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The development of a novel method of recording centre of gravity location in bipedal stance in healthy adults.

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Abstract

Standing balance in humans requires that the centre of gravity (COG) remains within boundaries of the base of support (BOS). Clinically force-plate technology (for example, the NeuroCom Balance Master® 6.0, Oregon (BM)) is used increasingly to gain objective data when assessing clients' balance. In addition to the primary outcome (sway velocity) provided by the BM in four tests of the modified Clinical Test of Sensory Interaction on Balance (mCTSIB) a representation of COG location is also provided .

Currently, there is no objective method for clinicians to record COG location. The purpose of this thesis was to develop a novel method of recording COG location in bipedal stance in healthy adults. The aims were: 1, explore literature associated with COG behaviour and location in healthy adults when sensory inputs and BOS are altered; 2, develop a method for categorising COG location based on the BM results diagram and assess tester reliability for this method; 3, test the new categorical method of recording COG location for (i) between-session repeatability and, (ii) comparability between different force plate systems; 4, test whether the data obtained when applying the method of categorising COG location is sensitive to changes under the different mCTSIB conditions and age; 5, test whether this categorisation or COG location is sensitive to varying BOS test conditions of feet apart to feet together as well as single limb stance, and 6, compare the COG start location to COG mean location obtained simultaneously for the mCTSIB conditions and varying BOS conditions.

A literature review incorporating the impact of ageing on sway behaviours and COG location, particularly when sensory inputs or BOS are altered, formed the basis for Study 1 which addressed aim 1. Studies 2 and 3 were a secondary analysis of data from an earlier multidisciplinary study (Longitudinal Assessment of Women (LAW), 2000) of 481 independently-mobile, community-dwelling women aged 40-80 years, assessed on the BM. A new method was developed to categorize COG location data into sectors in Study 2. This categorization method was tested for inter- and intra-rater reliability by two independent raters thus addressing aim 2. For aim 3 two pilot studies assessed the repeatability of the measure between two test sessions and the comparability of results between two force plate systems. These additional aspects of COG location have not previously been tested. In Study 3 data from the LAW study were analysed to assess whether differences in COG start location could be demonstrated under altered sensory conditions using the new method of categorization and whether these were similar to other studies reporting on the location of COG thereby addressing aim 4. Studies 4 and 5 analysed COG location in 81 healthy adults (men, N=31) aged 30-80 years collected using Kistler force-plates. A customised software programme replicated

the BM set-up allowing for collection of additional information such as COG start and mean locations and additional BOS configurations. Study 5 analysed the COG start location for each mCTSIB condition and different BOS configurations (aim 5). Study 5 was designed to compare the COG start and mean locations for each test using the categorization method (aim 6). Study 2 demonstrated high inter- (κ 0.84, CI 0.82-0.86)) and intra-rater (Rater 1, κ 0.78, CI 0.74-0.79; Rater 2, κ 0.88, CI 0.86-0.90) reliability between two independent raters using the categorization method for COG start location. In Study 3 significant differences were shown for COG location in the antero-posterior plane for women when the surface was changed from a firm to a compliant surface with ($p<0.001$) and without ($p<0.001$) vision conditions. As difficulty increased from a firm surface with, then without vision, to a compliant surface with vision, a greater proportion of subjects had an anterior COG location relative to each subject's predicted centre of balance. When both surface and vision were compromised, the proportion of subjects whose COG remained anterior decreased compared with an altered surface alone. No significant difference was detected as age increased for the firm surface, eyes open test.

Study 4 (a mixed group of men and women) showed that as BOS size decreases and when vision is reduced (in feet apart and feet together tests), a greater proportion of subjects have an anterior COG location ($p\leq0.01$). In Study 5 we found there was substantial to near perfect observed agreement between the start and mean locations (κ 0.66 – 0.87) for all tests except for the right single limb stance test (κ 0.41, CI 0.10-0.83).

The findings from these studies provide support for the use of the proposed method to objectively record COG location in a range of test conditions. This removes the subjectivity from identifying COG location to assist in the interpretation of assessment findings and may then assist in the development of more targeted treatment programmes for clients with balance difficulties.

Declaration by author

This thesis is composed of my original work, and contains no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis.

I have clearly stated the contribution of others to my thesis as a whole, including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, and any other original research work used or reported in my thesis. The content of my thesis is the result of work I have carried out since the commencement of my research higher degree candidature and does not include a substantial part of work that has been submitted to qualify for the award of any other degree or diploma in any university or other tertiary institution. I have clearly stated which parts of my thesis, if any, have been submitted to qualify for another award.

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Publications during candidature

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   A modified version of this publication is incorporated as Chapter 2. The published manuscript appears in Appendix 3.

Contributor	Statement of contribution
Author 1: Boughen J	Designed the review (90%) Writing (65%)
Author 2: Nitz J	Designed the review (10%) Writing (20%)
Author 3: Johnston V	Writing (15%)

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Contributor	Statement of contributions
Author 1: Boughen J	Designed the experiment (50%) Data collection (50%) Writing (50%)
Author 2: Dunn K	Designed the experiment (10%) Data collection (50%) Writing (20%)
Author 3: Nitz J	Writing (15%)
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Contributions by others to the Thesis

Jennifer Nitz (primary advisor for the first half of the thesis programme), Venerina Johnston (primary advisor for the second half of the thesis programme) and Asad Khan made significant contributions to the study concept design and provided critical advice for the writing of the thesis.

Kylie Dunn was the second tester in Study 2 (Chapter 5) and was also involved in the analysis and presentation of data (15%) for this study. Jennifer Nitz, Venerina Johnston and Asad Khan contributed (30%) to the concept and study design in this study and also critically reviewed writing and presentation of the article. I was the first tester in the study devising the method of categorization and the primary writer for the published article.

Statement of Parts of the Thesis Submitted to Qualify for the Award of Another Degree

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Students' stories of their PhD journeys vary greatly. Some find it a rewarding experience, others less so. Some find it a reasonably straight forward journey while others feel it has been a struggle. One common thread throughout these stories, however, is that the journeys are never taken solely by the student. There are always others involved to offer support, to critique or to mentor. Many people have accompanied me on this journey.

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Keywords

Postural balance, centre of gravity, centre of pressure, base of support, ageing, vision.

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List of Abbreviations

BM – NeuroCom Balance Master®

BOS – Base of support

COG – Centre of gravity

COM – Centre of mass

COP – Centre of pressure

CTSIB – Clinical Test of Sensory Interaction on Balance

FAEO – Feet apart, eyes open

FAEC – Feet apart, eyes closed

FBOS – Functional base of support

FiEO – Firm surface, eyes open

FiEC – Firm surface, eyes closed

FoEO – Foam surface, eyes open

FoEC – Foam surface, eyes closed

FSB – Functional stability boundary

FTEO – Feet apart, eyes open

FTEC – Feet apart, eyes closed

mCTSIB – modified Clinical Test of Sensory Interaction on Balance

mVel – mean sway velocity

CHAPTER 1

Introduction

Standing balance in humans is complex. Viewed at the most basic level, maintenance of balance requires that the centre of gravity (COG), an imaginary plumbline from the centre of mass (COM) (the weighted average of all segments of the body) must remain within a person's base of support (BOS) (Winter, 1995). When the COG approaches any boundary of the BOS action must be taken to change the direction of COG movement back towards the central area of the BOS to retain control of balance. However, when the COG moves beyond those boundaries the BOS must be reconfigured, for example, by taking a step, or a fall will result. Injuries that are caused by falls incur great cost to both the individual and to society across all ages. In New South Wales alone the estimated cost associated with falls in the community in older adults in 2006-07 was $558.5 million (Watson, Clapperton, & Mitchell, 2010). Knowledge relating to the many attributes that are required to maintain control and location of COG within the BOS contribute to an understanding of how balance is preserved in steady state stance. Although there has been considerable research to study many aspects relating to the control of the COG within the BOS there has been less evaluation of the location of COG within the BOS in healthy adults particularly under different sensory conditions and with increasing age. An understanding of whether COG location alters in healthy adults in different environments is needed before the impact of different pathologies on COG location can be interpreted. Not only is there less evidence regarding COG location, there is currently no way for this to be measured objectively in a clinical setting.

A number of factors contribute to the preservation of the COG within the BOS in steady state stance. Firstly, collaboration between sensory, central and motor systems is needed to act on the multi-segmented human body to manage the high number of degrees of freedom of movement in stance. Secondly, control is made more difficult by the fact that the location of the COM in human bipedal stance is relatively high (two-thirds of the body mass is located within the upper two-thirds of the height above the ground (Winter, 1995) while the BOS within which the COM must be controlled is relatively small. Thirdly, unlike inanimate objects, humans are in a perpetual state of motion (Spaepen, Vranken, & Willems, 1976), and, finally, humans are highly variable in both size and shape and they function within a range of environments.

The exploration of how this highly mobile, highly variable mass is controlled within a small BOS has resulted in a large body of research to contribute to knowledge of the roles of sensory (somatosensory, visual and vestibular) (Baloh, Ying, & Jacobson, 2003; Low Choy, Brauer, & Nitz, 2008; Shumway-Cook & Woollacott, 2007b), central (processing and response selection) (Lockhart, Smith, & Woldstad, 2005; Yordanova, Kolev, Hohnsbein, & Falkenstein, 2004) and motor (neuromuscular) (Lockhart et al., 2005; Tanosaki, Ozaki, Shimamura, Baba, & Matsunaga, 1999) systems in standing balance and the interactions of these systems under a variety of circumstances. Researchers have also sought to understand the influences of mass (size and shape) (Allard, Nault, Hinse, LeBlanc, & Labelle, 2001) and BOS (size and shape) (King, Judge, & Wolfson, 1994; Melzer, Benjuya, & Kaplanski, 2004; Slobounov, Moss, Slobounova, & Newell, 1998) and the relationship between these (Pai & Patton, 1997; Slobounov et al., 1998; Tanaka, Takeda, Izumi, Ino, & Ifukube, 1999) in human stance. A major consideration in many of these studies has been the impact of ageing on the attributes that are necessary for successful balance control. As adults increase in age, the function of all body systems declines. Change in balance competency has been identified in healthy populations of women from fifty years of age (Low Choy, Brauer, & Nitz, 2003) and of men from sixty years (Nolan, Nitz, Low Choy, & Illing, 2010). Depending on the degree to which body systems decline in normal, healthy ageing, older adults may be less able to respond in a timely manner in order to take a step or to effect a change in direction of the COG even in the absence of major pathologies. It would seem then, that the location of the COG within the BOS might be a more critical factor as age increases.

Currently a range of tests are used in the assessment of balance. These include tests of sensory acuity, vision, muscle strength, joint range of movement, movement speed and reactive strategies. It may be helpful to clinicians to have a method by which COG location could be objectively identified as this additional information may assist in the interpretation of other test results (for example, reactive strategies). .

Anecdotally it is thought that the location of the COG with respect to the feet moves posteriorly as people age. However, a study by Schwab, Lafage, Boyce, Skalli and Farcy (2006) suggests that this is not the case. They considered the gravity line (the vertical projection of the COM) location in relation to the vertebral column and the feet in three subject groups, young (29.8 ± 5.8 years), middle (47.3 ± 6.2 years) and elderly (70.8 ± 5.2 years) in stance on a firm surface with eyes open. Simultaneous radiographic and force plate data were compared showing that while the distance between the gravity line and the vertebral column (in particular the 12th thoracic vertebra and the 3rd lumbar vertebra) increased with increasing age, the location of the gravity line with respect to the heels remained relatively constant. They suggest that the mobility of the pelvis through tilt and antero-posterior translation is an important factor in preserving the gravity line position in relation to the BOS. Geiger, Muller, Niemeyer and Kluba (2007) when comparing subjects with and without spinal pathology when standing on a firm surface with eyes open, also found that the gravity line position in the antero-posterior plane remained relatively constant being located at 60 and 61% of foot length measured from the great toe.

Apart from the scarcity of evidence provided in the literature on location of COG, the methods described in the available literature cannot be replicated in most clinics to assist clinicians in their assessment of COG location in standing balance. Further, the current evidence focuses on stance on a firm surface with less evidence for COG location in stance on a compliant surface (such as foam) or under changed visual conditions (for example, with eyes closed). In a clinical context an understanding of balance behaviours under different sensory conditions provides insights into which sensory systems might be compromised and how treatment should be directed. The additional information provided by an objective measure of COG location under these different test conditions may also contribute interpretation of assessment.

A group of test conditions known as the Clinical Test of Sensory Interaction in Balance (CTSIB) (Shumway-Cook & Horak, 1986), is used frequently in the clinical setting to differentiate performance on firm and compliant surfaces and under compromised visual conditions. Force plates are now available in many centres for the assessment of the CTSIB, as well as a range of other test conditions, and can also be used in the treatment of clients with balance impairments. The NeuroCom Balance Master® 6.0, Oregon (BM) is one such system used in some clinics. The BM has the capacity to test a modified CTSIB (mCTSIB) in which only four of the six conditions, namely, those for steady stance on a firm or foam (unstable) surface with and without vision. Its associated software programme summarizes these test results from centre of pressure (COP) readings and offers a diagrammatic representation of results for easy analysis and comparison by the clinician. The mean velocity of sway (mVel) is the parameter primarily used to interpret results for the mCTSIB on the BM but the software also provides a diagram depicting COG location derived from the COP data from each trial of each condition of the mCTSIB. An example of a BM results' page for the mCTSIB is provided in Figure 1.1. It provides pictorial representations of the sway trace for each test trial and for the COG start location. Also provided is a bar graph depicting the mean sway velocity for each test and the composite sway velocity across all four tests of the mCTSIB.

The depiction of the location of COG at the start of each test trial for the mCTSIB on the BM provides an opportunity for development of an objective method of identifying COG location for documentation. As an absolute measurement in millimetres is not provided, it was proposed that the results may be interpreted by allocation of the COG location into sectors such as anterior or posterior, left or right, to provide an objective, categorical method of presenting the COG location. This objective measure may prove to be a useful addition to the broad range of information which is gathered when assessing patients who present with impaired balance in those centres which have access to a BM or other force plate systems.

The COG location on the BM is identified at the start of each of the three, ten-second trials for the four test conditions. However, no mean location is provided across the three trials of each test condition. There is little evidence in the literature relating to the *start* location for COG particularly in the antero-posterior plane for bipedal steady state stance as most research evidence presents the COG location as a mean across an extended stance time (Carpenter, Frank, Winter, & Peysar, 2001; Merlo et al., 2012). There is also little evidence relating to the reliability of COG location in the antero-posterior plane between test sessions. In addition, there is considerable variability in how COG location is described in relation to the BOS. For example, location has been identified as a proportion of foot length measured from the heels of the feet (Azuma, Ito, & Yamashita, 2007; Fujiwara, Asai, Kiyota, & Mammadova, 2010), as a proportion of foot length measured from the ankles (Saha, Gard, Fatone, & Ondra, 2007), as a proportion of foot length measured from the first toe (Geiger et al., 2007) or as the distance (millimetres) from the heels (Merlo et al., 2012).

A review of the literature was conducted to explore more fully the current knowledge relating to centre of pressure behaviours for bipedal stance in healthy adults including the antero-posterior location of the centre of gravity within the base of support. The review was broadened to include the changes that occur in these measures as adults age and also to clarify terminology that is commonly used in discussions on outcomes used particularly when balance testing is conducted on force plates.

The overarching purpose of this thesis is: To develop a novel method of recording centre of gravity location within the base of support in bipedal stance in healthy adults and to determine its sensitivity to detect changes under different test conditions and with age. To this end, there were six aims for this thesis (Figure 1.1):

Aim 1:

To explore the literature associated with centre of gravity behaviour and location in healthy adults when sensory inputs of base of support are altered.

A literature review, presented as a Narrative Overview (Study 1, Chapter 2), was conducted to identify the gaps in knowledge relating to COG location and BOS relevant to clinical practice were identified. The review identified the following gaps in the literature: (i) the location of the COG relative to the boundaries of the BOS is one factor which may influence balance integrity, (ii) there is currently no method available in the clinical context that is used to record COG location within BOS, and, (iii) there are many changes in the sway attributes of the COG under different sensory (mCTSIB) and BOS (for example feet together and single limb stance) demands and (iv) there has been limited exploration of COG location under these different conditions and with increasing age. These factors suggest that there is a need for an objective measure of COG location to be developed and that this would be a useful tool for clinicians.

These findings guided the formulation of the subsequent aims for this thesis to support the development of a method of categorising COG location within BOS in the antero-posterior plane when applied to data obtained from healthy adults. Development of the categorisation method also included investigation of the sensitivity of the method to detect change under different test conditions and with age. These aims were:

Aim 2:

To develop a method for categorising COG location based on the Balance Master results' output and to assess tester reliability for this method (Study 2, Chapter 4).

Aim 3:

To test the new categorical method of recording COG location for (i) between-session repeatability and, (ii) comparability between different force plate systems (Chapter 5).

To address part (i) a small pilot study assessed the level of agreement for COG start location between two test sessions conducted on consecutive days. To address part (ii) a small number of subjects were tested on both the Balance Master and a second force plate system (Kistler) within the same test session to assess the comparability of results.

Aim 4:

To test whether the data obtained when applying this method of categorising COG location is sensitive to changes under the mCTSIB test conditions and with age in a healthy adult population (Study 3, Chapter 6).

Aim 5:

To test whether this categorisation of COG location is sensitive to the varying BOS test conditions of feet apart, feet together and single limb stance (Study 4, Chapter 7).

Aim 6:

To compare the start location and mean location of COG obtained simultaneously for the mCTSIB conditions and the varying BOS test conditions (Study 5, Chapter 8).

The hypothesis for Aim 2 (Study 2) was that the method we devised for categorising location of COG from the BM readout would be reliable both within and between raters.

The hypothesis for Aim 3 was that the antero-posterior COG location would be repeatable between test sessions on the Balance Master and that testing between force plate systems would be comparable.

The hypothesis for Aim 4 (Study 3) was that the COG start location categories recorded would be sensitive enough to demonstrate significant differences between the mCTSIB sensory conditions and for age.

The hypothesis for Aim 5 (Study 4) was that this categorisation of COG location would be sensitive to the varying BOS test conditions of feet apart to feet together as well as single limb stance.

The hypothesis for Aim 6 (Study 5) was that the COG start and mean locations for the antero-posterior plane would show high levels of agreement for the least complex test conditions but would show less agreement as the tests became more complex.

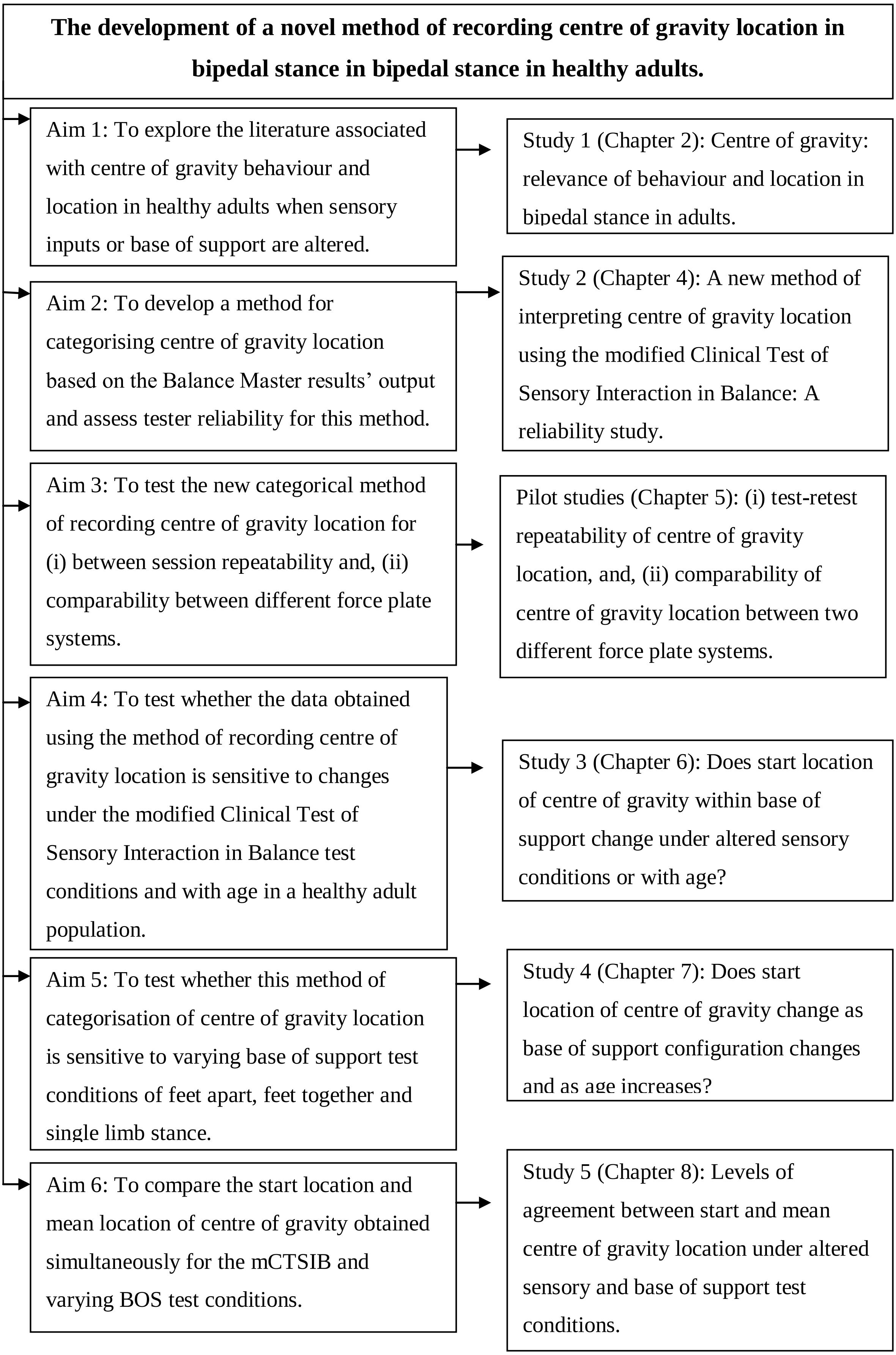

Figure 1.1 Flow chart of the thesis aims and studies.

