). However, it is unclear if the tools could be used to detect age-related changes in vestibular function, as ageing of the vestibular system has been identified as a potential fall risk factor (28). In order to answer this question, the first step would be to assess the reliability of the tools in both young and older persons. Study II (Chapter 4) is the first study that assesses the inter-trial reliability of three tools in young and older participants separately. The findings have shown that distance of displacement (DD) of the Fukuda Stepping Test was reliable in both young and older people. The study also found that DD was sensitive to age-related difference in the vestibular system.
This finding is consistent with a common rule: simplicity leads to reliability (29). Simplicity is especially important for clinical/research tools or tests used in older people, as older people may have decreased memory (including spatial memory) and cognitive ability (30;31). If a tool/test requires complex memory, or demands performance of dual tasks (e.g. walking-while-talking), this might decrease the reliability of the performance and may not reflect the true ability of older participants. Therefore, the findings from this study have suggested that the triangle walking test and straight walking test should not be used to examine the ability to maintain spatial orientation in older people as a screening tool for vestibular deficit or weakness.

Although the DD measure of the Fukuda Stepping Test exhibited high reliability in both groups, several previous studies (27;32;33) have shown that Fukuda Stepping Test is not a valid tool to screen for vestibular deficit and function. However, these studies all included older participants (>65 year older) but did not investigate the validity of the Fukuda Stepping Test separately in the young and older group, thereby failing to consider age as a possible confounding factor. Further, Honaker et al. (27;32) only used angle of self-rotation (AS\(\theta\)) but not distance of displacement (DD) or angle of displacement (AD) to screen for vestibular deficits; while Zhang and Wang (33) used AS\(\theta\) and lateral displacement which was not the same as the linear DD measure (regardless of direction) included in this study. These authors also adopted arbitrary criteria (falling, deviation by > 45°, or a lateral shift > 1 m) to differentiate patients with vestibular deficits from healthy persons. In the current study, the Fukuda Stepping Test
demonstrated moderate to high reliability only in one outcome measure (DD) in older participants. This measure was not included in the abovementioned studies. A recent study by Cohen et al. (34), which included the distance walked forward and the distance walked to the side as two different variables, examined the usefulness of the Fukuda Stepping Test in young (<60 year older) and older group (>60 year old) separately. The study still showed that the test was a poor screening test. However, in their study the participants were asked to step for only 20 steps. There is no evidence showing that Fukuda Stepping Test of 20-step protocol or the two variables included in the test are reliable in either young or older persons. Moreover, the number of steps may impact the reliability of the tool, as the 50 step Fukuda Stepping Test protocol exhibited higher reliability than that of the 100-step protocol (35). As a result, age, outcome measures and protocol could be three potential factors which may impact the reliability and validity of the vestibular screening tools based on spatial orientation, and should be taken in account in both clinical and experimental environment.

5.5 Future Directions

Recommendations for additional research have emerged from the results and limitations of both studies in this thesis. Areas of future research are outlined below.

In Study I, no significant GVS X narrow-based interaction was found, which shows that vestibular input did not specifically influence postural control with the M-L challenges imposed in this study. However, it is possible that applying GVS intensity at 2 times the
threshold may not be high enough to induce significant postural responses. Alternatively, it is possible that availability of some sensory information from vision and somatosensory information from the neck and trunk were able to compensate for the discordant vestibular input for the degree of challenge imposed in this study. Future studies may explore the impact of vestibular input on M-L head and trunk control in more challenging dynamic tasks such as tandem walking.

In Study I, head pitch angle increased in the narrow-based walking condition compared to that in the normal walking condition. However, the real purpose of increased head pitch angle in the narrow-based walking condition is unclear. The increase in head pitch angle could be a strategy to pay attention to the lines on the floor or to increase the sensitivity of the vestibular system. In the future, participants could be asked to perform dynamic tasks with eyes open and blindfolded. The dynamic tasks should pose challenges to postural control without specifically requiring visual feedback from the floor (such as tandem walking during which the participants do not need to look at their feet). Head pitch angle can be measured and the pattern (oscillating or constant) will be investigated in order to understand the real purpose of increased head pitch angle.

During locomotion hip muscle activity as well as hip moment plays a role in trunk control. In Study I, manipulation of lower limb somatosensory input resulted in poorer trunk control compared to walking on a firm surface. However, it is unclear if the manipulation of lower limb somatosensory information is associated with changes in hip
muscle activity and hip moment. Therefore, variables related to trunk control, hip muscle activity and hip moment could be measured during normal and narrow-based walking on the foam and firm surface, in order to understand the possible association.