There are nine chapters in this thesis. A review of the literature relating to COG behaviour under different conditions and the impact of ageing (Study 1) is presented in Chapter 2. Chapter 3 discusses the materials and methods used. Chapter 4 (Study 2) discusses the development of the categorisation method used throughout the studies. Two pilot studies which relate to technical aspects of the thesis are discussed in Chapter 5 while Chapters 6 to 8 present Studies 3-5 conducted as part of this thesis. Chapter 9 provides discussion and conclusions of the findings and implications for clinical practice and for further research.

CHAPTER 2

Centre of gravity: relevance of behaviour and location in bipedal stance in older adults. (Study 1)

The most basic premise of stability is the retention of the COM of a body within the BOS. Factors such as the distance of the COG from the boundaries of the BOS as well as the speed and direction of movement of the COG influence the ability to preserve this relationship. When considering balance in the context of ageing it is important to incorporate as well an understanding of both the systems that are implicated in the control of balance and the impact that increasing age has on these systems. This then provides the clinician with a broad perspective of all of the factors which may affect stability in standing in older adults. This chapter looks at the terminology used, particularly in relation to force plate technology, as well as current knowledge on sway properties and centre of gravity location. Consideration is given to the effect of increasing age on balance systems. It also raises questions about the reliability of a visual assessment of centre of gravity location in clinical practice in the antero-posterior plane and the importance of understanding how centre of gravity location changes under different test conditions.

Boughen J, Nitz J, Johnston V. Centre of gravity: relevance of behaviour and location in bipedal stance in older adults. *Physical Therapy Reviews*. 2017 doi: 10.1080/10833196.2017.1283831

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2.1 Abstract

Background: The assessment of balance competency incorporates both qualitative and quantitative testing of multiple systems. These include tests for both peripheral (sensory and musculoskeletal test) and central (reaction times and strategies) systems and consider a variety of environmental contexts. The increasing use of force plate and pressure plate technologies (for example the Neurocom Balance Master® or Nintendo Wii-fit balance board) in the clinical setting, allow objective assessments of the behaviour and location of COG within the BOS. Sway parameters such as sway velocity are commonly used as outcomes in research. However, an understanding of COG location within BOS is also an important aspect of balance which receives less attention.

Objectives: The objective of this study was to review the literature that is available on the impact of age on COG parameters such as the features of sway and its location within BOS.

Major findings: This review presents basic balance concepts relating to both the sway characteristics and location of the centre of gravity within base of support and the changes that occur as age increases. The impact of changes in the base of support, such as size and compliance, are also addressed in the context of the ageing client. It is possible that the location of COG within BOS in conjunction with sway characteristics may be more critical in older age groups than in the young as all body systems (sensory, central and musculoskeletal) show declines with increasing age.

Conclusions: The information contained in this Chapter provide a basis upon which to explore the relevance of COG location and the implications of altered test conditions particularly in the context of older adults.

2.2 Introduction

Research on balance control over the last sixty years has resulted in a substantial volume of literature. In the last three decades exploration of the additional effects of ageing on balance control and falls incidence has added further to this volume of information (Alhanti, Bruder, Creese, Gregory, & Newton, 1997; Allum, Carpenter, Honegger, Adkin, & Bloem, 2002; Berger, Buisson, Chuzel, & Rougier, 2005b; Bryant, Trew, Bruce, Kuisma, & Smith, 2005; Fukuda, 2012; Horak, 2010; N. Low Choy et al., 2008; Murray, Seireg, & Sepic, 1975; Nitz, Stock, & Khan, 2013; Patla, Frank, & Winter, 1990; Peters, McKeown, Carpenter, & Inglis, 2016; Qiu & Xiong, 2015; Zettel-Watson, Suen, Wehbe, Rutledge, & Cherry, 2017). For clinicians working with older clients, accessing and integrating this array of information is both time-consuming and, at times, confusing. Clinically, the management of older clients with balance anomalies requires an understanding not only of the declining function of sensory and motor systems (Horak, 2006; Thomas et al., 2014; Woollacott, 2000) but also an awareness of the characteristics of, and relationships between, the body and its base of support (BOS) particularly in healthy adults (Amiridis, Hatzitaki, & Arabatzi, 2003; Era et al., 2006; Nichols, Glenn, & Hutchinson, 1995) so that the impact of pathologies on this control might be considered and efficacy of treatment measured.

Normal balance control requires competency in most, if not all, of the systems involved in maintaining balance but as people age there is a progressive decline in all of the systems needed for successful balance (Horak, Henry, & Shumway-Cook, 1997; Lord, Clark, & Webster, 1991; Shumway-Cook & Woollacott, 2007a). Studies of healthy men (Allum et al., 2002; Illing, Choy, Nitz, & Nolan, 2010; Nolan, et al., 2010) and women (Low Choy et al., 2003; Low Choy et al., 2008; Nitz & Low Choy, 2004) of different ages have shown that balance declines are measurable by 50 to 60 years in both genders. Whether decline is an inevitable consequence of ageing or whether, as Imms and Endholm (1981) have suggested, it is secondary to the onset of pathologies, there is considerable evidence of reduced function in both peripheral and central systems (Low Choy et al., 2008; Mecagni, Smith, Roberts, & O'Sullivan, 2000; Menz, Morris, & Lord, 2005; Tanaka, Noriyasu, Ino, Ifukube, & Nakata, 1996; Yordanova et al., 2004) as people age. Reduced performance has been demonstrated in a wide range of attributes such as somatosensation and strength (Gehlsen & Whaley, 1990; Lord et al., 1991; Low Choy et al., 2008), flexibility (Chiacchiero, Dresely, Silva, DeLosReyes, & Vorik, 2010; Nolan et al., 2010), vision (Foran, Mitchell, & Wang, 2003; Haran et al., 2010), vestibular function (Illing et al., 2010; Park, Tang, Lopez, & Ishiyama, 2001) and reduced central processing speeds (Lockhart et al., 2005; Yordanova et al., 2004) in older adults. All of these have been implicated in reduced balance function.

There is ample evidence of the impact of peripheral and central changes with ageing on the relationship between the centre of gravity (COG) and BOS of the body in steady state balance through the study of body sway characteristics such as sway area (Berger, Buisson, Chuzel, & Rougier, 2005a; Era et al., 2006; Slobounov et al., 1998), sway path length (Lord et al., 1991) and sway velocity (Berger et al., 2005a; Era et al., 2006; Low Choy, Brauer, & Nitz, 2007). However, less attention has been paid to the location of the COG within the BOS and whether this changes with ageing or under different test conditions. Much of the evidence relating to sway is gathered through the use of force plate technology and analysis of the resulting centre of pressure (COP) data. Location, in conjunction with direction and velocity of COG movement, determines the time within which a subject must react to retain balance (Pai & Patton, 1997; Slobounov et al., 1998).

This review explores the literature relating to basic balance concepts and changes that occur with ageing in steady state bipedal stance. In addition, the available literature relating to the location of COG within the BOS is considered.

2.3 Components of balance and changes with age

The basic elements which impact on the balance of a body are the mass of the body, the height of the centre of mass (COM), the movement characteristics and location of the COG with respect to the BOS (LeVeau, 2011) as well as the size, configuration and compliance of the BOS. Changes in the location and the velocity of COM displacement as well as changes in the size and shape of the BOS will impact on stability, and changes in all of these elements have been demonstrated with ageing. Table 2.1 provides a summary of terms used in this review.

Table 2.1 Abbreviations and definitions of common terms.

Term	Abbreviation	Definition
Base of support	BOS	Area covered within the outer borders of the feet
Centre of gravity	COG	Resultant vertical vector acting downwards on a body
Centre of mass	COM	The point at the centre of the total body mass
Centre of pressure	COP	Resultant ground reaction (upward) forces
Functional base of support	FBOS	Maximal antero-posterior COP movement distance
Functional stability boundary	FSB	Area represented by limits of stability in anterior, posterior, lateral and diagonal movements when foot position is fixed
Sway velocity		Distance (total path length) divided by time (millimetres per second)
Sway path length		Total distance travelled by the COP during test duration. This may also be recorded separately for antero-posterior and medio-lateral directions
Sway area		The total area over which COP travels during test duration.

2.3.1 Centres of mass, gravity and pressure

The COM of a body is defined as 'the point that is at the centre of the total body mass' (Shumway-Cook & Woollacott, 2007) (p158) representing the central point of equilibrium of a body. For the multi-segmented human body this point is the weighted average of the centres of mass of all of the segments (Winter, 1995) and its location varies according to the organization and size of the segments. Although the BOS remains constant in steady state stance, there are continual small oscillatory movements of the COM (Spaepen et al., 1976). Three factors contribute to this perpetual movement: (i) respiration with its rise and fall of the diaphragm and movement of the rib cage results in constant shifts of COM (Roberts & Stenhouse, 1975), (ii) changes in body alignment also contribute through changes in the gravitational forces which act to destabilize COM (Woodhull, Maltrud, & Mello, 1985), and (iii) the muscles involved in resisting the effects of gravity produce phasic rather than constant forces (De Luca, Lefever, McCue, & Xenakis, 1982). Other destabilizing features in bipedal stance include the relatively high COM of the human body (two-thirds of the body mass is located within the upper two-thirds of the height from the ground (Winter, 1995)) and the relatively small BOS. As the position of COM is an estimate for each individual it cannot be measured directly (Hasan et al., 1996a) although its movement (or sway) can be tracked indirectly with the use of force plates.

Force plates have been used by researchers in the study of balance control since the 1950s and provide multiple measures of the ground reaction forces (or COP) through the feet as the body responds to movements of the body's COM. When dual force plates are used, both the horizontal, or shear forces (representing anterio-posterior and medio-lateral components) and the vertical forces (Rougier, 2008) are measured. The software used to process the data may produce a trace or stabilogram of COP movements throughout the test time to provide a two dimensional (antero-posterior and medio-lateral) visual representation of the COP path recorded over a series of time points (Figure 2.1). The position of the COG, the point at which a plumb line from the COM intersects with the BOS, can be estimated from this COP data. This then provides researchers and clinicians with an indirect method to track COM movements as the body sways. In steady state conditions, that is, when the size and shape of the BOS remain constant, both the COP and the COG must remain within the boundaries of the BOS for balance to be sustained.

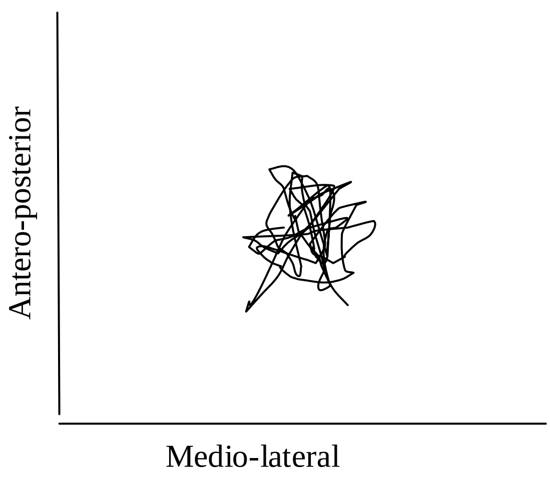

Figure 2.1 An example of a trace of sway from centre of pressure data for stance on two feet.

While COG and COP are frequently used interchangeably in the literature and are both measures of displacement, they are not identical measures (Winter, Prince, Frank, Powell, & Zabjek, 1996). The COG is the vertical vector (downwards gravitational force) from the COM (Winter et al., 1996) and represents real movement of the body. Its position within the BOS is influenced by both change in the position of body segments and by the moment of the body's inertia (Rougier, 2008). This is quite distinct from the COP which is a reflection of the motor or net neuromuscular responses that are required to control COG (Baratto, Morasso, Re, & Spada, 2002; Berger et al., 2005a; Patla et al., 1990) i.e. COP is the resultant ground reaction force vector on the force platform (Winter et al., 1996). A number of researchers have shown that movements of COG and COP are not equal and that the size and frequency of movements of COP are larger than COG (Hasan et al., 1996b; Patla et al., 1990; Roberts & Stenhouse, 1975; Spaepen et al., 1976; Winter et al., 1996). These differences between COP and COG locations at various time points within a test time are particularly evident towards limits of stability ranges such as in the outer range of anterior or posterior displacement but they are much more synchronous through the middle ranges of movement. Despite these differences, if enough points are plotted for both COG and COP the average locations are considered to be approximately equivalent (Rougier, 2008) with an increase in movement of COP reflecting an increase in movement of COG (Hasan et al., 1996b). The greater accessibility of COP, via force plate technology, makes it a more objective and convenient measure for researchers and clinicians to use (Hasan et al., 1996a). Additional information relating to the specific force plate systems used in the studies in this thesis is provided in Chapter 3.

2.3.2 Measures of sway

The continual movements of the body that occur in stance are referred to as 'sway'. This reflects movement of the COG rather than the COP (Palmieri, Ingersoll, Stone, & Krause, 2002). Features of sway include area of sway, sway path length and sway velocity (Table 2.1). These measures of sway are known as summary measures and have been used by researchers to gain insight into characteristics of balance in both steady state and dynamic conditions. Reliability has been demonstrated for sway area (Bauer, Groger, Rupprecht, & Gassmann, 2008; Benvenuti et al., 1999; Doyle, Hsiao-Wecksler, Ragan, & Rosengren, 2007; Pinsault & Vuillerme, 2009; Qiu & Xiong, 2015), sway length (Bauer et al., 2008; Qiu & Xiong, 2015) and sway velocity (Benvenuti, et al., 1999; Lafond, Corriveau, Hebert, & Prince, 2004; Moghadam et al., 2011; Pinsault & Vuillerme, 2009) parameters.

Stance tests in which the participant adopts a fixed stance position (for example, standing with the feet apart or together and with the eyes either open or closed) may be referred to as static stance

(Baratto et al., 2002; Geldhof et al., 2006; Granacher, Muehlbauer, Gollhofer, Kressig, & Zahner, 2011), quiet stance (Fujiwara et al., 2010; Gatev, Thomas, Thomas, & Hallett, 1999) or unperturbed stance (Pinsault & Vuillerme, 2009). The term 'static', in the context of posturography, has been defined as tests in which the surface is flat and unperturbed. That is, disturbance of the body is internal and predictable (Baratto et al., 2002). It has also been defined as a test in which the BOS and the ground remain still while the COM is free to move through sway (Granacher et al., 2011). These tests provide information on spontaneous sway under fixed, predictable conditions. Dynamic tests may be defined as those in which the position of the participant is subjected to different types of unpredictable stimuli (Baratto et al., 2002) thus resulting in reactive responses. This use of the term 'dynamic' implies the presence of an unexpected external stimulus such as a movable stance surface or a destabilizing force applied to the body and gives information on reactive strategies. It is used in this context particularly in posturographic studies. However, Granacher et al. (2011) use the term 'dynamic' to denote tests in which both the BOS and the COM shift. This broader interpretation of the term encompasses both anticipatory (there is no unexpected perturbation – for example functional tests such as sit-to-stand or walking tests) and reactive (presence of an unexpected perturbation - for example movement of the platform) tests.

Although some researchers suggest that analysis of dynamic movement is more relevant to normal function, Baratto et al. (2002) note that static (or quiet stance) and dynamic studies address different aspects of postural control and produce different types of information. Static tests provide information on spontaneous sway and in this context the control system has the advantage of anticipatory feedback loops to manage the balance (Baratto et al., 2002). Dynamic tests require the systems to respond to unexpected stimuli, that is, there must be reactive strategies, such as taking a step, to maintain a position of balance. These reactive strategies are dependent on reflex responses. However, both approaches (that is, both static and dynamic tests) remain useful to researchers and clinicians although static assessments on force plates are more usual in the clinical context and are frequently included in balance assessments in rehabilitation settings.

2.3.3 Changes with ageing

Changes in sway attributes have been noted as people age and have been linked to declines in sensory and motor function. Increased sway, when standing on a firm surface, is associated with reduced tactile thresholds, reduced joint position sense (Anson et al., 2017; Choy, Brauer, & Nitz, 2007; Lord et al., 1991) and increased vibration thresholds (Choy et al., 2007). Cutaneous sensation (or tactile sensitivity) is implicated in the regulation of small oscillations around the vertical axis whereas proprioceptive input from muscles (evidenced by vibration thresholds) is more involved in larger body sway (Kavounoudias, Roll, & Roll, 2001) or larger velocity movements (Fitzpatrick & McCloskey, 1994). Tactile sensitivity (Menz et al., 2005), vibration thresholds (Baloh et al., 2003; Choy et al., 2007), and joint position sense (Lord et al., 1991) have all been shown to decline with ageing.

Sway area is the total area over which the COP moves during the time of a test. It is often reported as the area covered by 95% of all COP positions during the test time (Bauer et al., 2008). Sway area has been shown to increase for older healthy adults compared with younger adults (Berger et al., 2005a; Slobounov et al., 1998) reflecting greater COP movement within the BOS in quiet stance. Studies have shown associations between reduced sensation and reduced vision and an increase in sway area (Anson et al., 2017; Deshpande et al., 2016; Hageman, Leibowitz, & Blanke, 1995; Lord et al., 1991; Tanaka et al., 1996). Conversely, there is a reduction in sway area when somatosensation is enhanced through the use of spike insoles (Palluel, Nougier, & Olivier, 2008), which further reinforces the importance of somatosensory function to sway area. Older adults have reduced function of both tactile sensitivity (Choy et al., 2007; Lord et al., 1991; Melzer et al., 2004; Tanaka et al., 1996) and joint position sense (Choy et al., 2007; Lord et al., 1991) in the lower limbs. This reduced sensory function is thought to be a contributing factor to postural instability (Tanaka et al., 1996) and falls (Melzer et al., 2004).

Another factor which may affect sway area is body somatotype. This has been implicated in altered sway area in a group of primary and secondary school age girls (Allard et al., 2001). These researchers found that body weight and height influence sway area with ectomorphs (those with low weight and small musculature) having a larger sway area than other body types. This combination of low weight and small musculature may also be a factor to consider when assessing sway area in older adults as muscle cross-sectional area is reduced in this group (Doherty, 2003; Frontera et al., 2000).

Sway path length also increases with ageing (Colledge et al., 1994; Laughton et al., 2003; Slobounov et al., 1998). It also increases in both young and old when tests become more challenging (for example, standing on a soft surface with eyes open or closed). However, the sway path length increases in older adults are greater than those in young adults under more challenging test conditions (Colledge et al., 1994). Furthermore, fallers, when standing with their feet together, show higher COP path length than non-fallers (Melzer et al., 2004). Reduced strength, particularly of the ankle muscles is also associated with greater sway path length in the antero-posterior plane. Butler, Lord, Rogers and Fitzpatrick (2008) found that subjects (aged 60-69 years) with weak dorsi-flexor muscles but equivalent sensory function (N=17) when compared to controls (N=34), showed increased maximal sway in the antero-posterior direction for the eyes closed condition in steady state stance. Based on these findings they suggest a link between reduced dorsi-flexor strength and reduced proprioceptive control in steady state balance.

Alterations in body position also affect sway path length. Buckley, Anand, Scally and Elliott (2005) found that COP displacements in the antero-posterior plane increased to a similar degree for both the head-flexed and head-extended positions when elderly subjects (72.1 ± 2.5 years) stood on a firm surface with eyes open. Some researchers question whether larger excursions of COP are indicative of reduced balance control in older adults or whether this increased movement serves to provide the elderly with a greater sensory input, particularly from the ankle joint, which is then used to successfully manage their balance (Patla et al., 1990). However, although there is an increase in sway path length associated with spontaneous sway in older adults, the *maximal* excursion distances, or limits of stability (that is, the maximal COP distance in each direction through which a subject is able to move without loss of balance), for older people have been shown to reduce (Cavanaugh et al., 1999). The increased sway path length in older adults may offer, in part, an explanation for the decreases in sustained movement to limits of stability as with increased sway length there is a greater likelihood that at the point of maximal sway, the COP may exceed the limits able to be controlled within the BOS boundary.