Based on results of Study II, a cut-off level of distance of displacement in Fukuda Stepping Test could be established for identifying age-related deterioration of vestibular function, as deteriorated vestibular function may exhibit subclinical disturbances which may not be detected by the Dynamic Gait Index. The Fukuda Stepping Test and caloric test, as the gold standard, could be performed in healthy young and older participants. Distance of displacement in Fukuda Stepping Test could be compared to the gold standard so that cut-off points may be identified.

5.6 Summary

The studies included in this thesis have contributed to the understanding how vestibular input and sensory interactions are used by the CNS to maintain postural control during locomotion, as well as the reliability of the tests used to screen for vestibular deficits. The first study of this thesis has contributed to foundation knowledge on which targeted rehabilitation methods may be developed. Further analysis of the mechanism of how sensory inputs and interactions influence postural control can be explored based on the findings in Study I. Based on the findings in Study II, age-appropriate cut-off of Fukuda Stepping Test could be identified and tools with high reliability in both young and older could be developed in the future.
5.7 Reference


Appendix A

Curriculum Vitae of the Author

Education:
**PhD Candidate**: Rehabilitation Science, Queen’s University, Sep. 2010-June 2015
**Master**: Molecular and Statistical Genetics, Hunan Normal University (China) (National “211 Project” University), 2007-2010.
**Bachelor**: Animal Science, Huazhong Agricultural University (China) (National “211 Project” University), 2003-2007.

Computer Skill:
SPSS, SAS, Visual Basic programming

Academic and Research Experience:
**PhD Candidate**: Motor Performance Laboratory, School of Rehabilitation Therapy, Queen’s University
**Researching Field**: sensory systems, neuroscience, motor performance

**Participated in following projects as a Student PI:**
1. The role of vestibular system information in spatial orientation: effect of auditory cues and ageing

**Participated in following projects as a RA:**
1. Does diabetes mellitus-induced vestibular system dysfunction contribute to higher prevalence of balance and mobility impairment in community-dwelling diabetic elderly? Canadian Institutes of Health Research (CIHR): Catalyst Grant. 2011
2. Dynamic visual acuity across the adult lifespan: understanding clinical relevance and underlying mechanism. Botterell Fund, Queen’s University. 2013
3. Working as a research assistant in the Center of Health Services and Policy Research, Queen’s University (doing research on time use of disabled people) 2012-2015.

**TA works as a PhD candidate:**
1. Objectively Structured Clinical Examination (3 times: worked as a standard patient, examiner and organizer)
2. PT-856 Neuromotor Function I
3. PT-858 Neuromotor Function II

**Teaching experience:**
1. Statistics (t-test and ANOVA)
2. PT-856 Neuromotor Function I (Motor Learning)

**Master**: Molecular and Statistical Genetics laboratory (attached to Key Laboratory of Protein Chemistry and Developmental Biology of Ministry of Education), Life Science College, Hunan Normal University, Changsha, Hunan, China
**Researching Field**: molecular and statistical genetics, epidemiology, pathology, osteoporosis, obesity
Participated in following projects as a RA:
1. Gene positioning and subtype identification in a large pedigree affected with benign familial adult myoclonus epilepsy (fame) for the first time in china. I am responsible for gene sequencing and its data analysis. (National Science Foundation of China (NSFC) (No. 20470534))
2. Verification and identification of differentially expressed protein of osteoclast precursors between high and low end of peak bone mass groups. (Natural Science Foundation of China (No.30600364))
3. Study of candidate genes of obesity in Chinese and Canadian populations: evidence of replication and investigation of ethnic and sex differences. (NSFC-CIHR (joint project between China and Canada) (No.30811120436))

Bachelor: College of Animal Science, Key Laboratory of Agricultural Animal Genetics, Breeding and Reproduction of Ministry of Education, College of Animal Science, Huazhong Agricultural University, Wuhan, Hubei, China.

Publications:

Peer Reviewed Journal Publications:
8. Xi Li, Lijun Tan, Xiaogang Liu, Shufeng Lei, Tielin Yang, Xiangding Chen, **Fang Zhang**, Yue Fang, Yan Guo, Liang Zhang, Han Yan, Feng Pan, Zhixin Zhang, Yumei Peng, Qi Zhou, Lina He, Xuezhen Zhu, Jing Cheng, Lishu Zhang, Yaozhong Liu, Qing Tian, Hongwen Deng (2010). A genome wide association study between copy number variation (CNV) and human height in Chinese population. J Genet Genomics. 37(12):779-85.
Peer Reviewed Conference Abstracts:


3. **F Zhang**, N Deshpande. Normal and narrow-based walking under deteriorated sensory conditions: effects of aging. 16th Annual Meeting for Health Sciences Research Trainees, Queen's University, Kingston, Canada, 2013, June. (Poster Presentation)


5. **N Deshpande**, **F Zhang**. Trunk and head characteristics during normal and narrow-based walking under deteriorated sensory conditions: effects of aging. 2nd Joint World Congress of International Society for Gait and Postural Research and Gait and Mental Function, Akita, Japan, June 2013. (Poster Presentation)


Volunteer works:

1. CIHR Cafe: Increasing age and declining mobility: What do we need to know? May, 2014
2. Brain Awareness Day, June, 2014
Appendix B

Ethics Approval for Study I (Chapter 3)

QUEEN'S UNIVERSITY HEALTH SCIENCES & AFFILIATED TEACHING HOSPITALS RESEARCH ETHICS BOARD

June 17, 2010

Dr. Nandini Deshpande
School of Rehabilitation Therapy
Louise D. Acorn Building
Queen's University

Dear Dr. Deshpande,

Study Title: The role of vestibular system information in adaptive locomotion in young and older adults: a pilot study

I am writing to acknowledge receipt of your recent ethics submission. We have examined the protocol, recruitment poster and consent form for your project (as stated above) and consider it to be ethically acceptable. This approval is valid for one year from the date of the Chair's signature below. This approval will be reported to the Research Ethics Board. Please attend carefully to the following list of ethics requirements you must fulfill over the course of your study:

➢ Reporting of Amendments: If there are any changes to your study (e.g. consent, protocol, study procedures, etc.), you must submit an amendment to the Research Ethics Board for approval. (see http://www.queensu.ca/vpr/retb.htm).

➢ Reporting of Serious Adverse Events: Any unexpected serious adverse event occurring locally must be reported within 2 working days or earlier if required by the study sponsor. All other serious adverse events must be reported within 15 days after becoming aware of the information.

➢ Reporting of Complaints: Any complaints made by participants or persons acting on behalf of participants must be reported to the Research Ethics Board within 7 days of becoming aware of the complaint. Note: All documents supplied to participants must have the contact information for the Research Ethics Board.

➢ Annual Renewal: Prior to the expiration of your approval (which is one year from the date of the Chair's signature below), you will be reminded to submit your renewal form along with any new changes or amendments you wish to make to your study. If there have been no major changes to your protocol, your approval may be renewed for another year.

Yours sincerely,

[Signature]
Chair, Research Ethics Board

[Date]

Study Code: REH-474-10

➢ Investigators please note that if your trial is registered by the sponsor, you must take responsibility to ensure that the registration information is accurate and complete.
QUEEN'S UNIVERSITY HEALTH SCIENCES & AFFILIATED TEACHING HOSPITALS RESEARCH ETHICS BOARD

The membership of this Research Ethics Board complies with the membership requirements for Research Ethics Boards as defined by the Tri-Council Policy Statement; Part C Division 5 of the Food and Drug Regulations, OHRP, and U.S. DHHS Code of Federal Regulations Title 45, Part 46 and carries out its functions in a manner consistent with Good Clinical Practices.

Federalwide Assurance Number: #FWA00004184
#IRB00001173

Current 2010 membership of the Queen's University Health Sciences & Affiliated Teaching Hospitals Research Ethics Board

Dr. A.F. Clark
Emeritus Professor, Department of Biochemistry, Faculty of Health Sciences, Queen's University (Chair)

Dr. H. Abdollah
Professor, Department of Medicine, Queen's University

Dr. M. Evans
Community Member

Dr. S. Irving
Psychologist, Providence Care, St. Mary's of the Lake Hospital Site

Dr. L. Keepping-Burke
Assistant Professor, School of Nursing, Queen's University

Dr. J. Low
Emeritus Professor, Department of Obstetrics and Gynaecology, Queen's University and Kingston General Hospital

Ms. D. Morales
Community Member

Dr. W. Racz
Emeritus Professor, Department of Pharmacology & Toxicology, Queen's

Dr. B. Simchison
Assistant Professor, Department of Anesthesiology, Queen's University

Dr. A.N. Singh
WHO Professor in Psychosomatic Medicine and Psychopharmacology Professor of Psychiatry and Pharmacology Chair and Head, Division of Psychopharmacology, Queen's University Director & Chief of Psychiatry, Academic Unit, Quinte Health Care, Belleville General Hospital

Dr. E. Tsai
Associate Professor, Department of Paediatrics and Office of Bioethics, Queen's University

Rev. J. Warren
Community Member

Ms. K. Weisbaum
LL.B. and Adjunct Instructor, Department of Family Medicine (Bioethics)

Dr. S. Wood
Director, Office of Research Services (Ex-Officio)
Appendix C

Ethics Approval for Study II (Chapter 4)

QUEEN'S UNIVERSITY HEALTH SCIENCES & AFFILIATED TEACHING HOSPITALS RESEARCH ETHICS BOARD-
DELEGATED REVIEW

February 05, 2013

Mr. Fang Zhang
School of Rehabilitation Therapy
Louise D. Acton Building
Queen's University