Velocity of sway also increases as age increases (Berger et al., 2005a; Cavalheiro, Almeida, Pereira, & Andrade, 2009; Low Choy et al., 2003; Slobounov et al., 1998) particularly in the medio-lateral plane (Berger et al., 2005a; Lajoie & Gallagher, 2004). In their study of COM velocity-position predictions Pai and Patton (1997) found that as the COP moves closer to the boundary of the BOS the feasible velocities that can be controlled without loss of balance must reduce. Sway velocity has been found to be higher in fallers than non-fallers of similar ages (Lajoie & Gallagher, 2004; Lazaro, Gonzalez, Latorre, Fernandez, & Ribera, 2011; Melzer et al., 2004) and increases further in the absence of vision (Magnusson, Enbom, Johansson, & Pyykko, 1990; Melzer et al., 2004; Slobounov et al., 1998). It should be noted, however, that even in young adults sway velocity increases as the size of the BOS decreases and in the absence of vision (Slobounov, Slobounova, & Newell, 1997). This raises the possibility that increased sway velocity in older adults is linked, in part, to a reduction in the effective size of the BOS and/or reduced visual function although there is nothing in the current literature addressing this possibility.

The number of degrees of freedom may also impact on sway velocity results. In a study to compare ‘freeze’ stance (subjects instructed to prevent movement at hip and knee joints as much as able) with ‘free’ stance (no instruction to limit movement at any joint), Slobounov et al. (1997) found significantly reduced sway velocity in the ‘freeze’ condition. This condition effectively limits movement to the ankle joints resulting in fewer degrees of freedom of movement compared to the ‘free’ condition in which all joints of the lower limbs may move. This suggests that the instructions given to subjects can impact on findings. Some researchers request that the subject stand as still as possible while others do not include this in the instructions. In a comparison between two instructions, ‘stand quietly’ and ‘stand as still as possible’, Zok, Mazza and Cappozzo (2008) found that the different instructions produced different results in all measured parameters. The ‘stand quietly’ instruction was associated with greater variability thus producing higher standard deviation values.

The length of time a position is required to be maintained may also impact on test results particularly in inter-session reliability. In a systematic review of the literature to investigate evidence for test-retest reliability of COP summary measures when non-specific low back pain subjects were compared to controls, Ruhe, Fejer and Walker (2011) found a number of factors which influence reliability. They recommend that duration of testing should be at least ninety seconds when using summary measures as outcomes. However, this may not be realistic in some subject groups (for example, those with neurological pathologies) who have compromised balance function (Doyle et al., 2007).

While many researchers have used COP summary statistics such as sway path area, length and velocity to differentiate between age groups (Berger et al., 2005a; Cavalheiro et al., 2009; Patla et al., 1990; Slobounov et al., 1998), between fallers and non-fallers (Melzer, Kurz, & Oddsson, 2010) and between test conditions (Lord et al., 1991; Tanaka et al., 1996) in the study of balance, there seems to be no single parameter of sway that is considered the most sensitive for determining changes in balance related to ageing. Sway velocity has been shown to have the highest test-retest reliability of the commonly used sway parameters (Lafond et al., 2004; Moghadam et al., 2011; Ruhe, Fejer, & Walker, 2010; Salavati et al., 2009) while both sway velocity (Lafond, et al., 2004) and medio-lateral sway amplitude (Maki, Holliday, & Topper, 1994; Melzer et al., 2010) have been found to be sensitive measures for predicting future falls. However, in a group of subjects with hemiparesis in which sway velocity was the outcome parameter, Liston and Brouwer (1996) found that stance on a firm surface with the eyes closed had only moderate test-retest reliability while in the eyes open test reliability was poor. Thus it may be that different outcome parameters are needed for different pathologies.

Some researchers contend that COP summary measures do not provide the best interpretation of performance. These researchers believe that more sophisticated methods of analysis of COP traces such as stabilogram diffusion analysis (Collins & De Luca, 1993; Vette, Masani, Sin, & Popovic, 2010) and fractal measures (Thurner, Mittermaier, & Ehrenberger, 2002) offer better insights into the control strategies for balance and give a more sensitive analysis of data. Thurner et al. (2002) in comparing healthy young (N=57; age 30.5 ± 5.0 years) and older (N=19; age 62.9 ± 10.9 years) adults found that the COP movement patterns of the healthy young were highly complex while the older group showed much less complexity. They suggest that complex movement patterns allow better adaptation to rapidly changing environmental conditions with more regular, or less complex, patterns resulting in less stability. While these more complex analyses are useful in a research environment, they are less accessible to clinicians in a treatment environment.

2.3.4 COG location

The location of COG within the BOS is one of the factors which influences stability (LeVeau, 2011). Maintenance of balance in quiet stance is dependent on preservation of the COG within the BOS and although there is continual movement of the COG it generally remains towards the centre of the BOS (Spaepen et al., 1976). This gives the greatest freedom of movement within the area of the base without impinging on the boundaries. The closer the COG is to any of the BOS boundaries, the shorter the distance before the COG is at risk of exceeding the BOS requiring action to avert a loss of balance and a fall.

In a group of young adults used as controls, COG has been found to be located anterior to the ankle joint at approximately 61% of foot length measured from the first toe (Geiger et al., 2007). Schwab et al. (2006) compared simultaneous radiographic and force plate data to study changes in the gravity line location in relation to the vertebral column and the feet in three, healthy, subject groups (N=25 for each group) – young (29.8 ± 5.8 years), middle (47.3 ± 6.2 years) and elder (70.8 ± 5.2 years). They found that with increasing age, while the distance between the gravity line and the vertebral column increased (the vertebral column moved more posteriorly), the location of the gravity line with respect to the heels remained relatively constant. The posterior shift of the thoracic and lumbar vertebrae may explain the perception of a posterior shift of COG with respect to BOS by clinicians. These researchers suggest that the mobility of the pelvis through anterior or posterior tilt and antero-posterior translation is an important factor in preserving the gravity line position in relation to the BOS. Participants in this study were required to stand with the arms in 45° of shoulder flexion potentially impacting on COG location in relation to both BOS and vertebral column. Also in this study the ‘heel’ was defined as the posterior most triggered force-plate sensor so that actual location of COG relative to anatomical landmarks of the feet was not identified.

The influence of increasing trunk flexion has also been found to cause no change in the mean COP location in a group of young adults (Saha et al., 2007). Despite the increase in trunk flexion, mean COP location within BOS was preserved through an increase in plantar flexion and hip flexion ranges. In another study, however, the position of the cervical spine has been found to have an effect on COG location with a head flexed position resulting in a more posterior COG within the BOS (Buckley et al., 2005). For older adults, in the presence of reduced somatosensory inputs, there is likely to be a more persistent neck-flexed posture when walking so as to enhance visual inputs of the environment and for foot placement especially when walking in complex environments. Further, if there is an unexpected shift of the COG to an even more posterior position, there may not be the spatial or temporal capacity in older adults to avert a backwards loss of balance.

Flexibility of the ankle joint, particularly for dorsiflexion, may also impact on location of the COG within the BOS. In a study looking at the response to prolonged stretch to the calf muscles, Rougler, Burdet and Genthon (2006) found that increased calf length as a result of prolonged stretch of the plantar flexor muscles, results in a forward shift of the COP. Conversely the COP moves more posteriorly in subjects in whom the triceps surae has been fatigued (Berger, Regueme, & Forestier, 2011). Decreased dorsiflexion range has been implicated in reduced functional balance (Mecagni et al., 2000; Menz, Morris, & Lord, 2006) and in falls (Menz et al., 2005; Nitz & Low Choy, 2004) in older adults.

Others have considered loading in the medio-lateral direction. Two studies found increased loading on the right foot (Haddad et al., 2011; Schwab et al., 2006) when standing on a firm surface with feet comfortably apart. Another group considered the pressure under the plantar surface of the left and right great toes when standing on a firm surface but with feet together (Romberg position) and observed greater pressures under the great toe of the non-dominant (left) foot (Tanaka et al., 1996). In this study the dominant foot was defined as the preferred kicking leg for the subject which, in this study, was the right foot.

In a study to assess postural preparation for movement, Mille and Mouchnino (1998) looked at anticipatory postural adjustments for three different initial COG positions in the medio-lateral direction prior to lifting one leg in standing. They found that the location of the initial COG was linked to the duration of the anticipatory postural adjustments and the duration of the initial COP thrust with a longer duration of COP thrust for a larger distance of COG movement. Centre of pressure thrust in this study was considered to be the early displacement of the COP towards the moving leg to initiate the shift of the COG to the supporting leg. A longer COP thrust duration may present problems for older adults. In a study of platform perturbations at varying velocities, Inglis, Horak, Shupert and Jonesrycewicz (1994) found that in the presence of reduced somatosensation there is altered ability to scale magnitude of response to magnitude of perturbation in both velocity and amplitude. Although this study design related to surface (external) perturbation, it may be that there are similar difficulties for older adults for internal perturbations.

Location of COG is particularly relevant for older adults because of the changes in many of the systems involved in managing the body's response to movement. Although age on its own may not result in reduced postural control (Anson et al., 2017; Barbosa & Vieira, 2017) there is ample evidence of reduced inputs from sensory systems (Baloh et al., 2003; Lord et al., 1991; Menz et al., 2005) and slowed central processing (Lockhart et al., 2005; Yordanova et al., 2004) as well as deficiencies in the musculoskeletal system (Endo, Ashton-Miller, & Alexander, 2002; Johnson, Mille, Martinez, Crombie, & Rogers, 2004; Low Choy et al., 2008) with ageing. When multiple systems become compromised, a COG which is located closer to the boundary has the potential to be associated with a higher risk of instability. Although COG location was not identified, Teasdale, Stelmach and Breunig (1991) found that older adults spent more time away from the mean COG position than young particularly when standing on a compliant surface both with and without vision. Antero-posterior COG location has been linked to the incidence of falls in older adults. Merlo et al. (2012) found that COG location in the antero-posterior direction was associated with fall history in stance on a firm surface with the eyes opened or closed and also for stance on a foam (soft) surface with the eyes open.

2.4 Base of Support

There are three concepts which have been studied that relate to the BOS in bipedal stance. The first is usually referred to simply as the BOS although it may be referred to more specifically as the geometric BOS. This is 'the area defined by the outer boundaries of the feet at the surface of contact' (Slobounov et al., 1998) and is related to the size and position of the feet. The second is the area over which the COP moves in quiet stance which is referred to as the sway area. Finally, there is the concept of the area representing the maximum limits (or limits of stability) within which the COP can move without loss of balance. Slobounov et al. (1998) tracked the limits of stability in anterior, posterior, lateral and diagonal movements of the COP to provide an estimate of the functional boundaries of the BOS. They refer to this area as the functional stability boundary (FSB). It has been found that, for all age groups, the area of the FSB is less than the BOS area when standing on a firm surface (Slobounov et al., 1998).

Another term used in relation to the BOS is the functional base of support (FBOS) (King et al., 1994). This is defined as the proportion of the BOS in the antero-posterior direction used during sustained maximal movement in forward and backward lean divided by the subject's foot length. In contrast to the FSB, the FBOS represents movement in just one plane (antero-posterior) and is a measure that relates to distance rather than to area. These increases are greater in older than in younger subjects. The area of the BOS is an important consideration in postural stability as it determines the available space within which the COG can move (Horak, 2006). When the size of the BOS is reduced, for example standing on one foot compared with standing on two feet, sway velocity (Low Choy et al., 2003) and path length (Amiridis et al., 2003; Era et al., 2006) both increase. These increases are greater in older than in younger subjects. Other aspects of BOS such as the shape and the surface compliance can influence sway parameters in both young and old adults.

The shape of the BOS has implications for the available path length. For example, stance with the feet comfortably apart results in a reasonably long medio-lateral path dimension while the antero-posterior path length is limited to the length of the foot. However, for stance with the feet heel-to-toe (sharpened Romberg or tandem stance) the medio-lateral path length is reduced to approximately the width of one foot while the antero-posterior length is related to the length of the two feet end to end. The feet-apart position has greater stability in the medio-lateral direction while the tandem position has greater stability in the antero-posterior direction (Hasan et al., 1996b).

It has been proposed also that a change in the BOS shape results in a change in strategy to maintain balance, that is, different control mechanisms are required. When standing with feet apart the predominant strategy employed to control movement in the antero-posterior direction is the ankle strategy while the hip load/unload strategy is employed for medio-lateral control (Winter et al., 1996). However, the use of these strategies to control antero-posterior and medio-lateral sway changes when the foot position is changed. Winter et al. (1996) noted that stance in the tandem position resulted in a change to these strategies with an ankle strategy being used more for the medio-lateral direction and the hip load/unload used for control of antero-posterior movement.

An additional feature to include when considering BOS is the surface compliance. Researchers have found that a more compliant surface results in increased velocity of sway for both young (Haibach, Slobounov, Slobounova, & Newell, 2007) and old (Illing et al., 2010; Low Choy et al., 2003) adults. A more compliant surface also impacts on the FSB even in young adults with reduced boundaries evident when standing on a surface which has greater compliance (Haibach, et al., 2007). Patel, Fransson, Lush and Gomez (2008) compared torque variance when subjects stood on three different foam densities (firm, medium and soft) with eyes open and eyes closed. They found that there was greater instability when standing on firm foam than on soft foam and that there was greater variance in the lateral direction than in the antero-posterior direction. From both a clinical and a research perspective, as stance on firm foam is less stable than on soft foam (Patel et al., 2008), the degree of compliance of the surface of the BOS also needs to be considered when interpreting or comparing assessments as well as in designing treatments.

2.4.1 Base of support and ageing

Several studies have shown decreases in FBOS with ageing (King et al., 1994; Slobounov et al., 1998; Tanaka et al., 1999) for stance on a firm surface. King et al. (1994) found that subjects under the age of 60 years used a mean sway path length of 60% of available foot length while those over 60 years used a mean of only 42%. They also noted much greater variability of results for the older group. This reduction in forward movement has implications for stability in activities that require, for example, forward arm reach. Endo et al. (2002) also found reduced FBOS in older compared with younger subjects. They reported their findings as a percentage of functional toe length and found that older adults used 28.3% less of available toe length than younger adults in the Functional Reach Test (Duncan, Weiner, Chandler, & Studenski, 1990) and linked this finding to a reduction in toe-flexor strength. In their study on FSB, Slobounov et al. (1998) found that the area within the FSB decreases with age and that there is a further reduction in area in the absence of vision.

The reduced size of the FSB in older adults (Baloh et al., 2003; Tanaka et al., 1999) impacts on the area or space available for movement of the COG. Reduction in the size of the geometric BOS, for example by standing on just one foot, results in higher COG movement velocities and poorer balance performance in older adults (Amiridis et al., 2003; Illing et al., 2010; Low Choy et al., 2003). This is also the case when there is a change in the shape of the BOS (such as in tandem stance) (Amiridis et al., 2003; Era et al., 2006). In addition to higher sway velocity, as the size of the BOS decreases (e.g. from feet apart to Romberg to single limb stance) sway path length increases. This is the case in both young and old subjects but the increase and variability is greater in older subjects than in the young (Amiridis et al., 2003).

In standing, the size and shape of the geometric BOS is affected by physical deformities such as bunions, hammer and mallet toes which are more common in older feet (Menz & Lord, 2001). These deformities influence the size and shape of the forefoot in particular. Older age groups show difficulty in using the forefoot (especially the toes) in maintaining balance on two feet (King et al., 1994; Tanaka et al., 1999) and this has the effect of reducing the FBOS. Older adults also seem to be more hesitant to use a smaller BOS, for example, standing on one foot or rising on to the toes when reaching forward (Cavanaugh et al., 1999). In their study on ageing feet, Menz and Lord (2001) found that 87% of subjects (aged 75-93 years) had at least one foot problem ranging from toe deformities to ulcers, corns and deformed nails. Certainly physical deformities will contribute to an altered BOS but the presence of other pathologies and the presence of pain also will impact on the FSB.

At the same time as the BOS is decreasing in older people, the area over which the COP moves in quiet stance increases (Berger et al., 2005a; Slobounov et al., 1998) producing a higher ratio between area of COP and area of BOS and a higher frequency of COP 'close-to-boundary' incidents (Slobounov et al., 1998). This results in greater control requirements in a group whose systems are less able to manage that control. Reduced somatosensory (Baloh et al., 2003), visual (Cummings et al., 1995; Ivers, Cumming, Mitchell, Simpson, & Peduto, 2003) and vestibular (Paige, 1994; Park et al., 2001) function as well as longer response times (Allum et al., 2002; Lockhart et al., 2005) in older adults, mean that the COG has moved much closer to the boundary before action can be taken. An additional problem is that the necessary corrective action is produced by a motor system which has reduced force production capacity available (Lockhart et al., 2005) to arrest movement. Pai, Rogers, Patton, Cain and Hanke (1998) found in their studies of predictive models of loss of balance and the need to take a step to recover balance, that a step became imminent when the COM came within 10% of the boundary of the BOS. This might suggest that for older adults with a reduced FSB and FBOS and greater sway path displacements, the need to step occurs sooner when an anterior shift of COG is required such as in forward reach.

Increased surface compliance also results in changes in balance for older adults. It is associated with a greater sway area (Lord et al., 1991), sway velocity (Schieppati, Hugon, Grasso, Nardone, & Galante, 1994) and a greater proportion of time is spent further from the mean COP location compared with young adults (Teasdale et al., 1991). In men, there is a significant reduction in stability evident in the 60s when standing on a compliant surface with eyes closed (Illing et al., 2010) while in women reduced stability for this condition is evident in the 50s (Low Choy et al., 2003).

The size, shape and surface of the BOS becomes relevant to the function of older adults when walking on grass, managing stairs, reaching for items on shelves or when there is a requirement to reduce width of BOS such as in crowded or cluttered environments. Function under these conditions may be further compromised if vision is poor such as in the presence of reduced lighting.

2.5 Conclusions

The characteristics of COG in relation to BOS are always of relevance to clinicians when considering stability in standing. Balance is the result of the interaction of multiple systems including sensory (somatosensory, visual, and vestibular), motor (central nervous system factors including central processing speeds and nerve conduction speeds), musculoskeletal (joint ranges and muscle strength) and cognitive capacity. The integrity of balance may be impacted by reduced performance in one or many of these systems. Thus, based on the findings of each individual assessment, intervention strategies must be multifaceted ensuring that all of the impairments have been addressed. In the clinical setting an understanding of balance is derived in part through assessment of steady state balance incorporating changes in BOS size (e.g. tandem stance, or single leg stance positions), altered somatosensory (via a compliant surface) and altered visual (open or closed eyes) test conditions.

Although movement characteristics of COG are well studied there remain some areas which require further study. There is less information relating to the location of COG within BOS and nothing which provides a measure of COG location that might easily be utilised in the clinical setting. For older adults, reduced sensory inputs, reduced central processing speeds, increased reaction times and compromised musculoskeletal system have been identified in the literature as part of the ageing process. These, in combination with increased sway velocity and reduced BOS, all contribute to the potential for greater vulnerability to loss of balance if the COG is habitually located nearer to any boundary of the BOS in older adults.

A reliable, objective method of measuring the location of COG which is easily applied in clinical settings needs to be developed and its sensitivity to change tested under varying conditions of sensory input and BOS.

CHAPTER 3

Materials and Methods

This chapter describes the study methods, tests and equipment used for the studies in this thesis. In addition to providing explanations for equipment and test choices, the challenges of endeavouring to match data collection and analysis methods on a commercially available force plate system with inbuilt software, with the Kistler force plate system are also discussed.

3.1 Introduction

The use of force plate technologies in research settings is well established. Force plate systems track centre of pressure (COP) movement within the base of support (BOS) and the centre of gravity (COG) can be estimated from this COP data. This provides objective data on, for example, sway (or movement) path length, path direction, area and velocity in both the antero-posterior and the medio-lateral planes in both static and dynamic tests. Methods that are used to analyse COP data derived from force plates are highly variable with common examples including root mean square of a range of measures, mean velocity (both total and for antero-posterior and medio-lateral separately), sway area (both total and 95% confidence ellipse) and either maximum or mean sway path length. These measures of sway velocity, sway area and sway path length are also referred to as 'summary measures' of sway. Of the summary measures widely used in research, mean velocity of sway is considered to provide the most consistent results for inter- and intra-session reliability in both children (De Kegel et al., 2011) and older adults (Lafond et al., 2004; Moghadam et al., 2011).

However, there has been some discussion in the literature on the best way to analyse these summary measures. Methods such as generalizability theory (Clark, Rose, & Fujimoto, 1997; Doyle et al., 2007) and fractal analysis (Duarte & Zatsiorsky, 2000) are just two examples. Researchers have also investigated the optimal test duration and number of test repetitions to ensure reliability of outcomes. Despite extensive research there is still no gold standard for the most reliable way to interpret the data from force plate systems (Ruhe et al., 2010).

In a review of the literature to investigate evidence for the test-retest reliability of COG summary measures (for example, sway path length, sway area and sway velocity), Ruhe et al. (2010) found a number of factors which influence reliability. They concluded that COP mean velocity generally had good test-retest reliability and that eyes closed tests generally had greater reliability than eyes open tests. In addition, they recommended that duration of testing should be at least ninety seconds when using summary measures as outcomes. Others, however, believe that sway velocity must be considered in conjunction with direction and distance from a subject's limits-of-stability boundary (Haibach et al., 2007; Hof, Gazendam, & Sinke, 2005; Slobounov et al., 1998) as velocity alone is not necessarily an indicator of instability.