Dear Mr. Zhang

Study Title: REH-546-13 The role of vestibular information in spatial orientation: effect of auditory cues and ageing File # 6007723

Co-Investigators: Dr. N. Deshpande, Dr. E. Culham

I am writing to acknowledge receipt of your recent ethics submission. We have examined the protocol, appendices, recruitment poster and revised letter of information/consent form for your project (as stated above) and consider it to be ethically acceptable. This approval is valid for one year from the date of the Chair's signature below. This approval will be reported to the Research Ethics Board. Please attend carefully to the following listing of ethics requirements you must fulfill over the course of your study:

Reporting of Amendments: If there are any changes to your study (e.g. consent, protocol, study procedures, etc.), you must submit an amendment to the Research Ethics Board for approval. Please use event form: HSREB Multi-Use Amendment/Full Board Renewal Form associated with your post review file # 6007723 in your Researcher Portal (https://eservices.queensu.ca/romeo_researcher/)

Reporting of Serious Adverse Events: Any unexpected serious adverse event occurring locally must be reported within 2 working days or earlier if required by the study sponsor. All other serious adverse events must be reported within 15 days after becoming aware of the information. Serious Adverse Event forms are located with your post review file 6007723 in your Researcher Portal (https://eservices.queensu.ca/romeo_researcher/)

Reporting of Complaints: Any complaints made by participants or persons acting on behalf of participants must be reported to the Research Ethics Board within 7 days of becoming aware of the complaint. Note: All documents supplied to participants must have the contact information for the Research Ethics Board.

Annual Renewal: Prior to the expiration of your approval (which is one year from the date of the Chair's signature below), you will be reminded to submit your renewal form along with any new changes or amendments you wish to make to your study. If there have been no major changes to your protocol, your approval may be renewed for another year.
Yours sincerely,

[Signature]

Chair, Research Ethics Board
February 05, 2013

Investigators please note that if your trial is registered by the sponsor, you must take responsibility to ensure that the registration information is accurate and complete

QUEEN'S UNIVERSITY HEALTH SCIENCES & AFFILIATED TEACHING HOSPITALS RESEARCH ETHICS BOARD

The membership of this Research Ethics Board complies with the membership requirements for Research Ethics Boards and operates in compliance with the Tri-Council Policy Statement; Part C Division 5 of the Food and Drug Regulations, OHRP, and U.S DHHS Code of Federal Regulations Title 45, Part 46 and carries out its functions in a manner consistent with Good Clinical Practices.

Federal wide Assurance Number: #FWA00004184, #IRB00001173

Current 2012 membership of the Queen’s University Health Sciences & Affiliated Teaching Hospitals Research Ethics Board:

Dr. A.F. Clark, Emeritus Professor, Department of Biomedical and Molecular Sciences, Queen's University (Chair)

Dr. H. Abdollah, Professor, Department of Medicine, Queen's University

Dr. R. Brison, Professor, Department of Emergency Medicine, Queen's University

Dr. C. Cline, Assistant Professor, Department of Medicine, Director, Office of Bioethics, Queen's University, Clinical Ethicist, Kingston General Hospital

Dr. M. Evans, Community Member

Ms. J. Hudacin, Community Member

Dr. J. MacKenzie, Pediatric Geneticist, Department of Paediatrics, Queen's University

Mr. D. McNaughton, Community Member

Ms. P. Newman, Pharmacist, Clinical Care Specialist and Clinical Lead, Quality and Safety, Pharmacy Services, Kingston General Hospital
Ms. S. Rohland, Privacy Officer, ICES-Queen's Health Services Research Facility, Research Associate, Division of Cancer Care and Epidemiology, Queen's Cancer Research Institute

Dr. B. Simchison, Assistant Professor, Department of Anesthesiology and Perioperative Medicine, Queen's University

Dr. A. Singh, Professor, Department of Psychiatry, Queen's University

Dr. J. Tang, Medical Resident, Department of Emergency Medicine, Queen's University

Ms. K. Weisbaum, LL.B. and Adjunct Instructor, Department of Family Medicine (Bioethics)
Appendix D

Letter of Information and Consent for Study I (Chapter 3)

Project Title: The role of vestibular system information in adaptive locomotion in young and older adults: a pilot study

Investigator: Dr Nandini Deshpande, School of Rehabilitation Therapy, Faculty of Health Sciences, Queen’s University, Kingston, Ontario

The inner ear balance detecting system is critical for maintaining balance while walking. Significant number of falls in older persons are associated with improper functioning of this system. The first purpose of this study is to understand how our brain uses sensory information from inner ear balance detectors for controlling positions of body’s segments and for maintaining balance while walking in challenging environments. The second purpose is to understand whether normal/healthy aging has any effect on when and how this sensory information is used when walking under similar challenges.