There is less evidence relating to test-retest reliability and test procedures for antero-posterior COG location. One study has found excellent test-retest reliability (ICC=0.83) of the antero-posterior COG mean location for a range of test conditions (both firm and compliant surfaces with eyes open and eyes closed) (Benvenuti et al., 1999) in a group of rehabilitation patients (age range 62-86 years) with various pathologies, for a forty second test duration. Testing in that study was conducted on three occasions with the second session conducted four hours after the first and the third session conducted one week after the first. In a study of young adults standing on a firm surface with eyes open, Carpenter et al. (2001) noted that in a test length of 120 seconds (divided into 15, 30, 60 and 120 second samples) the mean COP location in the antero-posterior plane was remarkably consistent regardless of which sample was analysed. This suggests that for the mean location of COP, test time is less critical.

The use of force plate and pressure plate technology in clinical settings provides clinicians with an opportunity to measure COG location objectively. The studies undertaken in this thesis were devised to develop a novel method of recording centre of gravity location in bipedal stance in healthy adults using force plates commonly found in clinical practice.

3.2 Study methods

The methodology is described for the studies based on the data sets used.

3.2.1 Studies 2 and 3 (Chapters 4 and 6)

Design

To address Aims 2 (Study 2, Chapter 4) and 4 (Study 3, Chapter 6) (refer to Figure 1.1), data collected from the Longitudinal Assessment of Women (LAW) Study was analysed. This is a multidisciplinary cross-sectional observational cohort study which commenced in 2000 (Khoo, O'Neill, Travers, & Oldenburg, 2008). Five hundred and eleven women with an age range of 40-80 years were enrolled in the study with testing conducted in years 1, 3 and 5 of the study. Data continues to be collected for some aspects of this study. The data analysed for Studies 2 and 3 were collected at the initial assessment in 2001 at which time participants undertook the modified Clinical Test of Sensory Interaction in Balance (mCTSIB) on the Basic Balance Master (BM) in addition to a range of other measures (for example ankle range of movement and movement speed).

Participants

The data for Studies 2 and 3 were drawn from the LAW Study for which the author was a research assistant participating in the tests of balance. The participants were recruited from the electoral roll in south-east Queensland comprising urban as well as rural communities. One thousand, five hundred and ninety-eight of the fifteen thousand eligible women who were aged 40-80 years were contacted by mail and invited to participate in the study. From the 598 women invited to participate, 511 women were recruited for the study (Khoo et al., 2008). In order to focus on the attributes of normal ageing, women were excluded from the balance components of the study if they had dementia or any neurological conditions or major musculoskeletal pathologies that would impact on balance. The women were divided into four age groups: 40-49, 50-59, 60-69 and 70-80 years.

3.2.2 Studies 4 and 5 (Chapters 7 and 8)

Design

To address Aims 5 (Study 4, Chapter 7) and 6 (Study 5, Chapter 8) a cross-sectional observational study was designed to collect data from a subset of a healthy adult population.

Participants

Recruitment of participants was achieved via organization newsletters, information emails to staff within the School of Health and Rehabilitation Sciences at The University of Queensland, flyers on University notice boards as well as social media and personal (both social and work) contacts. The study was designed to collect data from 89 participants in order to achieve a power of 80% with an effect size of 0.3 standard deviation within each age group and 5% level of significance (discussed further in Section 3.4, Statistical Methods). Time constraints resulted in a total of 81 participants (31 male) with different numbers in each age decade. As a result of this smaller number of participants the age grouping was adjusted to incorporate just three age groups (30-49 years, 50-64 years and 65-80 years). It has been demonstrated that changes in balance are evident in the fifties (Low Choy et al., 2003; Nitz & Choy, 2008) and sixties (Nolan et al., 2010) for women and men respectively. Thus participants were grouped to incorporate age ranges prior to major changes in balance (30-49 years), ages during which changes have been demonstrated in both women and men (50-64 years) and ages beyond this (65-80 years).

Inclusion criteria for participants were broad with all independently mobile, healthy, community-dwelling adults aged 30-80 years being eligible to participate. Exclusion criteria included the presence of any pathology which would be known to affect balance, for example, neurological diagnoses or current problems with dizziness, known sensory or vision loss, or major joint pain. More detail on the recruitment process and participant characteristics is provided in Chapter 7.

3.2.3 Pilot studies (Chapter 5)

Although test-retest reliability has been demonstrated for the BM in the mCTSIB for the composite mean velocity (mVel) across the four tests in children (Geldhof et al., 2006) and for the mVel of the firm surface, eyes closed test in adults with stroke (Liston & Brouwer, 1996), no studies were located which investigated the repeatability of COG location results produced for the mCTSIB on the BM. Separate studies by Schwab et al. (2006) and Carpenter et al. (2001) have suggested that the mean location of the COG in the antero-posterior plane remains relatively constant even in older adults although the data from these studies were collected on other force plate systems. Benvenuti et al. have demonstrated high intra-class correlation coefficients for COG mean location for the four test conditions of the mCTSIB in older adults (N=36; age range 60-86 years). In order to address this, a pilot study was conducted to assess between session repeatability on the BM (Chapter 5).

As data for Studies 4 and 5 were collected using a different force plate system (see section 3.3.2 below), an additional preliminary study was also conducted to assess the comparability of COG location results between the BM and Kistler force plate systems for within-session testing on a small number of participants. This is also presented in Chapter 5.

3.2.4 Measurements

(i) Demographics

General measurements (Figure 3.6) such as height and weight, as well as physical activity levels (Hirvensalo, Rantanen, & Heikkinen, 2000) and number of prescription medications were recorded. The Physical Activity Levels scale (Hirvensalo et al., 2000) has been shown to provide an accurate measure of physical activity (Webster, Khan, & Nitz, 2011). The Physical Activity Levels are shown to the participant who is then asked to nominate which level is currently most applicable. The use of four or more prescription medications as the highest of the three medication categories in these studies was selected as this level of medication use has been found to be associated with falls incidence (Richardson, Bennett, & Kenny, 2015; Robbins et al., 1989). Table 3.1 shows categories for these data that were utilized in analyses.

Table 3.1 Description of Physical Activity Levels and Medication categories

Parameter	Descriptor
Physical Activity Levels	
1	Moving only for necessary chores
2	Participating in outdoor activities 1 or 2 times per week
3	Participating in outdoor activities several times per week
4	Exercising 1 or 2 times per week to the point of perspiring or puffing
5	Exercising several times per week to the point of perspiring or puffing
6	Keep-fit heavy exercising or sport several times per week
Medications	
1	No prescription medications
2	1-3 prescription medications
3	4 or more prescription medications

(ii) Centre of gravity location

The measurement used in this thesis was the location of COG in the antero-posterior plane (method of measurement described in Chapter 4). There were a number of reasons for this choice. Firstly, there is anecdotal evidence that as age increases the COG in quiet stance tends to shift more posteriorly. Secondly, there is limited evidence in the literature relating to the behaviour of COG location in the antero-posterior plane as age increases in healthy, independently ambulant adults, particularly under different sensory conditions. Thirdly, the COG location relative to the boundaries of the BOS is one of the factors influencing stability. This being the case, greater knowledge about this relationship and whether it changes with increasing age and altered test conditions is a relevant factor in understanding balance integrity. Finally, as age increases sway ranges and speeds increase while stability boundaries decrease resulting in potentially more 'close to boundary' incidents than in young adults. This suggests that a better understanding of COG location may be a more critical factor in the balance of older adults than it is in young adults.

In this thesis the location of the COG is identified as being anterior or posterior of each subject's predicted centre of balance. The centre of balance in standing is the point within the BOS over which the subject's COM would fall in the absence of any sway. The method used to determine this centre of balance is discussed in section 3.3.1.

(iii) Test choices

A range of tests which are commonly used in balance assessments were conducted as part of the assessment of the participants. These included, for example, the Timed Up and Go Test and the Step Test as well as strength and sensory tests (vision, cutaneous sensation and vibratory sense). However, only the tests relevant to the development of the categorical method of recording COG location in this thesis are being discussed in this section.

The tests used in this thesis were (i) a modified version of the Clinical Test of Sensory Interaction on Balance (CTSIB) (Shumway-Cook & Horak, 1986), (ii) standing with feet together eyes open (FTEO) then eyes closed (FTEC), and, (iii) standing on one foot (single limb stance) for both the left (LSLS) and right (RSLS) foot with eyes open.

(a) The mCTSIB was chosen primarily because this was the test battery for which start location of COG is recorded on the BM and formed the basis for the development of the categorical method developed in the thesis to record COG location. The CTSIB is a battery of six tests used frequently in clinical balance assessments. The tests manipulate sensory inputs via the use of firm or foam surfaces (manipulation of proprioceptive inputs) under with- and without-vision (manipulation of visual inputs) and visual conflict conditions. The modified format (mCTSIB) uses only four of the six tests: firm surface eyes open (FiEO) and closed (FiEC), and foam surface eyes open (FoEO) and closed (FoEC). The CTSIB has been shown to be a valid measure of disequilibrium in older adults (Benvenuti et al., 1999). Older adults are less able to preserve balance when vision and/or the surface are compromised compared with young adults (Era et al., 2006; Low Choy et al., 2003; Nitz et al., 2013). Stance on a foam surface is considered more difficult than stance on a firm surface as the proprioceptive input from foam is less reliable than that on a firm surface. This results in greater reliance on the visual and vestibular systems to resolve the conflict that results when the proprioceptive input is unreliable. In combination with alterations to visual inputs, these tests assist the clinician in determining an individual's reliance on each of the three sensory systems (somatosensory, visual and vestibular) and the ability to resolve conflict that may arise between the systems in some environments.

The COG start location from these tests was analysed in Study 3 (Chapter 6). This addressed Aim 4: To test whether the data obtained when applying this method of categorising COG location is sensitive to changes under mCTSIB test conditions and with age in a healthy adult population. The proportion of participants with an anterior COG location for both the start location and the mean location of COG from these tests was analysed as part of Study 5 (Chapter 8). This contributed to Aim 6: To compare the start location and mean location of COG obtained simultaneously for the mCTSIB conditions and the varying BOS test conditions.

Both an increase in sway velocity and an increase in failure rates (that is, a loss of balance) have been identified for older adults as the tests progress from the least challenging (FiEO) to the most challenging (FoEC) test of the mCTSIB (Berger et al., 2005a; Low Choy et al., 2003). This increase in sway velocity has also been linked with falls (Nitz et al., 2013; Pajala et al., 2008). An association between COG location and falls has also been identified for the mCTSIB with single fallers showing a more anterior COG position for the FiEO, FiEC and FoEO test conditions (Merlo, et al., 2012).

Test-retest reliability has been demonstrated for the mCTSIB when subjects are tested while standing on force plates, using mean sway velocity as the outcome, in both young (De Kegel et al., 2011; Tesio, Rota, Longo, & Grzeda, 2013) and older adults (Benvenuti et al., 1999; Moghadam et al., 2011). However, Jorgensen et al. (2012) found that sway velocity results can differ according to the time of day that testing is conducted. It is not known whether COG location is similarly affected by time of day although Benvenuti et al. (1999) demonstrated high intra-class correlation coefficients (ICC) for COG location in the antero-posterior plane for a range of test conditions which encompassed manipulation of vision and surface.

(b) In the FT and SLS tests the size of the BOS is reduced. When the BOS is smaller the COG is effectively closer to the boundaries resulting in an increased risk of loss of balance. Older adults have been found to have greater sway than young adults (Amiridis et al., 2003) and are less able to control balance than younger adults (Low Choy et al., 2003) when the BOS is reduced. The start location of COG from these tests was analysed in Study 4 (Chapter 7) to fulfil Aim 5: To test whether this categorisation of COG location is sensitive to the varying BOS test conditions of FA, FT and SLS. Both the start location and the mean location of COG from these tests was analysed in Study 5 (Chapter 8) to contribute the Aim 6 as described above.

3.2.5 Procedure

In Studies 2, 3, 4 and 5 all data were collected in one test session. The use of one test session was appropriate for the cross-sectional observational design of the studies as this provides a snapshot of performance at one point in time (Thiese, 2014).The test session in the LAW study (providing the data for Studies 2 and 3) lasted one hour while the test session for data collection relating to Studies 4 and 5 lasted one-and-a-half hours. The session commenced with a short interview to gain information on date of birth, activity level and number of prescription medications. Height and weight were also recorded. Each subject was required to repeat three, ten second trials for each of the four tests of the mCTSIB. The trials were run consecutively in order of difficulty progressing from FiEO to FiEC to FoEO to FoEC. This would be the usual protocol in clinical testing. Also it is safer to progress through the test conditions in increasing order of difficulty as some participants may not manage the foam surface tests (in particular, the FoEC test condition). Prior to the foam pad being placed onto the force plate, the subjects were asked to stand on the foam to familiarize themselves with the different surface. The instructions given once the subject was positioned on the force plate, were, *'I'd like you to stand quietly with your arms by your side and look straight ahead'*. The added instruction of '*Please close your eyes when you are ready'* was added for the eyes closed conditions. Timing then began when the researcher observed the eyes to be closed.

The feet together eyes open (FTEO) and eyes closed (FTEC) tests and the SLS tests were conducted on the firm surface only. The procedure was as for the mCTSIB tests with three, ten second trials. While the instructions for the FT tests were the same as for the mCTSIB, those for the SLS differed. The instructions were, *'I'd like you to stand on your Left/Right foot. During the test your left /right leg must not touch the other leg. Please stand with your arms by your sides and look straight ahead.'* The position was also demonstrated by the researcher.

In Study 5 COG locations (distance in millimetres from the medial malleolus) were recorded: (i) location at the commencement (COG start location) of each trial, and, (ii) the average location (mean COG location) for each test trial. The conversion of these measures from a distance to a categorical measure is discussed in Sections 3.3.1 and 3.3.5 below.

3.3 Equipment

The force plate systems used in the studies in this thesis were the NeuroCom Basic Balance Master® 6.1, NeuroCom, Oregon (BM) (Studies 2 and 3 (Chapters 4 and 6)) and the Kistler force plate (Studies 4 and 5 (Chapters 7 and 8)). The BM was selected for two reasons: (i) it is a system used in a number of rehabilitation clinics for both assessment and treatment of clients, and (ii) it provides some COG start location results (only for the mCTSIB). However, there were limitations when testing on the BM. Although the FA and SLS tests could be conducted, there was no protocol for FT tests and no COG location data is provided for the FA and SLS tests on this system. A further limitation was that the mean location data is not available, only start location. Thus there was no way to compare start location and mean location outcomes. Use of the Kistler force plate allowed an existing software programme to be altered in order to include both start location and mean location results for COG to be recorded. This was the case for the mCTSIB, stance with feet together and stance on one leg.

3.3.1 Balance Master (BM)

This commercially available force plate system is easy to use in both research and clinical settings. It has a range of static and dynamic tests for use in assessment and also has available some protocols for balance training. There are a range of systems available including the Basic Balance Master, the Balance Master Pro and the Smart Balance Master. While all have an integrated software programme to provide the researcher/clinician with results in user-friendly formats for a range of static and dynamic tests, some have additional features (for example, a tilt capability for the force plate and a movable visual surround) to allow for more complex tests to be carried out.

The BM (Basic Balance Master 6.1) used in Studies 2 and 3 has a 46 x 46 x 5cm platform (Figure 3.1) consisting of two 23 x 46cm foot plates which are joined by a centrally located pin. There are four transducers (two for each plate) which are positioned at the four corners of the 46 x 46cm platform. A piece of covered, closed cell high density (3.75 lb/ft^3) foam measuring 46 x 46 x 13cm is also supplied for use in the compliant (foam) surface tests. Both the firm and foam surfaces are marked with an identical grid containing a series of markings (Figure 3.1) to standardize the distance between the feet (small (S) at 76-140cms, medium (M) at 141-165cms and tall (T) at 166-203cms, based on the height of the subject) in standing and the position of the medial malleoli of the ankles.

Figure 3.1 Image of the Basic Balance Master system. The foam cushion provided with the equipment is shown propped up behind the firm surface force plate.

The BM presents COG location results as a diagram (Figure 3.2) rather than as a numeric measurement. Each recording on the diagram represents the location of the COG at the start of each 10 second trial (there are 3 trials for each test condition). The horizontal line, or x-axis (90° - 270°), on the diagram represents the zero point (that is, the predicted centre of balance) for antero-posterior movement (refer to Section 3.3.4 for further discussion of this). The position for this line is determined by the location of the predicted centre of balance for each individual based on the individual’s height.

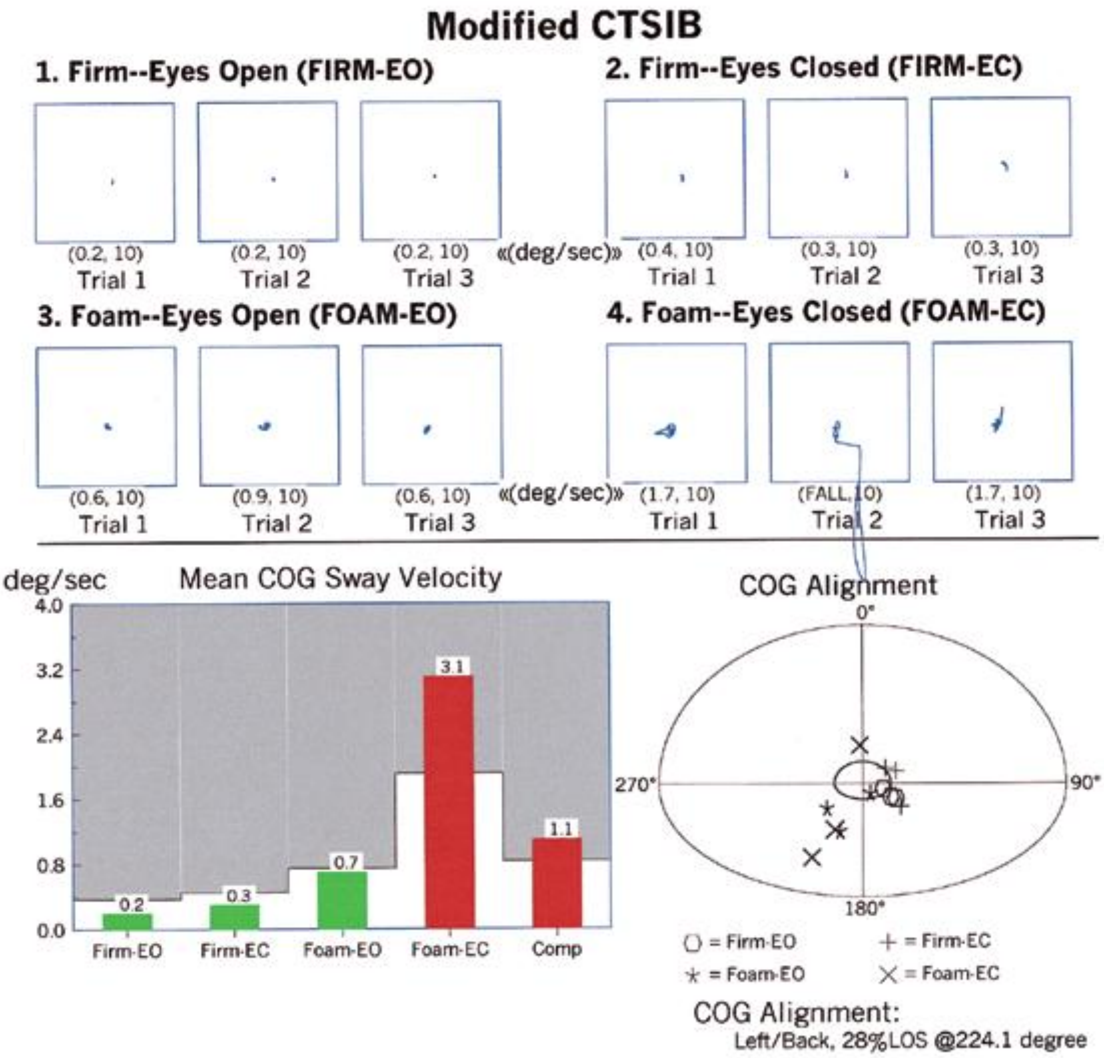

Figure 3.2 Example of the presentation of results for the modified Clinical Test of Sensory Interaction on Balance on the Balance Master. The sway trace is shown at the top while the lower diagrams depict mean sway velocity (left) and centre of gravity location at the commencement of each test trial (right).

3.3.2 Kistler force plate

Although the Kistler force plate was used for Studies 4 (Chapter 7) and 5 (Chapter 8), any force plate or pressure plate system in which the programme can be personalised could have been used.