You are invited to participate in this study if you are in the age group of 20 to 30 or ≥ 65 years and if you do not have medical problems of your vision, inner ears and neuromuscular system or pain in your legs while walking. You will be required to complete a medical screening form. There is one session of three hours to this study.

Procedure:
The testing will involve approximately two hours visit to the laboratory.

1. You will be asked to wear your pair of regular walking shoes. Your height and weight will be recorded. Vision will be tested using vision charts (similar to those at optometrist). The ability to detect touch on the skin of the foot-sole will be tested. The function of the inner ear balance detectors will be tested by, a. asking you to read the vision chart while walking on a treadmill and b. by asking you to align a line in a vertical direction on the wall in front of you. The strength of your knee muscles will be measured by asking you to push against resistance and balance will be assessed using Frailty and Injuries Cooperative Studies of Intervention Techniques (FICSIT) balance test by asking you to stand with your feet in different configurations, with eyes open and then with eyes closed.

2. Two electrodes will be placed behind your ears and the intensity of a current for feeling mild pin-prick sensation will be measured.

3. A total of 10 markers will be fitted on your body (2 above the ears, 1 on backside of the head, 2 on shoulders, 1 in between two shoulders, 1 in the middle of the back, 1 on the lower back and 2 on each foot. These markers will allow us record your body movements.

4. You will be required to walk a distance of 6 meters straight ahead in 4 walking conditions: a. Walking on a narrow path (path width 25 cm) that will constrain stepping in the medio-lateral direction, b. Walking at a normal pace while performing a secondary verbal task that will divide the attention while walking, c. Walking on a 5 inch thick firm foam surface and, d. walking at self-selected normal pace without any challenge (control condition). The control condition will be performed first. Conditions a, b and c will be randomized.
5. On some walking trials we will control the sensory information from your inner ear system that your 
can brain receives. For this purpose a very mild current will be momentarily applied behind your ears 
(approx. 0.6 – 0.8 m Amp).

6. The head and torso movements and placement of the feet will calculated. For your safety, one of the 
team members will walk with you during all trials.

With your agreement, you will also be videotaped for the purpose of tracking the responses to these 
sensory manipulations as well as a means of verifying results from other data collected.

Risks: The use of mild galvanic current will cause pinprick sensation behind the ears and a mild instability 
during walking; however, no health risk of any sorts has been reported in literature for up to 1.2 m Amp 
intensity. One of the team members will walk closely besides you to prevent a fall. There are no 
anticipated health risks in these procedures.

However, the testing session will be terminated as soon as you indicate that you wish to discontinue, for 
whatever reason.

Benefits: Young participants will receive an opportunity to get familiarized with the research activities in 
the department. The results will provide useful information about how the brain used this sensory 
information for walking in complex environments. The older adults may not receive direct benefit from 
participating. However, the results will provide the information that can be used for improving balance 
and mobility of this population and the knowledge can be further extended to develop the strategies that 
can be taught to patients who suffer from deficits of this critical sensory system, for safer mobility in 
complex environment.

Confidentiality: Any information obtained in this study will be retained indefinitely and will be held in 
strict confidence. It will be available only to the investigators. The computers are password protected and 
computer data files will contain a code number rather than the name. The video tapes will be stored in 
locked cabinets accessible only to the investigators. When the information from this study will be 
published in scientific journal or in professional meetings, your identification will be kept strictly 
confidential.

Free parking will be available for you in a parking lot that is located very close to the laboratory. You will 
be given a $15 Walmart gift card on completion of the test session.

Your participation in this study is voluntary and you are not obliged to answer any questions that you find 
objectionable or complete any aspect of the study which make you feel uncomfortable. 
If you have any questions now or later, please feel free to contact the investigator.

Dr Nandini Deshpande: 613 533 2916 / 613 449 6760 
This project has been reviewed by, and received ethics clearance through, the Office of Research Ethics at 
the University of Waterloo. If you have any comments or concerns resulting from your participation in this 
study, you may contact the Director, Office of Research Ethics at (519) 888-4567 ext. 6005.

Your signature below indicates that you are aware that you may contact the principle investigator or the 
department head or the General Research Ethics Board if you have any questions, concerns or complaints 
about the research procedures.

172
Principle investigator: Dr Nandini Deshpande
Tel: 613 533 2916 / 613 449 6760, email: nandini.deshpande@queensu.ca
Research Assistant: Fang Zhang

Department Head: Dr Elsie Culham
Tel: 613 533 6727, email: elsie.culham@queensu.ca
General Research Ethics Board Chair: Dr. Joan Stevenson
Tel: 533-6081, email: chair.GREB@queensu.ca

Your signature below indicates that you have read this Letter of Information and have had any questions answered to your satisfaction. Please keep a copy of this letter for your records.