The Kistler force plate consists of a 40 x 60 cm stable surface. Matlab (MathWorks®) was used for data extraction. This force plate system was used for Studies 4 and 5 to facilitate programme modifications so that both start and mean COG location could be recorded for each test trial of the mCTSIB. The intention was to replicate as closely as possible the BM system with the Kistler force platform. Email communications with the BM manufacturers initially in January 2013 provided assurance that the horizontal x-axis provided in the results diagram on the BM corresponded to the line between the medial malleoli. Based on this information the software programme for Studies 4 and 5 using the Kistler force plate was designed with the medial malleoli as the zero point for antero-posterior balance. A tracing was taken of the markings on the BM and this was affixed to the Kistler force plate (Figure 3.3) to ensure consistent distance between the heels and also the alignment of the medial malleoli in line with the zero point of balance for the antero-posterior plane. The foam used on the BM, with the appropriate foot position markings, was used for the compliant (foam) surface tests conducted on the Kistler force plate.

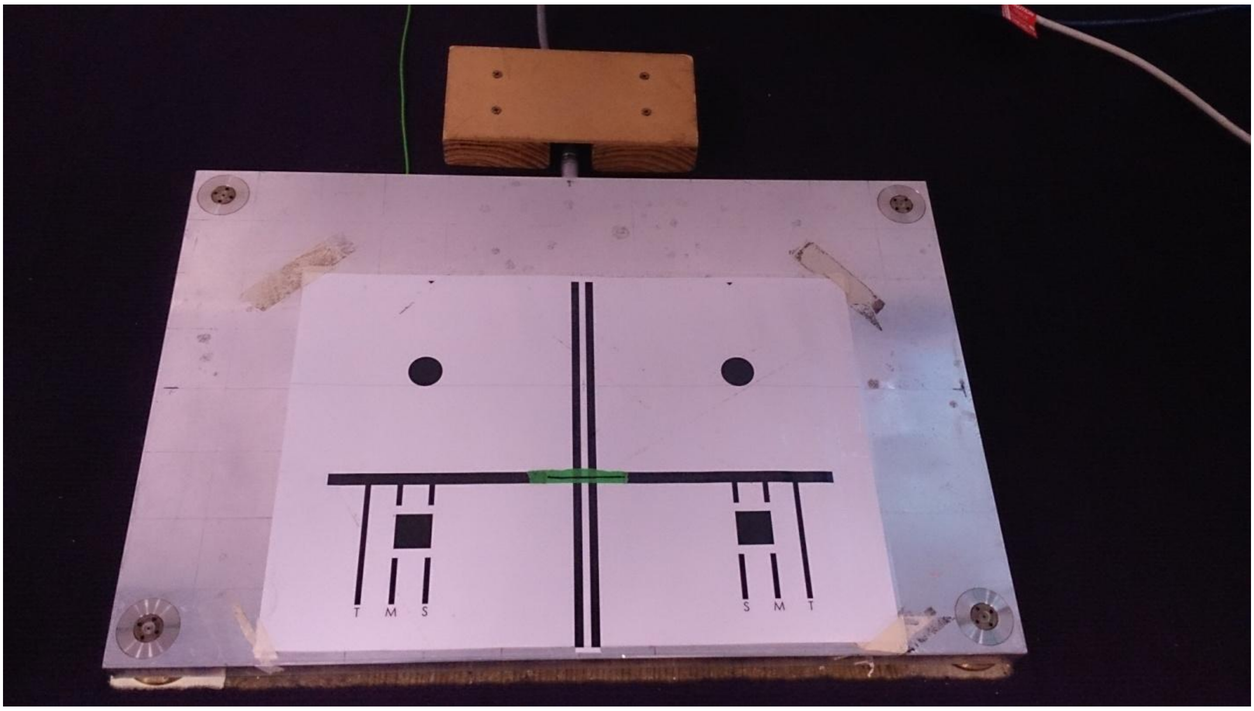

Figure 3.3 Template of Balance Master feet alignment positioned on Kistler force plate for firm surface test conditions.

3.3.3 Comparability between BM and Kistler Data

There were some difficulties in attempting to replicate the BM representation of COG location on the Kistler force plate. These related to, (i) the relationship between the depicted zero point on the results diagram (the intersection of the horizontal and vertical axes, Figure 3.2) and the anatomical position of the zero point in relation to the feet (the medial malleoli), and, (ii) confusion over whether the COG locations of each test trial depicted on the diagram of the BM represented the average or start location of COG for each trial.

A pilot study was conducted with a subset of participants from Studies 4 (Chapter 7) and 5 (Chapters 8) who repeated the mCTSIB testing on both the BM and the Kistler systems in the same test session, to compare levels of agreement for the COG location on the BM and the Kistler. This comparison was necessary to ascertain whether the adjustments made to the data from the Kistler force plate were appropriate. These results are presented in Chapter 5.

3.3.4 Zero point representation

It became apparent as testing progressed for Studies 4 and 5, that the results produced in testing on the Kistler in these studies were quite different from data derived on the BM from earlier studies of ageing in women (N=511) (Low Choy et al., 2003) and men (N=106) (Nitz & Fu, 2009).

The use of the medial malleoli as the zero point for antero-posterior balance appeared to be the source of the discrepancy. Further communication with the BM manufacturers and BM technicians in May 2015 produced two different responses: (1) the zero point is located two inches anterior to the medial malleoli, and, (2) the zero point is an imaginary point depicting the predicted centre of balance for each subject based on the subject's height. Initially the data from the Kistler force plate were adjusted based on definition (1) above of the zero point, but the results obtained suggested that this adjustment was inconsistent with the data from the earlier studies above. Further, a correction of two inches for each and every subject did not take into account the different foot lengths or subject heights. Therefore advice was sought on a mathematical solution to find the predicted centre of balance for each individual based on the subject's height. Based on the diagram provided in the BM Operator's Manual (Figure 3.4) it was determined that the appropriate correction should be $0.5527 H \sin 2.3°$ where H equals the subject's height in millimetres. This provides the corrected distance anterior to the malleoli for the predicted centre of balance and became the reference point for categorizing the COG location for each test as being anterior or posterior. The development of this method is presented in Chapter 4.

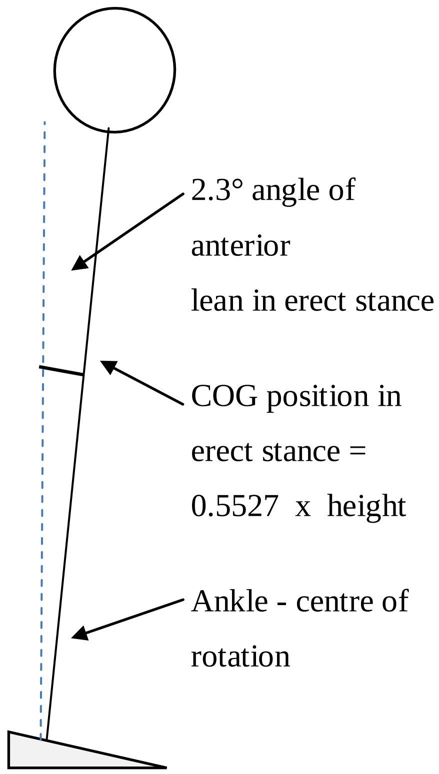

Figure 3.4 Diagram and explanation of adjustment to zero for Balance Master.

Data collected on the BM in earlier studies of women (LAW study) (Nitz & Low Choy, 2004) and men (Nitz & Fu, 2009) provided the basis for comparison with the un-adjusted (no correction for the slight anterior displacement of the pelvis relative to the ankles) and adjusted data (adjusted as shown in Figure 3.4) collected for Studies 4 and 5 (Chapters 7 and 8). These separate comparisons for men (data from study of men) and women (data from LAW study) are shown in Figure 3.5. Although there are still some discrepancies between the adjusted Kistler results in the current studies and the BM results from larger numbers in earlier studies (in particular for the FoEO and FoEC tests in the men and FiEO and FiEC for the women), it was considered that the adjusted values were a better match than the un-adjusted values.

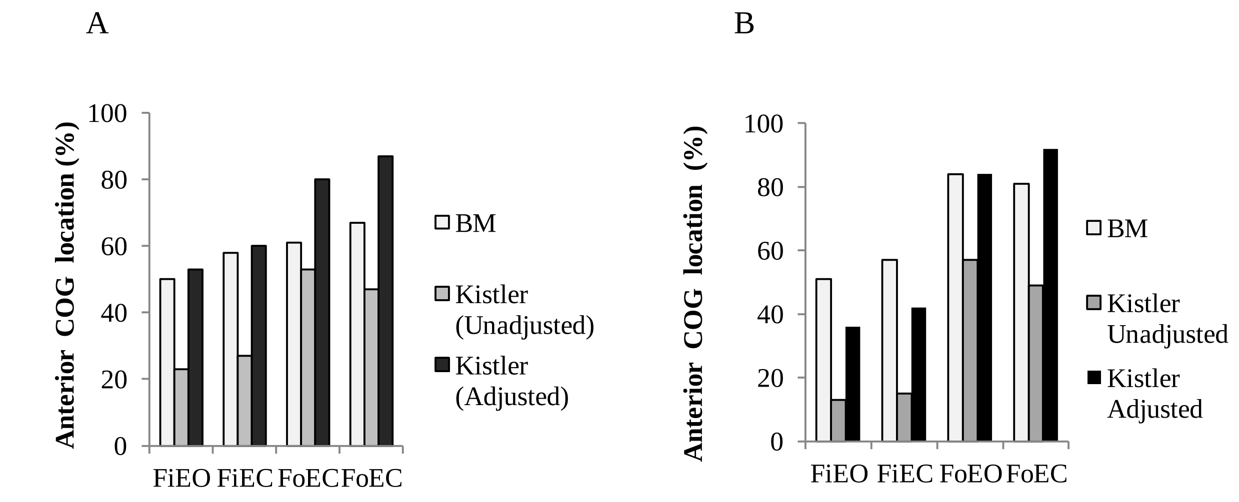

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Figure 3.5 Proportions of participants with an anterior COG start location on different force plates with and without, data correction for men (A) and women (B).
BM= Balance Master; COG= centre of gravity; FiEO= Firm surface, eyes open; FiEC= Firm surface, eyes closed; FoEO= Foam surface, eyes open; FoEC= Foam surface, eyes closed.

3.3.5 COG: Start or mean?

There was some confusion in determining whether the COG represented in the results diagram on the BM actually represented the start location for each condition trial or the mean location for each trial. In the 1998 NeuroCom International Inc, Clackamas Oregon Operator's Manual the COG location was described as "the average position of the COG during each 10 second trial" (NeuroCom International, 1998). However, in the 2002 operator's manual it was described as the "initial COG position" (NeuroCom International, 2002). The online version of the Manual also refers to the "COG position relative to the center of the base of support at the start of each mCTSIB trial" (NeuroCom International, 2007). This thesis has prescribed to the view that the COG location presented in the BM results diagram for the mCTSIB represents the start location of COG at the commencement of each test trial.

3.4 Statistical Methods

Statistical analyses were conducted using Stata version 11 (StataCorp LP) statistical package for Studies 2 and 3 and version 13 for Studies 4 and 5. In Studies 2 and 5 an unweighted Kappa analysis was used to determine the degree of consistency between two raters when rating COG location in the tests of the mCTSIB (Study 2, Chapter 4). In order to test H_0: Kappa=0.06 against H_1: Kappa=0.09 at a power of 80% it was determined that 66 participants would be required in this study. The Kappa statistic was also used to determine the level of agreement between the proportions of participants for COG start and mean locations (Study 5, Chapter 8) for the four test conditions of the mCTSIB. To achieve a power of 90% in testing H_0: Kappa=0.06 against H_1: Kappa=0.09 in this study, 89 participants were required. The unweighted Kappa was also used to analyse the levels of agreement of the anterior location of COG between two test sessions on the BM (Chapter 5.1) and also on two different force plate systems in the same test session (Chapter 5.2). The Kappa statistic is appropriate for reliability analysis of categorical data and also takes into account the existence of agreement by chance. The scores for Kappa range from 0 to 1. Table 3.3 shows the different levels of agreement recommended by Landis and Kock (1977).

Table 3.2 Description of Kappa values

Range	Description
≤0	Less than chance agreement
0.01-0.20	Slight agreement
0.21-0.40	Fair agreement
0.41-0.60	Moderate agreement
0.61-0.80	Substantial agreement
0.81-0.99	Almost perfect agreement

The Kappa statistic does have some limitations. Firstly, the analysis is influenced by the positions and sizes of results in each cell in the two-by-two table particularly in cells which have marginal values (Sim & Wright, 2005), for example, results in which there is 100% agreement. Also, the ability to predict chance agreement may not be applicable to all test situations and in particular for marginal values (McHugh, 2012). Thus some authors suggest that when reporting Kappa statistics the percentage of observed agreements should also be included in the results to aid interpretation (McHugh, 2012; Viera & Garrett, 2005).

In Studies 3 (Chapter 6) and 4 (Chapter 7) Pearson's Chi-square test was used to determine if there was an association between the proportions of participants with an anterior COG location for the four tests of the mCTSIB (Chapter 6) and for the six tests in which the size of the BOS was altered (Chapter 7). The chi-square test is applicable to categorical data and the assumption of expected cell frequency (≥5) was examined to ensure validity of the test. Significance was set at $p<0.05$ with a

95% confidence interval. Fisher's Exact test was used for instances in which expected cell frequency was ≤ 5.

Studies 2 (Chapter 4) and 3 (Chapter 6) used data from the LAW study. Power analyses were conducted by the primary researchers in this project. They determined that 100 women per age decade were needed for an effect size of ≥0.35 standard deviations (SD) within each age group and that for pooled age groups this effect size would be ≥0.23 (SD) at a power of 90% (Khoo et al., 2008).

3.5 Ethical considerations

Ethical approval of the LAW study (data for Studies 2 and 3) was obtained from the ethics committee of the Royal Brisbane and Women's Hospital and The University of Queensland Medical Ethics Committee (Khoo et al., 2008).

Ethics clearance for the research project conducted as part of this thesis (data for Studies 4 and 5) was obtained from The University of Queensland Medical Research Ethics Committee (Approval Number 2013001298) (Appendix 1).

3.5.1 Informed consent

Participants for all studies provided consent prior to the commencement of testing. Prior to consenting to participate in the study an information leaflet was posted or emailed to each participant outlining the purposes of the study as well as the right of participants to withdraw at any time without need for an explanation and without penalty (Appendix 2). On attending the assessment session participants were given the opportunity to ask any questions about the study which were then answered by the tester. Once the participant was happy to proceed they signed the consent form (Appendix 2) which described the procedure and their rights as participants.

3.5.2 Participant Information collected

In addition to results from testing, data collected during the study included information on personal attributes (for example height and weight) as well as activity levels and medications (Figure 3.6). This information was recorded initially on paper forms (Figure 3.6) which were stored in a locked cupboard. The information from all participants was then de-identified and recorded on an excel spreadsheet.

DATA COLLECTION FORM

DATE:	**Consent Form:**		**Feedback:**		
NAME:	**ID:**				
AGE:	**Gender:**	F	M		
Height:	**Weight:**				
Falls (in last 12mnths):	**Employ:**	FT	PT	NE	R
Diabetes:	No	Yes	Type 1	Type 2	

Activity Level: 1 2 3 4 5 6

Prescription Medications	Drug Name	Purpose
1		
2		
3		
4		
5		
6		

Figure 3.6 Participant information recorded at the commencement of the test session ID Identification number; FT Full-time work; PT Part-time work; NE Not currently employed; R Retired.

3.5.3 Risks and benefits

As some testing involved reduction in vision (eyes closed tests) and alteration of the stance surface (stance on a foam pad) the main risk to participants was loss of balance. To cater for this possibility, the testing on the force plates was conducted within a relatively confined area with a raised plinth on one side of the participant for easy hand support if needed. Furthermore, the person conducting the testing stood close to the other side of the participant in a position to intervene if needed. No adverse events were reported during testing.

No identified direct benefits were identified to the participants in this study. However, participants were provided with a summary and explanation of their test results on conclusion of testing (LAW study) or by email within a fortnight of testing (Studies 4 and 5).

3.5.4 Privacy, confidentiality and disclosure

All information collected in the study remains confidential. Publications and presentations arising from the study do not contain any material which may lead to the identification of any participant.

CHAPTER 4

A new method of interpreting centre of gravity location using the modified Clinical Test of Sensory Interaction on Balance: A reliability study. (Study 2)

Following the review of the literature it was apparent that the use of visual assessment to identify the location of the COG in bipedal stance is unreliable. The alignment of the human body does not necessarily point to the location of the COG within the BOS as adjustments can be made by the individual through a range of joints to preserve a relatively constant COG location. Yet there is no method currently available to physiotherapists in the clinical setting to obtain an objective measure of COG location.

The NeuroCom Balance Master® 6.0, Oregon (BM) is used in some clinical settings for both assessment and treatment of clients with balance problems. As the BM software does provide some information on COG location in both the antero-posterior and medio-lateral planes, it was proposed that this limited data might be able to be used more effectively to provide clinically useful information on COG location. The first phase of this work was to devise a method that is representative of these data from the BM that might be suitable for analysis and to undertake a study on the inter- and intra- rater reliability for this new method of representation.

- Boughen J, Dunn K, Nitz J, Johnston V, Khan A. A new method of interpreting the centre of gravity location using the modified Clinical Test of Sensory Interaction on Balance: A reliability study. *Hong Kong Physiotherapy Journal. 2013;31*:64-8. doi: http://dx.doi.org/10.1016/j.hkpj.2013.04.002

This chapter is a modified version of the published paper to better suit the style and format of this thesis. The published manuscript is presented in Appendix 3.

4.1 Abstract

Background/Purpose: This study tests the inter- and intra-rater reliability of a new method of interpreting centre of gravity (COG) location results of the modified Clinical Test of Sensory Interaction on Balance (mCTSIB) tested on the NeuroCom Balance Master™ (BM).

Methods: Sixty-three women (40-80 years) were randomly selected from a cohort of 500 women from the Longitudinal Assessment of Women (LAW) study. Start location of COG, as provided diagrammatically in the BM test results, for each of the four tests of the mCTSIB (firm surface, eyes open and closed; foam surface, eyes open and closed) was subjectively allocated by two raters (blinded to one another), to one of nine location categories. This allocation of COG location was repeated on two occasions separated by at least 2 weeks.

Results: An unweighted Kappa (κ) analysis of the data showed a substantial level of both inter-rater [κ=0.84 (95% CI = 0.82-0.86)] and intra-rater [rater 1 κ = 0.78 (95% CI = 0.74-0.79), rater 2 κ = 0.88 (95% CI = 0.86-0.90)] reliability. The narrow CI range reinforces the strength of these results.

Conclusion: The strong inter- and intra-rater reliability of this new interpretation of COG location in the mCTSIB test on the BM suggests that this may be an additional reliable method for clinicians to use when interpreting results from steady state balance tests on the BM.

4.2 Introduction

Preservation of standing balance depends on the ability of an individual to control movement of the body's centre of mass (COM) within the base of support (BOS) (Hasan et al., 1996a). There are several factors that influence movement of the COM. These include: the location or position of the centre of gravity (COG) (the vertical projection of the COM) within the BOS, the velocity (i.e. both the speed and direction of movement) of the COM, and the size and configuration of the BOS. As force plate technology has become more available in rehabilitation settings, clinicians are now able to access more accurate information on the velocity of the COG in assessment of patients. In addition, the size of the BOS being used can be identified via limits of stability measures. However, it is still not possible to track the location of the COG in the clinical setting.

It has been shown that the proximity of COG location to the boundary of the BOS is linked with the need to take a protective step (Pai et al., 1998). Furthermore, an association has been identified between the antero-posterior position of COG and fall incidence (Merlo et al., 2012) in a group of older adults who had fallen once or twice in the previous twelve months. Given these findings of the relevance of the location of COG in the preservation of balance stability, a method by which COG location could be tracked would be of value to clinicians. It would provide additional information as part of the assessment process on COG location adjustments that occur under different environmental and physiological challenges. For those patients who require training to manage under these different challenges, COG location also may provide a useful indicator of the impact of the therapeutic interventions.

The aim of this study was to examine the inter- and intra-rater reliability of a new method to monitor the location of the COG within the BOS. This was based on an analysis of the results produced by the NeuroCom Balance Master® 6.0, Oregon (BM) for the modified Clinical Test of Sensory Interaction on Balance (mCTSIB). The mCTSIB is an abridged version (4 tests) of the Clinical Test of Sensory Interaction on Balance (Shumway-Cook & Horak, 1986) (6 tests) which allows clinicians to bias the three sensory (somatosensory, visual and vestibular) inputs involved in postural stability during a steady state balance assessment. The BM software provides a diagrammatic record of the location of the COG at the commencement of each trial (Figure 5.1; also refer to Chapter 3, Figure 3.2). In addition an average composite location of COG across all four tests for the mCTSIB is recorded. An average composite COG location across the four test conditions of the mCTISIB is not useful clinically because it does not provide specific information for each of the surface and visual conditions.

A novel method of categorizing the COG location is proposed based on the results provided by the BM. An analysis of the separate diagrammatic start location COG recordings from the BM for each of the mCTSIB tests forms the basis for this new method of interpretation of COG location under the different test conditions in which vision and surface are manipulated. The intra- and inter-rater reliability of this method for identifying COG location in healthy adults under these different test conditions is explored in this study. Such a measure provides the basis for comparisons between different age groups and for different pathologies to inform focused treatments for balance deficits.

4.3 Method

4.3.1 Participants

Balance Master results' printouts from 63 subjects were selected from a larger sample of 500 independent, community-dwelling women (age range 40-80 years) who participated in the Longitudinal Assessment of Women (LAW) study (Khoo et al., 2008). Paper copies of results from participants were stored in seven, four-drawer filing cabinets. The first drawer in each cabinet housed data from the 40-49 years group, while the second, third and fourth drawers held data for the 50, 60 and 70 year age groups respectively. Using systematic sampling every second file from a single drawer in each of the seven four-drawer filing cabinets was selected: (i) drawer one in cabinet one, (ii) draw two in cabinet two, (iii) drawer three in cabinet three, and so on, returning to drawer one for cabinet five. This method enabled an unbiased sample to be extracted and ensured that all age groups were represented in the sample (19 in their 40s, 19 in their 50s, 12 in their 60s and 13 in their 70s). Ethical approval for the LAW study was obtained from the ethics committees of the Royal Brisbane and Women's Hospital and The University of Queensland. All participants provided written consent prior to the start of the study (Khoo et al., 2008).

4.3.2 Measurements

The mCTSIB carried out on the BM consists of four test conditions to explore balance on different surface types with and without vision: (i) firm surface, eyes open (FiEO), (ii) firm surface, eyes closed (FiEC), (iii) foam surface, eyes open (FoEO), and, (iv) foam surface, eyes closed (FoEC). The summary results provided by the BM software package give three measurements of COG : (i) the mean sway velocity (degrees/second) for each test condition as well as an average of the mean sway velocity across all four tests (twelve trials in total), (ii) the composite Limits of Stability across all four test conditions and (iii) the COG alignment, also calculated as a composite score across all four test conditions, which reflects an average of the subject's start positions relative to the centre of the BOS. A diagram (Figure 4.1) is also provided using symbols (o = FiEO, + = FiEC, * = FoEO, X = FoEC) to represent the location of the COG at the start of each trial. This reliability study is based on an interpretation of the location of the test symbols (described in Section 4.3.4) for each 10-second trial as depicted on the diagram.

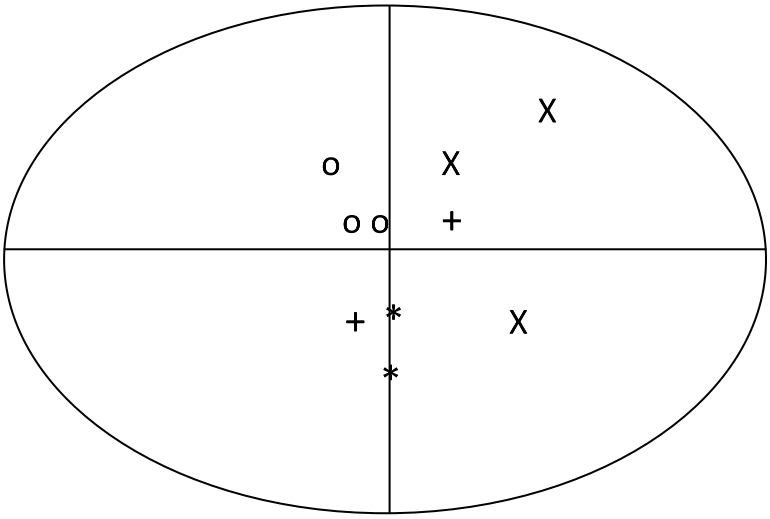


Figure 4.1 Example of the centre of gravity results diagram presented on the Balance Master

o = Firm surface, eyes open (FiEO); + = Firm surface, eyes closed (FiEC); * = Foam surface, eyes open (FoEO); X = Foam surface, eyes closed (FoEC)

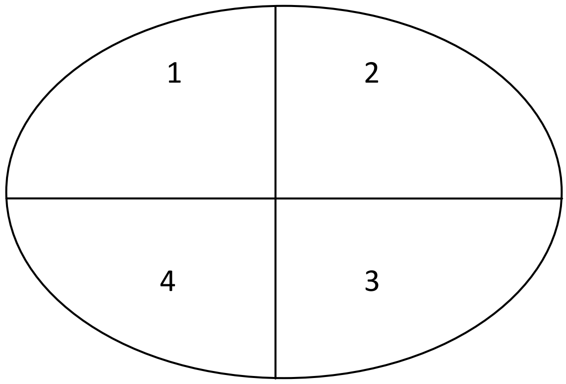
4.3.3 Procedure

The test protocol for the mCTSIB on the BM requires that the subject stands on the force plate with their two feet apart. The stance width is determined by the BM software based on the height of the subject. The three possible widths (small (S), medium (M) and tall (T)) are marked on the force plate for the FiEO and FiEC tests. For the FoEO and FoEC tests they are marked on the square of foam. Three trials of each of the four conditions of the mCTSIB (FiEO x 3, FiEC x 3, FoEO x3, FoEC x 3) were conducted. Each trial lasted 10 seconds (Low Choy et al., 2003). This procedure was repeated on three occasions over the five-year time phase of the study. There was a minimum of one year between assessments. Altogether four tests on three occasions gave a total of twelve test conditions which were rated for each participant. A total of 756 test condition results for the sample were obtained from the 63 subjects' files and were used in the reliability testing. Two raters scored the 756 test condition results on two separate occasions in order to calculate intra-rater as well as inter-rater reliability. There were at least two weeks separating the first and second rating allocation. The raters required no experience of balance testing and consisted of one qualified Physiotherapist and one fourth year student who had some clinical experience. The raters were blinded to one another.

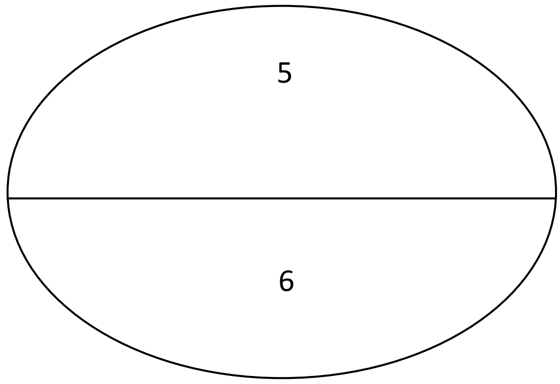
4.3.4 Categorization

Analysis of the results diagram generated by the BM software showing COG locations for the three trials of each test via the symbols o, +, *, X (see example in Figure 4.1), was used to determine the location of the COG for each condition and formed the basis for category allocation.

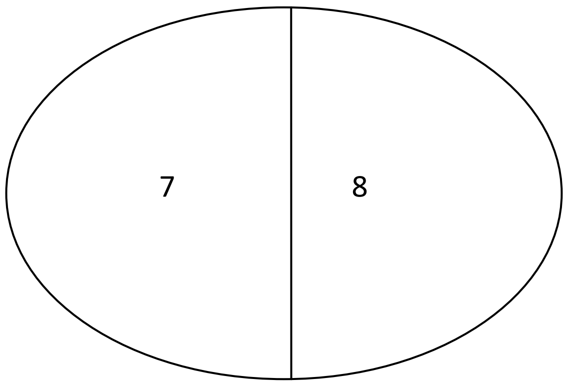
Nine sectors were identified and these are shown in Figure 4.2. In order to be allocated to a particular sector at least two of the three symbols must occur in the same sector. In some cases the symbols could be allocated to more than one sector so the numbers of the sectors are prioritized with the quadrants taking precedence over the hemispheres. For example, in Figure 4.1, 'X' could be allocated to sector 2 (right/anterior quadrant) or to sectors 5 or 8 (anterior hemisphere or right hemisphere respectively). However, as the quadrants take priority over the hemispheres, the allocation is made to sector 2. When only two symbols are visible and they fall in different sectors (for example, '+' in Figure 4.1) no allocation is made. Allocation to sector nine (9) occurs only when the symbols fall directly in the centre and cannot be allocated to any other sector. The use of both quadrants and hemispheres allows flexibility for data analysis depending on the parameter being investigated (anterior/posterior location of COG or left/right location of COG).



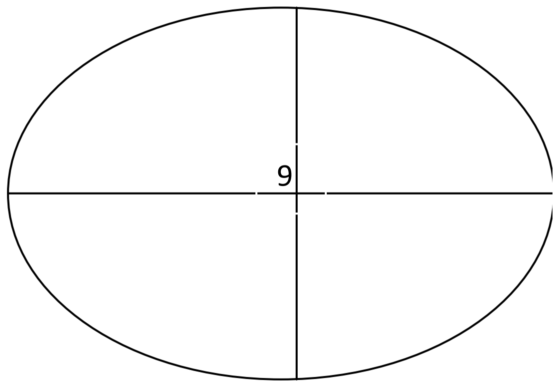
(a) Quadrants: Left anterior (1), Right anterior (2), Right posterior (3), Left posterior (4).



(b) Anterior (5) and posterior (6) hemispheres



(c) Left (7) and right (8) hemispheres



(d) Centre (9)

Figure 4.2: Explanation of categories for anterior COG location

4.3.5 Data Analysis

A reliability analysis using the unweighted Kappa statistic was performed to determine the degree of consistency for both intra- and inter-rater reliability when categorizing the COG location as anterior or posterior for each of the four tests of the mCTSIB. Kappa was chosen for its ability to take into account agreement by chance and its applicability to categorical data for just two raters. In order to assess Kappa 0.60 against a Kappa of 0.90 to achieve a power of 80% in a two-rater study, 66 participants were required for the study. Scores for Kappa range between 0 (consistent with agreement by chance) and 1 (perfect agreement). A Kappa value of 0.61-0.80 represents substantial reliability while a value range of 0.81-0.99 represents almost perfect agreement (Landis & Kock, 1977). A 95% confidence interval (CI) was also calculated for each kappa statistic to give further information regarding the strength of the reliability analysis. Inter- and intra-rater reliability was assessed for each test condition as well as for the reliability across the four test conditions. The proportions of anterior COG location for all four tests was combined for this analysis. Statistical analysis was performed using Stata version 11.0 StataCorp LP.

4.4 Results

The results of the kappa analyses with a 95% CI are presented in Table 4.1.

An overall inter-rater reliability of 0.84 (95% CI 0.82-0.86) would be described as almost perfect agreement. The intra-rater reliability for rater 1 was substantial at 0.78 (95% CI 0.74 - 0-79) and for rater 2 was almost perfect agreement at 0.88 (95% CI 0.86 – 0.90) (Landis & Kock, 1977). Analysis of each individual test showed inter-rater agreement ranged from substantial to almost perfect agreement and intra-rater agreement were substantial for rater 1 and almost perfect for rater 2. In addition to the strong Kappa values the CI range is small emphasizing the precision of the reliability coefficients. The combined rating also presented in Table 4.1 represents the Kappa values when the results of all four test conditions were combined. That is, the intra- and inter-rater reliability when the results of the four test conditions of the mCTSIB were combined.

Table 4.1 Intra- and inter-rater reliability using Kappa (κ) and 95% confidence interval (CI)

TEST	**INTRA-RATER** (Kappa (95%CI))		**INTER-RATER** (Kappa (95% CI))
	Rater 1	Rater 2	
FiEO	0.80 (0.76-0.81)	0.88 (0.84-0.91)	0.80 (0.77-0.84)
FiEC	0.78 (0.74-0.81)	0.89 (0.87-0.93)	0.85 (0.82-0.90)
FoEO	0.76 (0.73-0.78)	0.89 (0.87-0.91)	0.86 (0.80-0.90)
FoEC	0.73 (0.70-0.75)	0.87 (0.81-0.90)	0.82 (0.78-0.84)
Combined	0.78 (0.74-0.79)	0.88 (0.86-0.90)	0.84 (0.82-0.86)

FiEO= Firm surface, eyes open; FiEC= Firm surface, eyes closed; FoEO= foam surface, eyes open; FoEC= Foam surface, eyes closed

4.5 Discussion

The usefulness of any outcome measure in the clinical assessment of patients relies on the capacity of the measure to be consistently applied by different clinicians. This study has assessed the reliability of a new method of monitoring the COG start location adapted from data produced in the mCTSIB test conditions on the BM. Levels of agreement ranging from substantial (κ 0.61-0.80) to perfect (κ 0.81-0.99) for both inter- and intra-rater reliability have been demonstrated. The results from two raters for this method of categorization are in good agreement. This is the first time that the start location of COG has been assessed in a defined, categorical way for each of the four test conditions of the mCTSIB on the BM.

The objective of devising this new method of categorizing the COG location was, principally, to provide clinicians with a simple way to assess the COG location in the clinical setting. The mean COG location is a summary measure that is reported less often in research papers. In a study to assess sampling duration effects on the reliability of summary measures in a group of young adults (N=49), Carpenter et al. (2001) found that the mean COG location for the antero-posterior and medio-lateral planes showed high reliability. Subjects in this study were assessed standing only on a firm surface with their eyes open. Although the BM provides COG location data under different surface and vision test conditions, it only offers a measure of the mean COG location across all of the tests. This does not help clinicians to differentiate between responses for the different test conditions. The ability to identify differences in COG location as the test conditions become more challenging is important if the contributions of the visual, proprioceptive and vestibular systems of the individual are to be exposed in balance assessments.

Further research is needed in order to show whether or not this new method can identify differences in COG location with ageing or under different surface or visual conditions in healthy adults. Studies which identify the COG location within the BOS mostly test subjects on a firm surface only with the subjects standing with their feet apart (Carpenter et al., 2001; Danis, Krebs, Gill-Body, & Sahrmann, 1998). Low Choy et al. (2007), reporting on the same data set used in the current study, found no changes to stability across age groups (40-80 years) when subjects stood with their feet apart on a firm surface with eyes open using sway velocity data. They were able to demonstrate, however, significant increases in sway velocity speeds for stance stability across age groups when participants stood on a compliant surface as well as for stance with eyes closed. Merlo et al. (2012) found that the COG location in firm surface tests showed no difference between groups of fallers and non-fallers. This finding is consistent with that for healthy young and older adults (Danis et al., 1998; Murray et al., 1975). However, they did find an association between COG location on a compliant surface with eyes open and the incidence of falls in older adults. These research findings support the need for a clinically reliable measure of COG location in tests which manipulate sensory inputs to be available to clinicians.

There is increasing information available on the behaviour of COG location in the presence of pathology. For example, teenage girls with scoliosis had a more posterior location of COG than controls when standing on a firm surface with their eyes open (Dalleau, Allard, Beaulieu, Rivard, & Allard, 2007). This was also the case for subjects with chronic low back pain (Mientjes & Frank, 1999) although in this study the same posterior location of COG was also noted when these subjects were standing on foam with their eyes open. As knowledge of differences in COG location increases for subjects with different pathologies, there is a need for normative data against which to make comparisons. It would be useful for clinicians to be able to monitor COG location in the treatment setting and to be able to compare the results in the presence of pathology against the results for healthy adults. It may also be possible in the future for the location of COG to be used to evaluate treatment effectiveness.

This preliminary reliability study has developed a categorical method by which the COG location can be monitored when the mCTSIB is assessed on the BM. Further work, including the use of more raters, is needed in order to assess the use of this categorising method as a valid measure of the location of COG in different patient groups. This method was based on outcomes provided on the BM. Additional research is required to determine whether the corrections proposed in Chapter 3 for use on other force plate or pressure plate systems will allow comparisons to be made across different equipment. It should be noted that since, in this study, the COG location was measured only at the commencement of each test trial, the method does not purport to offer a true average of the COG location over the complete trial. In spite of these recognised limitations, it is hoped that these results will help to further research in this important field.

The location of the COG in stance warrants further investigation. This study has established the reliability for a novel method of categorising the location of COG under a range of test conditions using existing data from the mCTSIB on the BM. Its use provides an objective measure of COG location thereby eliminating the subjectivity of its assessment. This will facilitate further exploration by clinicians of COG-within-BOS characteristics across different test conditions for different age groups and in the presence of pathologies.

CHAPTER 5

Pilot studies of Balance Master (5.1) and Kistler (5.2) force plate data

Although there is evidence of reliability and repeatability for mean velocity data for tests on the Balance Master® (BM) there have been no studies to our knowledge which have evaluated the test-retest reliability of the antero-posterior location of centre of gravity (COG) on the BM. Furthermore, as two force plate systems were used in this thesis (the BM and Kistler force plates), there needed to be an assessment of the comparability of COG location between the two systems when the categorical method of recording COG location in the antero-posterior plane was used. This would also validate the corrections made to data collected on the Kistler force plates so as to align the test parameters with those used on the BM.

This chapter presents two pilot studies. The first (5.1) analysed the test-retest reliability of centre of gravity location in the antero-posterior plane for the four tests of the modified Clinical Test of Sensory Interaction in Balance on the BM. The second study (5.2) assessed the comparability of results when tests were conducted on the BM and Kistler force plates systems on the same day.

5.1 Test-retest reliability of Centre of Gravity (COG) on the Balance Master for the modified Clinical Test of Sensory Interaction in Balance

5.1.1 Abstract

Background/Purpose: The purpose this small pilot study was to test the reliability of COG location results for the mCTSIB on the BM for two test sessions conducted 24 hours apart. The repeatability of this has not previously been tested.

Methods: Participants (N=14), four of whom were male, were aged 20-60 years (mean 27.14 years). The mCTSIB (a group of 4 tests: 2 on a firm surface (eyes open, FiEO, then closed, FiEC) followed by 2 on a foam surface (eyes open, FoEO, then closed, FoEC)) was tested in two sessions on the BM and spaced 24 hours apart. Each test was repeated three times. COG location was categorised as anterior or posterior of each individual's centre of balance if two or more of the three trials were in the same sector.

Results: Between session agreement for the firm surface tests was moderate with $\kappa = 0.51$, (CI 0.04-0.99) for FiEO and $\kappa = 0.59$ (CI 0.21-0.96) for FiEC. No Kappa result was produced for the FoEO test and agreement was due to chance only for the FoEC test.

Conclusions: Between-session reliability is moderate for firm surface tests on the mCTSIB. Further research with larger participant numbers may provide clarification with the foam surface tests.

5.1.2 Introduction

There is limited evidence in the literature relating to the location of the centre of gravity (COG) within the base of support (BOS) in steady state bipedal stance particularly for stance under altered sensory conditions (for example, altered surface compliance or reduced vision). The evidence that is available for COG location presents the location as a factor of distance from an anatomical landmark on the feet (Danis et al., 1998; Merlo et al., 2012) or as a percentage of each participant's foot length (Fujiwara et al., 2010; Geiger et al., 2007). Although some authors have noted that COG location within the antero-posterior plane is relatively constant for stance on a firm surface with the eyes open for any time segment within a 120 second test time (Carpenter et al., 2001) or as age increases (Schwab et al., 2006), we are unaware of any studies which have analysed test-retest reliability for antero-posterior COG location.

The Balance Master®, Oregon (BM) is a force plate system which is designed for use in either research or clinical settings. Its software provides options for a number of balance tests including the modified Clinical Test of Sensory Interaction in Balance (mCTSIB). This group of four test conditions (Firm surface, eyes open; Firm surface, eyes closed; Foam surface, eyes open; and, Foam surface, eyes closed) manipulates proprioceptive (the participant stands on firm or foam surfaces) and visual (eyes are open or closed) systems to assess the sensory systems being relied on by the participant.

The primary outcome used in the mCTSIB on the BM is mean sway velocity with outcomes provided for each test condition as well as a composite result across all four test conditions. The software also provides a diagram of the COG location at the start of each test. If COG location is to be used as an outcome its test-retest reliability needs to be established.

Thus the purpose of this study was to evaluate the reliability of COG location in the antero-posterior plane for the four test conditions of the mCTSIB.

5.1.3 Method

Study design

This study was a repeat measures study. It was anticipated that testing would be conducted on 20 participants. As this was a pilot study using a small sample of convenience, age range was not specified.

Participants

Time limitations resulted in a reduction in participant numbers from the planned number of 20. Participants (N=15 ; males=4), some of whom had participated in Studies 4 and 5 of this thesis, were recruited from students and staff in the School of Health and Rehabilitation Sciences, The University of Queensland. The age range was 20-60 years (mean 27.14yrs). The age range was not thought to be a critical factor for this pilot study as the participant numbers were small and would be a sample of convenience. Exclusion criterion was that the participants should not have any pathology that may impact on balance (for example, any neurological conditions).

Measurements

The outcome measure for the study was the location of COG in the antero-posterior plane for each of the four test conditions of the mCTSIB (Firm surface, eyes open (FiEO); Firm surface, eyes closed (FiEC); Foam surface, eyes open (FoEO); Foam surface, eyes closed (FoEC)). This was determined using a categorisation method (a full description of this method is provided in Chapter 5) based on data provided by the BM (Figure 5.1). The COG location was categorised as being either anterior or posterior to the horizontal axis (270° - 90°) of the results diagram (Figure 5.1). The firm surface consisted of the metal force plate while the foam surface was a piece of foam provided with the BM. Markings on the firm and foam surfaces were identical to facilitate consistent foot placement on each surface (additional details in Chapter 3).