Name: ___________________________
Date: ___________________________
Signature: ________________________
Appendix E

Brief Medical/Clinical Information Form for Study I (Chapter 3)

Name: _________________________________________ Code: _________

Birth Date: __________ (d/m/y) Height: _______ cm Weight: ________ kg

Regular physical activity in one week:
1. ______________________________, 3. __________________________
2. ______________________________, 4. __________________________

Medical History:

Inner ear diseases/vertigo/balance problems/dizziness in last year? Y / N

Neurological diseases/neuropathy/Parkinso’s disease/diabetes (controlled?) Y / N

Pain in lower limbs while walking? Y / N

Falls in last year: Y / N; How many:

Vision problems other than glasses: Y / N
Appendix F
Letter of Information and Consent for Study II (Chapter 4)

Letter of Information and Consent

Project Title: The role of vestibular system information in spatial orientation: effect of auditory cues and ageing

Supervisor: Dr Nandini Deshpande, Assistant Professor, School of Rehabilitation Therapy, Faculty of Health Sciences, Queen’s University, Kingston, Ontario
Co-Principal Investigator: Dr Elsie Culham, Professor, School of Rehabilitation Therapy, Faculty of Health Sciences, Queen’s University, Kingston, Ontario
Principal Investigator: Fang Zhang, PhD Candidate, School of Rehabilitation Therapy, Faculty of Health Sciences, Queen’s University, Kingston, Ontario

Accurate spatial orientation is about having a sense of direction with respect to the surrounding environment during walking. Spatial orientation, which is not dependent on vision, is a crucial component of successful locomotion and independence in daily life. The vestibular system is important for maintaining spatial orientation. Auditory information may be used by human beings to increase the accuracy of spatial orientation in the absence of vision but this is not clear. The purpose of this study is to use the Fukuda Stepping Test, Triangle Path Completion test and walking straight test to determine the reliability of the tests and if there is difference in the ability of young and older people to use different types of sensory information for accurate spatial orientation.

You are invited to participate in this study if you are 20 to 35 years of age or are 65 years of age or older and if you 1) don't have any open sores or ulcers on your feet; 2) are not diagnosed with benign paroxysmal positional vertigo or report any history of overt vestibular pathology (e.g. vestibular neuritis) within the previous 6 months; 3) are not diagnosed with any other major neurological conditions (e.g. Parkinson’s disease, stroke, Multiple Sclerosis); 4) do not experience painful lower limb arthritis or require an assistive device for walking; 5) do not have hearing loss and 6) are able to raise both arms to shoulder level and maintain this position for about 30 seconds. You will be required to complete a medical screening form. The experiment will take about two hours in the Motor Performance Lab at Queen's University.

Procedure:
Session in the Motor Performance Laboratory:

The testing will involve approximately two hours in the laboratory.
1. You will be asked to wear a pair of regular walking shoes. Your height, weight and brief medical information will be recorded. After that, one experimenter will tell you the procedures involved in the following test.

2. In the Fukuda Stepping tests, you will be blindfolded and asked to stretch both arms straight forwards, and to step in the same spot without too much strain and at normal walking speed (about 110 steps per minute) for a total of 50 steps. When the 50 steps have been completed, you will be asked to stop stepping and stand upright in the last spot. You will complete this test 6 times.

3. In the triangle path completion test, you will be asked to walk around a triangle drawn on the floor as accurately as possible while blindfolded. You will be asked to stop at the point(s) which you perceive as the turning points and at the end point of the triangle. After stopping at the turning point you will be asked to continue after you hear a sound signal "go". You will complete the triangle walking task 6 times.

4. In the walking straight test, you will be asked to walk straight for 6m while blindfolded for 6 times.

With your agreement, you will also be videotaped for the purpose of tracking the responses to these sensory manipulations.

Risks: You may feel a little unstable when you are stepping or walking. For your safety, one of the team members will be near you during the stepping trials and will walk with you while you are doing all the tasks. The testing sessions will be terminated immediately if you indicate that you wish to discontinue testing for whatever reason.

Benefits: The results will provide information that can be used for improving accurate spatial orientation and mobility, especially in complex environments, for patients who have impairment of sensory systems.

Confidentiality: Any information obtained in this study will be retained indefinitely and will be held in strict confidence. Information that identifies participants by name will be available only to the investigators. The computers are password protected and computer data files will contain a code number rather than the participant name. The video tapes will be stored in locked cabinets accessible only to the investigators. When the information from this study is published in scientific journal or in professional meetings, your identification will be kept strictly confidential.

Free parking will be available for you in a parking lot that is located very close to the laboratory. You will be given $15 on completion of the test session to help cover costs associated with participation.

Your participation in this study is voluntary and you are not obliged to answer any questions that you find objectionable or complete any aspect of the study which makes you feel uncomfortable.