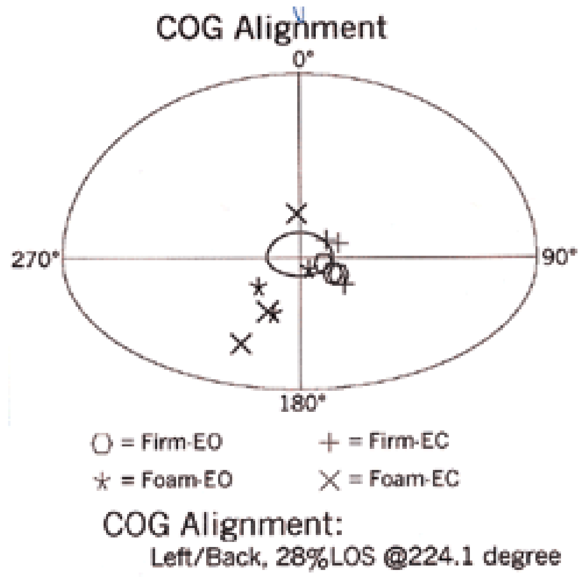


Figure 5.1 Example of Balance Master output for centre of gravity location

Procedure

Testing was conducted at the same time of day on two occasions spaced 24 hours apart. Participants stood barefoot on the BM force plate. There were three width options - Tall (T), Medium (M) or Small (S) - for the distance between the feet. This distance was based on the height of each participant (refer to Chapter 4 for a more detailed description). Three 10 second trials were conducted for each of the four test conditions of the mCTSIB. The order of the tests was the two firm surface tests (FiEO then FiEC) followed by the two foam surface tests (FoEO then FoEC). Participants were asked to stand quietly, looking straight ahead and with their arms hanging relaxed by their sides for the duration of each test condition trial.

Data analysis

Data from one participant was incomplete as illness prevented testing of this participant at the second test session. An unweighted Cohen's kappa (κ) was used to determine the levels of agreement for the anterior and posterior COG location categories between the two test sessions for each participant. Kappa was chosen as it is applicable to categorical data and it takes into account any agreement that may occur due to chance. Interpretation of results was based on that provided by (Landis & Kock, 1977) in which 0 = poor agreement (consistent with agreement by chance) and 1 = perfect agreement. The Kappa statistic examines variability in the category allocation between the two test days. A more detailed description of the interpretation of the levels of agreement is provided in Chapter 3. All analyses were conducted using Stata 13 (StataCorp LP) statistical package.

5.1.4 Results

A sample of the data is shown in Table 5.1 while the observed levels of agreement between the two test sessions are shown in Figure 5.2.

Table 5.1 A sample of the data set for repeatability of outcomes on the Balance Master.

ID	COG Location Category							
	FiEO1	**FiEO2**	**FiEC1**	**FiEC2**	**FoEO1**	**FoEO2**	**FoEC1**	**FoEC2**
26	5	5	5	5	5	5	5	5
75	5	5	5	5	5	5	5	5
83	5	5	5	5	5	5	5	5
84	5	5	5	5	5	5	5	5
85	6	5	6	6	5	5	5	5
86	5	5	5	6	5	5	5	5
87	6	6	6	6	5	5	5	5
88	6	6	6	6	5	5	5	5

ID= Identification number; 1=first measure, 2=second measure; FiEO=Firm surface, eyes open; FiEC=Firm surface, eyes closed; FoEO=Foam surface, eyes open; FoEC=Foam surface, eyes closed; 5=anterior COG location; 6=posterior COG location

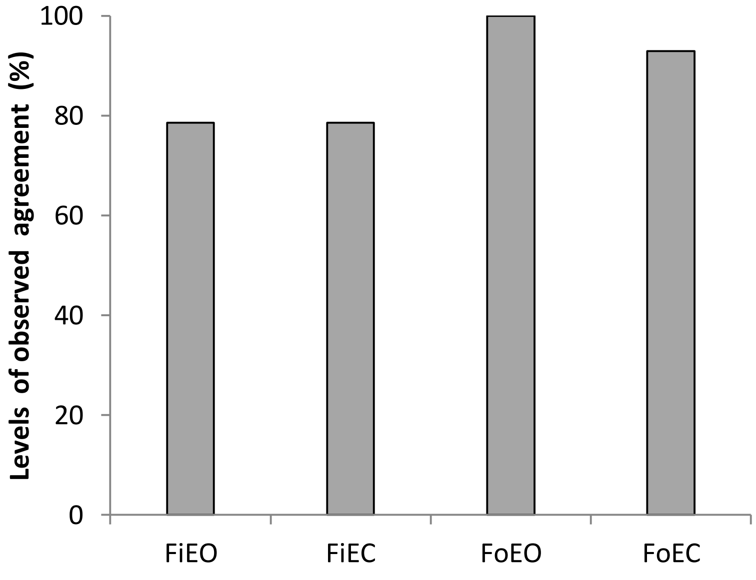


Figure 5.2 Observed levels of agreement for tests conducted on two occasions on the Balance Master. FiEO= Firm surface, eyes open; FiEC= Firm surface, eyes closed; FoEO= Foam surface, eyes open; FoEC= Foam surface, eyes closed

Although the observed levels of agreement were high (79%) for the FiEO and FiEC test conditions, the Kappa (κ) results were moderate and the confidence intervals (CI) were wide (FiEO ($\kappa = 0.51$, CI 0.04-0.99) and FiEC ($\kappa = 0.59$, CI 0.21-0.96)). The wide confidence intervals reduce the strength of the result for the firm surface test conditions. As the observed proportions for the FoEO on the two test occasions showed complete agreement (100%), there were too few ratings for a Kappa value to be calculated. While the FoEC observed agreement was high (93%), the Kappa value ($\kappa= 0$) indicates a result that is solely due to chance. However, this result may be a reflection of the limitations of the Kappa statistic for some result distributions (McHugh, 2012; Sim & Wright, 2005; Viera & Garrett, 2005) as previously discussed in Chapter 3 (Section 3.4).

5.1.5 Discussion

No previous studies have been identified which have assessed the test-retest reliability of COG location in the antero-posterior plane. The results of this study, using a categorical method to record COG location, show that while the observed levels of agreement between two test sessions on the BM for the mCTSIB are high (79% observed agreement) for each of the firm surface test conditions the statistical results are moderate. For the foam surface test conditions the observed level of agreement was perfect (100% observed agreement) for the FoEO test condition and substantial (93% observed agreement) for the FoEC test condition.

Test-retest reliability for stance on a firm surface with eyes open has been demonstrated for measures of mean sway velocity between tests conducted on the same day in healthy older adults (N=7) (Lafond et al., 2004) and for young adults (N=10) (Pinsault & Vuillerme, 2009). Reliability has also been shown for altered surface and vision test conditions in healthy older adults (N=16) when tests were separated by one week (Moghadam et al., 2011) although the authors noted that the mean velocity of medio-lateral sway had better intra-class correlation values than for antero-posterior sway. Despite these findings of test-retest reliability of sway velocity measures, there is evidence that sway velocity values are influenced by the time of day at which testing occurs with sway velocity increasing by 15.8% when testing was conducted in the afternoon compared with the morning of the same day (Jorgensen et al., 2012). Although this degree of variability at different times of the day may not apply to COG location, by conducting the tests at the same time each day, variability within individuals might have been minimized or negated.

It has also been shown that the instructions given to participants may also influence sway velocity reliability particularly if participants are requested ‘to stand as still as possible’ (Zok et al., 2008) or to only allow movement at the ankle joints (Slobounov et al., 1997). The instructions in the current study did not constrain movement through our instruction and the test protocol ensured the same instruction was provided at each test session. This thereby ensured consistent responses.

The consistency of COG location, although not the primary purpose of the study, was noted in a study by Carpenter et al. (2001) of quiet stance in young adults for each individual. In this study a range of summary measures were analysed at 30, 60 and 90 second time points from a total test time of 120 seconds. They noted that both the antero-posterior and medio-lateral locations of COG were the most reliable regardless of the time frame analysed. However, no other studies have been identified in the literature which have specifically analysed the test-retest reliability of COG location measures in the antero-posterior plane in either young or older adults.

The statistical results obtained in this pilot study may be due to the lack of variability in the data as well as insufficient ratings (FoEO test condition). This lack of variability and insufficient ratings may, in part, be as a result of the small number of participants. Although the high levels of observed agreement between test sessions (>79%) suggest that the use of this method to record COG location is consistent for individuals between two test sessions further investigation is needed to test the statistical significance of the results. The participants in this study were largely young adults. Further research with a larger participant group is warranted to confirm inter-session reliability of COG location for both young and older adults using this categorical method of the mCTSIB output from the BM.

5.2 Repeatability between the Balance Master and Kistler force plates

5.2.1 Abstract

Background/Purpose: The purpose of this pilot study was to determine whether COG location would be comparable for an individual when tested on two different force plate systems. It was also proposed that this would confirm that data corrections made for testing on the Kistler force plate were appropriate for comparison with the data collected on the Balance Master (BM).

Methods: This repeat measures study assessed participants (N=8) the anterior/posterior location of COG within base of support (BOS) in the modified Clinical Test of Sensory Interaction in Balance (mCTSIB). The mCTSIB consists of two firm surface tests conducted with eyes open (FiEO) then closed (FiEC) and two foam surface tests one with eyes open (FoEO) and the second with eyes closed (FoEC). Cohen's Kappa statistic was used to analyse the categorical data. Percentages of observed agreement are also provided.

Results: Moderate agreement was shown for FiEC (κ 0.71; observed 88%) and FoEO (κ 0.60; observed 88%) while there was poor agreement for FiEO (κ 0.38; observed 75%) and FoEC (κ 0.14; observed 88%).

Conclusions: Within session repeatability between two force plate systems was moderate for two of the four tests of the mCTSIB (FiEC and FoEO). Further research is warranted with a larger subject group.

5.2.2 Introduction

Different force plate systems were used in different sections of this thesis. Data analysed in Studies 2 and 3 (Chapters 4 and 6) were collected on the BM while data for Studies 4 and 5 (Chapters 7 and 8) were collected on a Kistler force plate. Although the COG location test-retest results for the BM may be reliable between test sessions, the comparability between the two force plate systems also needs to be assessed so that interpretation of results can be applied irrespective of equipment available in clinical practice. The antero-posterior alignment of the feet on the BM is referenced to the position of the medial malleolus. When data collection for Studies 4 and 5 on the Kistler force plates commenced, the zero point used to reference a location of anterior or posterior was set at the medial malleoli of the feet. Subsequent exploration revealed that this data required correction as the zero point (referred to as the predicted centre of balance) on the BM was, in fact, anterior to the medial malleoli and the adjustment was individualized based on the height of each participant. The formula provided by the manufacturers of the BM (discussed in Chapter 3) was applied to the antero-posterior alignment of the feet to determine the zero point for the data collected using the Kistler force plate. This adjustment was necessary to provide continuity for categorising COG location within this thesis. If the results for COG location from the BM and Kistler force plates can be demonstrated to be comparable there is potential for pooling of data between institutions even when collected on different force plate systems.

This pilot study explored the comparability between COG location for the mCTSIB when participants were tested on the BM and the Kistler force plate in the same test session.

5.2.3 Method

Study design

This study used a repeat measures design with the same tests being repeated on two different force plate systems within a single test session. The study was designed for 15 participants.

Participants

The participants (N=8, 3 of whom were men) in this study were a small subset of participants from Studies 4 and 5. Recruitment of participants for those studies is described more fully in Chapter 7. The extended time that was required to test participants on both force plate systems resulted in some difficulties in achieving the proposed number of participants (N=15) in this study. Equipment availability also contributed to this as the force plate systems were in different laboratories. The age range of the participants in this pilot study was 30-48 years.

Measurements

The outcome used was the location of COG (as in 5.1.2 above) categorised to anterior or posterior relative to the predicted centre of balance for each individual.

Procedure

Participants were asked to repeat the tests for the mCTSIB on the Kistler force plate shortly after these tests had been completed on the BM. The two force plate systems were in different areas of the building so by necessity the tests on the two systems were separated by at least 10 minutes. The test protocol (described in Chapter 3) was the same on each system and the same foam surface was used on both.

Data analysis

The positions of the COG from each force plate system were categorised according to the protocol described in Chapter 4. These data then were compared using unweighted Cohen's Kappa (κ) as described in the data analysis section of 5.1.2 above.

5.2.4 Results

While the observed levels of agreement were high(Figure 5.3) for the four tests of the mCTSIB, the Kappa values were not supportive. This may have been affected by the small sample size which would affect the distribution across the cells in the calculation of Kappa (refer to Chapter 3, Section 3.4 for additional discussion). A sample of the data set is shown in Table 5.2.

Table 5.2 A sample of the data set comparing outcomes on the Balance Master and Kistler force plates.

ID	**TEST**	**COG location category**	
		BM	Kistler
73	FiEO	6	5
	FiEC	6	5
	FoEO	5	5
	FoEC	5	5
74	FiEO	6	5
	FiEC	5	5
	FoEO	5	5
	FoEC	5	5
75	FiEO	6	6
	FiEC	6	6
	FoEO	5	5
	FoEC	5	5
76	FiEO	5	5
	FiEC	5	5
	FoEO	5	5
	FoEC	5	5
77	FiEO	6	6
	FiEC	6	6
	FoEO	6	6
	FoEC	5	6

ID=Identification number; BM=Balance Master; FiEO=Firm surface, eyes open; FiEC=Firm surface, eyes closed; FoEO=Foam surface, eyes open; FoEC=Foam surface, eyes, closed; 5=anterior COG location, 6=posterior COG location.

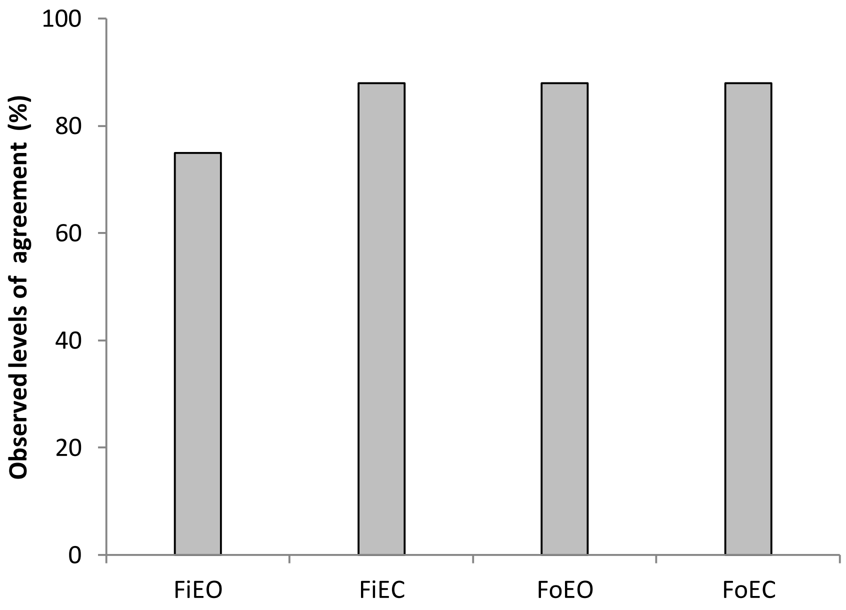


Figure 5.3 Levels of observed agreement for proportion of participants with an anterior centre of gravity location for testing on the Balance Master and Kistler force plates on the same day. FiEO= Firm surface, eyes open; FiEC= Firm surface, eyes closed; FoEO= Foam surface, eyes open; FoEC= Foam surface eyes closed.

Although the observed levels of agreement were substantial (88%) for the three more difficult conditions (FiEC, FoEO and FoEC), the Kappa values and confidence intervals were less consistent for FiEC (κ 0.71; CI 0.21-1.00), FoEO (κ 0.60; CI 0-1.00) and FoEC (κ 0.14; CI 0-0.17) test conditions. The observed level of agreement for the FiEO test was 75% (κ 0.38; CI 0-0.97).

5.2.5 Discussion

The results of this pilot study have demonstrated high observed levels of agreement for the mCTSIB conducted on both the BM and Kistler force plates in the same test session. If the percentage agreement were the only method of determining comparable performance then these results might be considered acceptable. Although Kappa statistical analysis has demonstrated moderate and substantial levels of agreement for the FiEC and FoEO tests respectively, the wide confidence intervals diminish the strength of the results. When the Kappa statistic is used, high observed levels of agreement may result in asymmetrical distribution of agreements thus affecting the results. Thus some authors (McHugh, 2012; Viera & Garrett, 2005) recommend that the percentage of observed levels of agreement should be taken into consideration in conjunction with the Kappa values. Another possibility for the Kappa results is that it may reflect the software adjustments made to the data collected on the Kistler force plates are still not as accurate as they might have been had the response regarding the zero point on the BM been more precise following our request for clarification. The low number of participants (N=8) in this study also may have affected the outcome. Clinically, the high observed levels of agreement suggest that the use of the categorical method to record COG location may be comparable between test systems when similar protocols are used although further investigation is needed to support this.

CHAPTER 6

Does start location of centre of gravity within base of support change with increasing age or altered sensory conditions? (Study 3)

The Balance Master® (NeuroCom, Oregon) is a commercially available force plate system that is used by Physiotherapists in some assessment and treatment centres. This system provides information on centre of gravity location in a group of tests, the modified Clinical Test of Sensory Interaction on Balance (mCTSIB). The purpose of this study was to determine whether there were any identifiable changes in centre of gravity location in the antero-posterior plane based on the new categorization method (Refer Chapter 5, section 5.3.4 Categorization) for recording COG location, for the different sensory test conditions across an age span of 40-80 years.

This study analysed data obtained from an earlier longitudinal study of women aged 40-80 years and will use the terms anterior and posterior to describe start COG location under various test conditions.

The content of this Chapter is in preparation for submission to Journal of Research, Rehabilitation and Development.

6.1 Abstract

Background/Purpose: Falls result when the centre of gravity (COG) moves beyond the boundaries of the base of support (BOS) in steady state stance. There is currently no means by which COG can be monitored within the clinical setting. This study examined whether a method to categorize COG start location (developed in Chapter 4) shows differences under various vision and surface conditions in women aged 40-80 years using test results from the modified Clinical Test of Sensory Interaction in Balance (mCTSIB).

Methods: Stance on a firm (Fi) then foam (Fo) surface with eyes open (EO) then closed (EC) was tested on the Neurocom Balance Master (BM) in 481 independent, community-dwelling women. There were three 10 second trials for each of the four conditions. The start locations for each condition were then allocated to a category (based on the BM results diagram) requiring at least two out of the three trial start locations to fall into the same category. The frequency of anterior/posterior start location was analysed using Pearson's Chi Square to determine differences (i) across four age decades, (ii) between EO and EC vision conditions and (iii) between Fi and Fo surfaces.

Results: No significant difference for COG start location across the four age decades for all conditions. There were significant differences in anterior COG location between the EO and EC conditions for stance on the firm surface ($p<0.001$) with a greater proportion showing an anterior COG location in the EC condition (FiEO 51.07% compared with FiEC 56.74%). On the foam surface there was a lesser proportion of participants with an anterior COG location for the FoEC condition (81%) compared with the FoEO condition (84.09%). Between the firm and foam surfaces ($p<0.001$) a greater percentage of participants showed an anterior COG location in the foam surface conditions (FoEO 84.9%, FoEC 81%) compared with the firm surface conditions (FiEO 51.07% compared with FiEC 56.74%). An increasing proportion of participants had an anterior COG as task difficulty increased from FiEO (51.07%) to FiEC (56.74%) to FoEO (84.09%). However, this trend was not consistent in the FoEC (81%) condition.

Conclusions: Irrespective of age, more participants started with an anterior COG location as task difficulty increased. This information may be of value to clinicians in interpreting balance test results in adults who present with impaired balance.

6.2 Introduction

The location of the centre of gravity (COG) within the base of support (BOS) is one of the determinants of stability for a body (LeVeau, 2011). Although there is continual movement of the body even when trying to remain still (Collins & De Luca, 1993) the COG of the body generally is controlled within a small range within the BOS (Geiger et al., 2007; Murray et al., 1975) in steady state balance. The movement attributes of the body's COG have been studied extensively through the use of summary measures such as sway velocity (Cavalheiro et al., 2009; Low Choy et al., 2007), sway area (Allard et al., 2001; Berger et al., 2005a) and sway path length (Bauer et al., 2008; Buckley et al., 2005; Wiesmeier, Dalin, & Maurer, 2015). Researchers have demonstrated changes in these summary measures under a variety of surface and vision conditions as age increases (Amiridis et al., 2003; Berger et al., 2005a; Cavalheiro et al., 2009; Haibach et al., 2007; Low Choy et al., 2007; Slobounov et al., 1998; Teasdale et al., 1991). In comparison with this large body of research on the COG movement attributes there have been fewer studies (Murray et al., 1975; Nichols et al., 1995; Schwab et al., 2006) which consider location of COG within the BOS in steady state stance.