If you have any questions now or later, please feel free to contact the investigator.

This study has been reviewed for ethical compliance by the Queen's University Health Sciences and Affiliated Teaching Hospitals Research Ethics Board. Your signature below indicates that you are aware that you may contact the principal investigator, supervisor, the department head or the Queen's University Health Sciences and Affiliated Teaching Hospitals Research Ethics Board if you have any questions, concerns or complaints about the research procedures.
Supervisor: Dr Nandini Deshpande  
Tel: (613) 533-2916, email:nandini.deshpande@queensu.ca  
Principal investigator: Fang Zhang  
Tel: (613) 453-1586 Email: 9fz1@queensu.ca  
Department Head: Dr Elsie Culham  
Tel: (613) 533-6727, email: elsie.culham@queensu.ca

If you have any concerns about your rights as a research participant please contact Dr. Albert Clark, Chair of the Queen's University Health Sciences and Affiliated Teaching Hospitals Research Ethics Board at (613) 533-6081.

Your signature below indicates that you have read this Letter of Information and have had any questions answered to your satisfaction. Please keep a copy of this letter for your records.

Name: ___________________________  
Date: ____________________________  
Signature: ________________________

Name of the person who obtained the consent: __________________

Date: __________________

Signature: __________________
Appendix G

Brief Medical/Clinical Information Form for Study II (Chapter 4)

Name: _________________________________________ Code: _________

Birth Date: __________ (d/m/y) Height: _______ cm Weight: ________ kg

Regular physical activity in one week:
1. ______________________________, 3. _________________________,
2. ______________________________, 4. __________________________

Medical History:

Inner ear diseases/vertigo/balance problems/dizziness in last year? Y / N

Neurological diseases/neuropathy/Parkinson’s disease/diabetes (controlled?) Y / N

Pain in lower limbs while walking? Y / N

Falls in last year: Y / N; How many:
Appendix H

Waterloo Footedness Questionnaire

Instructions: Answer each of the following questions as best you can. If you always use one foot to perform the described activity, circle Ra or La (for right always or left always). If you usually use one foot circle Ru or Lu, as appropriate. If you use both feet equally often, circle Eq.

Please do not simply circle one answer for all questions, but imagine yourself performing each activity in turn, and the mark the appropriate answer. If necessary, stop and pantomime the activity.

1. Which foot would you use to kick a stationary ball at a target straight in front of you?
2. If you had to stand on one foot, which foot would it be?
3. Which foot would you use to smooth sand at the beach?
4. If you had to step onto a chair, which foot would you place on the chair first?
5. Which foot would you use to stomp on a fast-moving bug?
6. If you were to balance on one foot on a railway track, which foot would you use?
7. If you wanted to pick up a marble with your toes, which foot would you use?
8. If you had to hop on one foot, which foot would you use?
9. Which foot would you use to help push a shovel into the ground?
10. During relaxed standing, people initially put most of their weight on one foot, leaving the other leg slightly bent. Which foot do you put most of your weight on first?
11. Is there any reason (i.e. injury) why you have changed your foot preference for any of the above activities? YES NO (circle one)

12. Have you ever been given special training or encouragement to use a particular foot for certain activities? YES NO (circle one)

If you have answered YES for either question 11 or 12, please explain:

___________________________________________________________________________
___________________________________________________________________________

179
Appendix I

Head roll angle, head pitch angle, trunk roll angle and trunk pitch angle in normal walking condition with GVS from one trial in one older participant
Appendix J

Head roll angle, head pitch angle, trunk roll angle and trunk pitch angle in normal walking condition with GVS from one trial in one young participant
Appendix K

Results of paired t test between two trials in the young and older group

<table>
<thead>
<tr>
<th>Variables</th>
<th>Young Group</th>
<th></th>
<th>Older Group</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>t value</td>
<td>P value</td>
<td>t value</td>
<td>P value</td>
</tr>
<tr>
<td>Gait Speed</td>
<td>0.90</td>
<td>p=0.37</td>
<td>-7.84</td>
<td>p&lt;0.001</td>
</tr>
<tr>
<td>Head Roll Angle</td>
<td>0.34</td>
<td>p=0.74</td>
<td>0.41</td>
<td>p=0.68</td>
</tr>
<tr>
<td>Head Roll Velocity</td>
<td>0.72</td>
<td>p=0.47</td>
<td>1.46</td>
<td>p=0.15</td>
</tr>
<tr>
<td>Head Pitch Angle</td>
<td>0.44</td>
<td>p=0.66</td>
<td>-0.41</td>
<td>p=0.68</td>
</tr>
<tr>
<td>Head Pitch Velocity</td>
<td>0.57</td>
<td>p=0.57</td>
<td>0.41</td>
<td>p=0.69</td>
</tr>
<tr>
<td>Trunk Roll Angle</td>
<td>0.70</td>
<td>p=0.48</td>
<td>0.35</td>
<td>p=0.73</td>
</tr>
<tr>
<td>Trunk Roll Velocity</td>
<td>-0.20</td>
<td>p=0.84</td>
<td>0.94</td>
<td>p=0.35</td>
</tr>
<tr>
<td>Trunk Pitch Angle</td>
<td>0.10</td>
<td>p=0.99</td>
<td>-1.36</td>
<td>p=0.18</td>
</tr>
<tr>
<td>Trunk Pitch Velocity</td>
<td>-1.87</td>
<td>p=0.06</td>
<td>-0.65</td>
<td>p=0.52</td>
</tr>
<tr>
<td>Step Length</td>
<td>-3.01</td>
<td>p=0.003</td>
<td>-7.24</td>
<td>p&lt;0.001</td>
</tr>
<tr>
<td>Step Length Variability</td>
<td>-0.54</td>
<td>p=0.59</td>
<td>1.84</td>
<td>p=0.07</td>
</tr>
<tr>
<td>Step Width</td>
<td>-1.06</td>
<td>p=0.29</td>
<td>0.53</td>
<td>p=0.60</td>
</tr>
<tr>
<td>Step Width Variability</td>
<td>-0.18</td>
<td>p=0.86</td>
<td>0.25</td>
<td>p=0.80</td>
</tr>
</tbody>
</table>
Appendix L

Results of bivariate correlation analysis between head roll angle / trunk roll angle / head-trunk correlation in normal (NB) and narrow-based walking condition (NBW) (without any manipulation) and all the sensory functions in Study I (Chapter 3)

<table>
<thead>
<tr>
<th></th>
<th>Head roll angle (NB)</th>
<th>Trunk roll angle (NB)</th>
<th>Head-trunk correlation (NB)</th>
<th>Head roll angle (NBW)</th>
<th>Trunk roll angle (NBW)</th>
<th>Head-trunk correlation (NBW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual acuity</td>
<td>r=0.22, p=0.26</td>
<td>r=-0.25, p=0.20</td>
<td>r=-0.17, p=0.40</td>
<td>r=-0.29, p=0.13</td>
<td>r=-0.16, p=0.43</td>
<td>r=0.02, p=0.92</td>
</tr>
<tr>
<td>Visual contrast sensitivity</td>
<td>r=0.02, p=0.93</td>
<td>r=-0.17, p=0.37</td>
<td>r=-0.31, p=0.11</td>
<td>r=0.12, p=0.53</td>
<td>r=-0.08, p=0.68</td>
<td>r=-0.23, p=0.25</td>
</tr>
<tr>
<td>SVV</td>
<td>r=-0.28, p=0.15</td>
<td>r=-0.14, p=0.49</td>
<td>r=-0.28, p=0.16</td>
<td>r=-0.11, p=0.60</td>
<td>r=-0.23, p=0.23</td>
<td>r=-0.39, p=0.05</td>
</tr>
<tr>
<td>Cutaneous press sensitivity</td>
<td>r=0.44, p=0.02</td>
<td>r=0.10, p=0.96</td>
<td>r=-0.03, p=0.89</td>
<td>r=-0.07, p=0.71</td>
<td>r=0.01, p=0.98</td>
<td>r=0.07, p=0.70</td>
</tr>
<tr>
<td>Vibration sensitivity</td>
<td>r=0.42, p=0.02</td>
<td>r=0.36, p=0.05</td>
<td>r=0.04, p=0.85</td>
<td>r=0.01, p=0.97</td>
<td>r=-0.06, p=0.76</td>
<td>r=-0.1, p=0.97</td>
</tr>
<tr>
<td>Ankle proprioception</td>
<td>r=0.27, p=0.16</td>
<td>r=0.04, p=0.85</td>
<td>r=0.02, p=0.92</td>
<td>r=0.16, p=0.43</td>
<td>r=0.14, p=0.49</td>
<td>r=0.24, p=0.23</td>
</tr>
<tr>
<td>DVA (near, 1m/s)</td>
<td>r=0.29, p=0.13</td>
<td>r=0.16, p=0.42</td>
<td>r=-0.15, p=0.44</td>
<td>r=-0.06, p=0.75</td>
<td>r=-0.19, p=0.33</td>
<td>r=-0.19, p=0.34</td>
</tr>
<tr>
<td>DVA (far, 1m/s)</td>
<td>r=-0.38, p=0.05</td>
<td>r=-0.10, p=0.62</td>
<td>r=-0.28, p=0.14</td>
<td>r=-0.17, p=0.39</td>
<td>r=0.17, p=0.37</td>
<td>r=-0.16, p=0.40</td>
</tr>
</tbody>
</table>