The displacement of the COG is influenced by both the speed and the direction of movement (Pai & Patton, 1997). However, as the COG moves away from its central location towards one of the boundaries of the BOS there is a smaller distance to travel and less time in which to correct shift before the COG exceeds the BOS limits resulting in a loss of balance and possibility of a fall incident (Berger et al., 2005b; Merlo et al., 2012). Reduction in the temporal and spatial factors such as speed and direction of movement when the COG moves closer to boundaries of the BOS become more relevant in older adults because of the declines in sensory (Baloh et al., 2003; Ivers et al., 2003; Low Choy et al., 2008; Menz et al., 2005; Peters et al., 2016)}, central (Lockhart et al., 2005; Yordanova et al., 2004) and musculoskeletal (strength and flexibility) function (Illing et al., 2010; Lockhart et al., 2005; Menz et al., 2005; Nitz & Low Choy, 2004) associated with ageing. These age-related changes in conjunction with age-associated qualities such as increased reaction times (Allum et al., 2002; Lockhart et al., 2005), result in reduced capacity to control movement, particularly for higher velocity displacements, as the COG approaches the BOS boundaries.

Anecdotally, clinicians suggest that the COG moves posteriorly with increasing age. However, this view does not seem to be supported by the available evidence (Murray et al., 1975; Schwab et al., 2006) when stance is on a firm surface with the eyes open. These studies have shown that for healthy subjects the mean COG remains in a similar location within the BOS for comfortable stance on a firm surface when the eyes are open despite increasing subject age. Other researchers have considered the impact of altered visual (Byl & Sinnott, 1991; Nichols et al., 1995) and surface (Merlo et al., 2012; Teasdale et al., 1991) conditions on the centre of pressure (COP) or COG location relative to BOS. Teasdale et al. (1991) in their study to compare young and old subjects under different vision and surface conditions found that older subjects spent a greater proportion of time away from the mean COG location than young subjects particularly when vision is obscured and the surface is altered. However, these studies do not compare changes in COG location across different age groups for the different test conditions.

There is also some evidence that the COG location within the BOS is altered in some groups such as those with chronic low back pain (Byl & Sinnott, 1991; Mientjes & Frank, 1999). Differences in the location of COG between fallers and non-fallers for different vision and surface conditions have also been identified (Merlo et al., 2012). This suggests that an understanding of the location of the COG within the BOS under a variety of sensory conditions may be more critical in the management of stability in healthy older adults and in those with pathology than it is for younger adults.

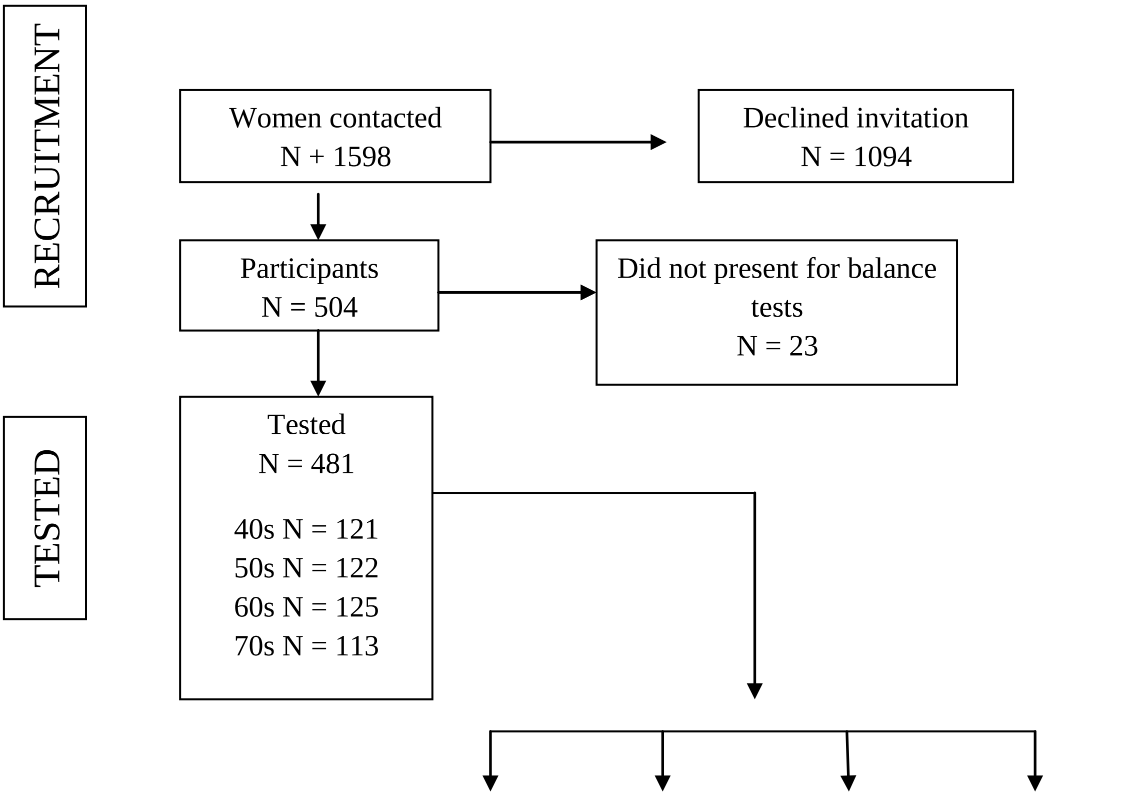
The development of a novel method to record COG location in Chapter 4 was based on one commonly used force-plate system, the NeuroCom Balance Master® 6.0, Oregon (BM). This provides the clinician with a visual representation (refer to Figure 3.2 in Chapter 3) of the start location for the COG at the commencement of each test condition trial in the modified form (mCTSIB) of the Clinical Test of Sensory Interaction in Balance (Shumway-Cook & Horak, 1986). However, it does not offer a method by which the COG location can be used to compare performance across different groups separately for each test condition. The mCTSIB was devised to assist clinicians to identify a patient's reliance on visual, somatosensory or vestibular systems by testing subjects under different surface and vision conditions and is frequently used in balance assessments**.**

The purpose of the current study was to apply the novel method of recording COG location developed in Chapter 4 to assess whether changes in the COG start location could be identified as visual and surface compliance test conditions changed and as age increased. That is, for the tests of the mCTSIB based on the BM output. This was assessed in a group of independently mobile, community-dwelling women aged from forty to eighty years. We proposed that the findings of this study from the healthy population may provide clinicians with a basis for monitoring and interpreting changes in COG location in a clinical setting.

6.3 Method

6.3.1 Participants

Four hundred and eighty-one independent, community-dwelling women who participated in the Longitudinal Assessment of Women (LAW) study (Khoo et al., 2008) were assessed on the BM. Participants were recruited randomly (Figure 6.1) according to postcode and age via the electoral roll of an urban and semi-rural area in Australia and had an age range of 40-80 years at the commencement of the study. Use of the electoral roll allowed researchers to access contact details for all women within the age range in the area (Khoo et al., 2008). It also allowed for sampling a variety of socio-economic strata of the population. The women in the study were eligible for inclusion if they were living independently within the community, were able to ambulate without the assistance of walking aids, had normal visual acuity (with or without correction) and were able to follow instructions in English. Women who were unable to walk or whose cognitive level precluded independent function within the community were excluded from this study (Nitz & Choy, 2007). This group was considered to represent a cross-section of healthy community-dwelling women in the region (Khoo et al., 2008). Ethical approval for the LAW study was obtained from the medical ethics committees of the Royal Brisbane and Women's Hospital and The University of Queensland with all participants providing written consent prior to commencement (Khoo et al., 2008).



CATEGORIZED

Age Group	FiEO (N)	FiEC (N)	FoEO (N)	FoEC (N)
40s	104	104	104	103
50s	110	108	114	114
60s	105	113	115	119
70s	105	105	107	108
UTC	59	51	41	37

Figure 6.1 Flow diagram of recruitment, testing and categorization
FiEO Firm surface, eyes open; FiEC Firm surface, eyes closed; FoEO Foam surface, eyes open; FoEC Foam surface, eyes closed; UTC Unable to be categorized as anterior or posterior.

6.3.2 Measurements

The testing for this study was conducted on the NeuroCom Balance Master® 6.0, Oregon (BM) which is a commercially available force-plate system. The force-plate consisted of a 46 x 46 x 5 cm platform which measured the ground reaction forces (COP) through the participant's feet (Chapter 3, Section 3.3.1). The mCTSIB is an abridged version of the Clinical Test of Sensory Interaction in Balance (CTSIB) (Shumway-Cook & Horak, 1986) and consists of four tests: (i) firm surface, eyes open (FiEO), (ii) firm surface, eyes closed (FiEC), (iii) foam surface, eyes open (FoEO), and (iv) foam surface, eyes closed (FoEC). The firm surface consisted of the metal surface of the force-plate while the foam surface was a closed cell, high density (3.75 lb/ft^3) piece of foam (dimensions: 46 x 46 x 13cm) provided with the force-plate at the time of purchase. This foam was placed on top of the force-plate for the compliant surface test conditions. These test conditions enable clinicians to bias somatosensory, visual and vestibular systems to better understand patient sensory reliance during steady state balance assessment. The BM software provides a diagrammatic record of the location of COG at the start of each of the three trials which are conducted for each test condition as part of the results summary. An example of the BM output from one of the participants is shown in Figure 6.2. These data for each participant were used to categorize the location of the COG for each test (Boughen, Dunn, Nitz, Johnston, & Khan, 2013) (previously presented in Chapter 4). Allocation to a sector requires that at least two of the three trials start locations fall within a sector. For the purpose of this study only locations categorized as anterior/forwards or posterior/backwards of the horizontal axis in the results diagram were used.

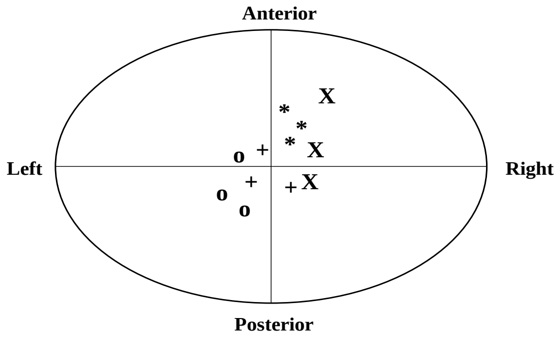


Figure 6.2 Example of centre of gravity location output as provided by Balance Master for each trial of the four mCTSIB tests.

NB: For this particular case example the categories are allocated as: FiEO (o) = posterior; FiEC (+) = posterior; FoEO (*) = anterior; FoEC (X) = anterior

6.3.3 Procedure

Each participant attended a laboratory on one occasion for assessment of standing balance. Participants were required to stand on the force plate (firm surface) with their feet apart. Stance width is determined by the BM software based on the height of the subject with the three possible width position (small (S), medium (M) and tall (T)) marked on the force plate (Figure 6.3).

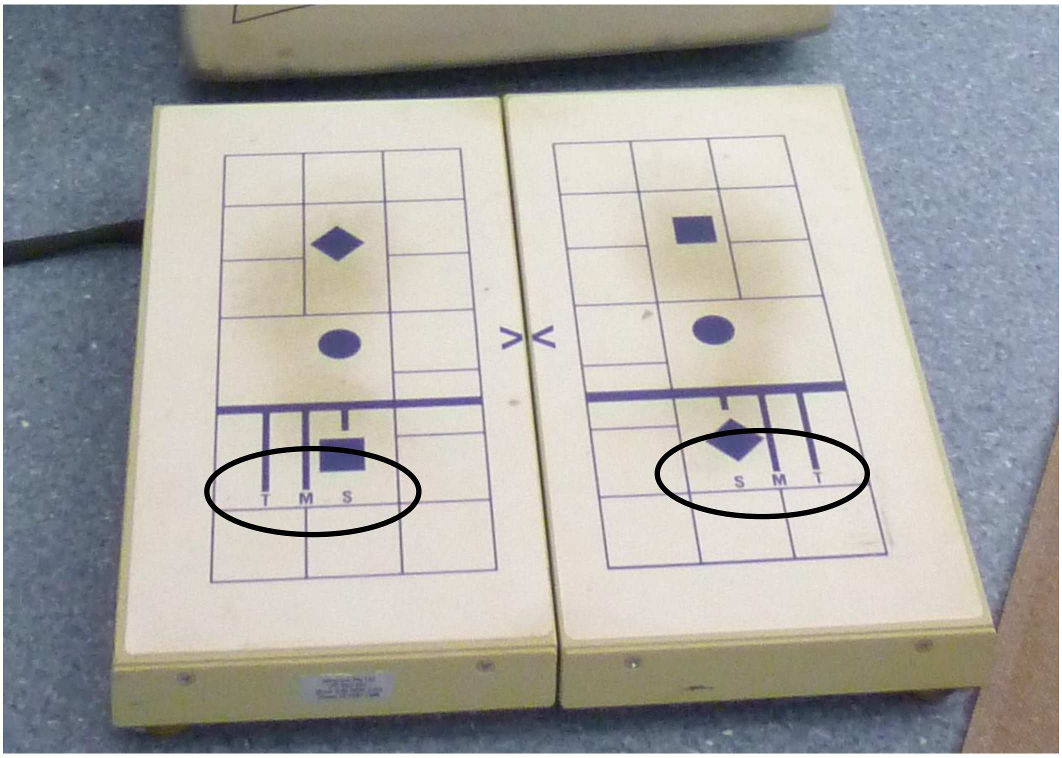


Figure 6.3 Image showing the tall (T), medium (M) and small (S) foot placement positions (circled) of the Balance Master force plate.

Three trials of each of the two firm test conditions of the mCTSIB test battery (FiEO x 3, FiEC x 3) were conducted with each trial lasting 10 seconds (Low Choy et al., 2003). A square block of foam (supplied by BM and with the same markings as for the force plate to enable consistent foot placement) was then placed on the force plate for the third and fourth tests (FoEO x3, FoEC x 3). Foot position was the same as for the firm surface condition for each participant. The method of categorization for the results of the diagrammatic record has been reported in an earlier paper (Figure 4.2 in Chapter 4) (Boughen et al., 2013).

6.3.4 Data analysis

Participants were grouped into four age groups for data analysis (40-49 years, 50-59 years, 60-69 years, and 70-80 years). These age-decade groups provided a transition from early middle- to old-age. Pearson's chi-square test was used to analyse the association between the proportions of participants with an anterior COG location for the with- and without-vision tests (FiEO/FiEC and FoEO/FoEC) and the altered surface tests (FiEO/FoEO and FiEC/FoEC). Furthermore, for each of the four tests the proportions of participants with an anterior COG location in each age decade were analysed separately in a pair-wise comparison against the 40-49 years group. The assumption of expected cell frequency (≥5) was examined in order to ensure validity of the chi-square test. Significance was set at $p<0.05$. All analyses were performed using Stata version 11.0, StataCorp LP.

6.4 Results

6.4.1 Vision

There was a significant association between the COG start location for the eyes open and eyes closed conditions in both the firm (FiEO and FiEC) ($p<0.001$) and the foam (FoEO and FoEC) ($p<0.001$) surface tests (Figure 6.4 and Table 6.1). On the firm surface a greater proportion of participants in the study started the test with the COG located anteriorly relative to the horizontal axis when eyes were closed versus eyes open (57% compared with 51%). However during the foam surface test conditions fewer participants (with the exception of the 50-59 years group) started the test with a forward COG start location when vision was removed (81% compared with 84%). That is, when standing on a compliant surface with the eyes closed, there were more participants preferring a posterior start location of their COG compared with the eyes open condition. The greatest variance between the eyes open and eyes closed tests on both the firm and foam surfaces was seen in the 70-80 years group.

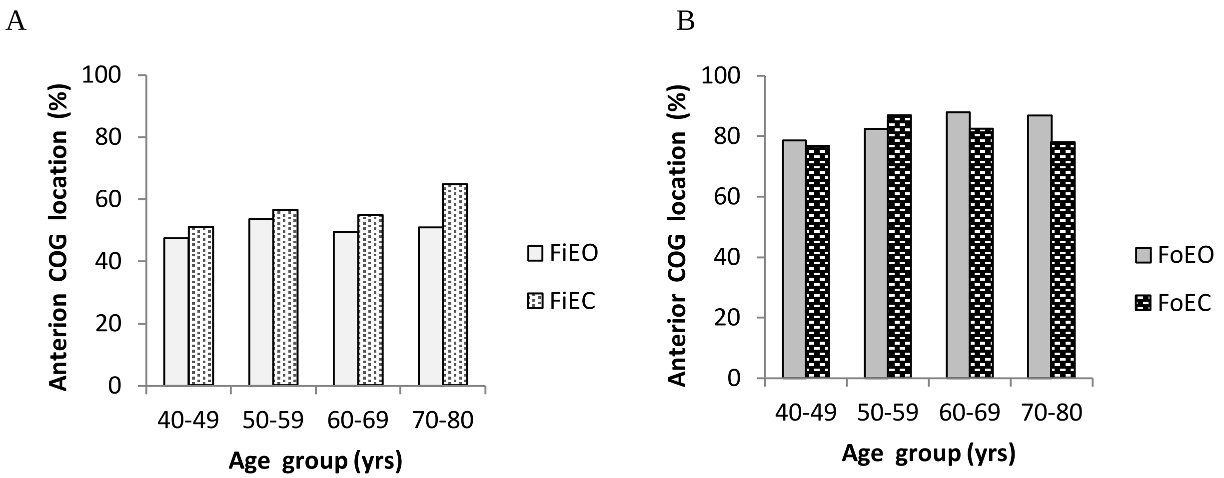


Figure 6.4 Observed proportions of participants with an anterior COG location when vision changes from eyes open to eyes closed on a firm (A) then a foam (B) surface.

FiEO=Firm surface, eyes open; FiEC=Firm surface, eyes closed; FoEO=Foam surface, eyes open; FoEC=Foam surface, eyes closed; COG=Centre of gravity.

6.4.2 Surface compliance

There was a significant increase (p<0.001) in the proportion of participants with an anterior start location of the COG in tests on a compliant surface (Figure 6.5 and also Table 6.1)) compared with a firm surface. These results were significant for comparison between the surfaces when the eyes were open (51% on the firm surface compared with 84% on the foam surface) and also when the eyes were closed (57% on the firm surface compared with 81% on the foam surface).

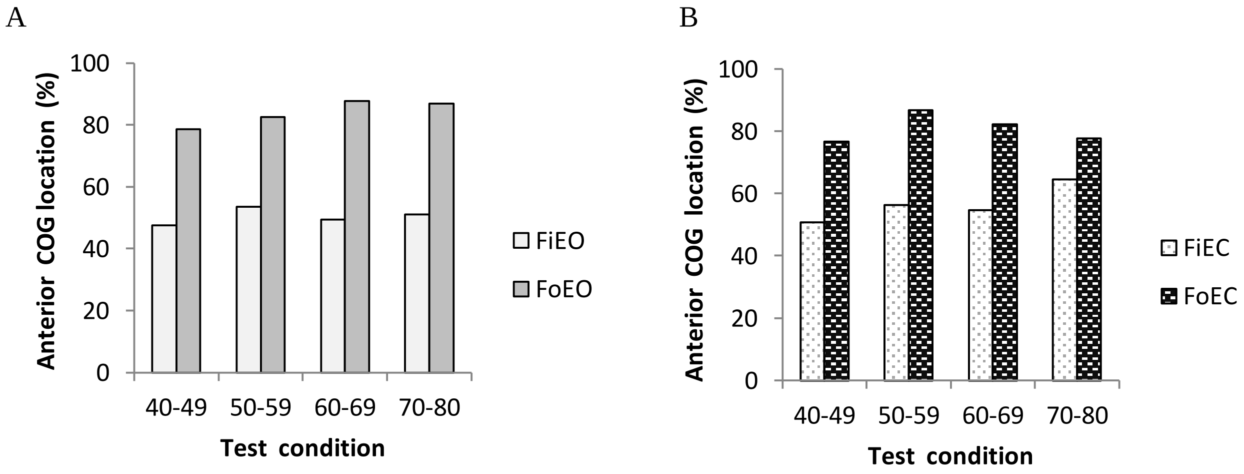


Figure 6.5 Proportions of participants with an anterior COG location when the surface alters from a firm to a foam surface with eyes open (A) and eyes closed (B).

FiEO=Firm surface, eyes open; FoEO=Foam surface, eyes open; FiEC=Firm surface, eyes closed; FoEC=Foam surface, eyes closed; COG=centre of gravity.

6.4.3 Age

There was no significant association overall with increasing age for the anterior start location of the COG for any of the four test conditions (Figure 6.6). However, when each age decade was tested separately in a pair-wise comparison against the 40-49 years group there were significant effects with age for the FiEC only in the 70-79 years group (64.8% in the 70-79 years group compared with 60% in the 40-49 years group; p=0.04) and for the FoEC test only in the 50-59 years group (86.8% in the 50-59 years group compared with 76.7% in the 40-49 years group; p=0.05). In each case a significantly greater proportion of participants started the test anterior or forward to the horizontal axis compared with the 40-49 years group. While not significant, there was a tendency for participants in the 60-69 years group (87.8%) to have a greater proportion of forward start positions for the FoEO test (p=0.07) when compared with the 40-49 years group (78.6%).

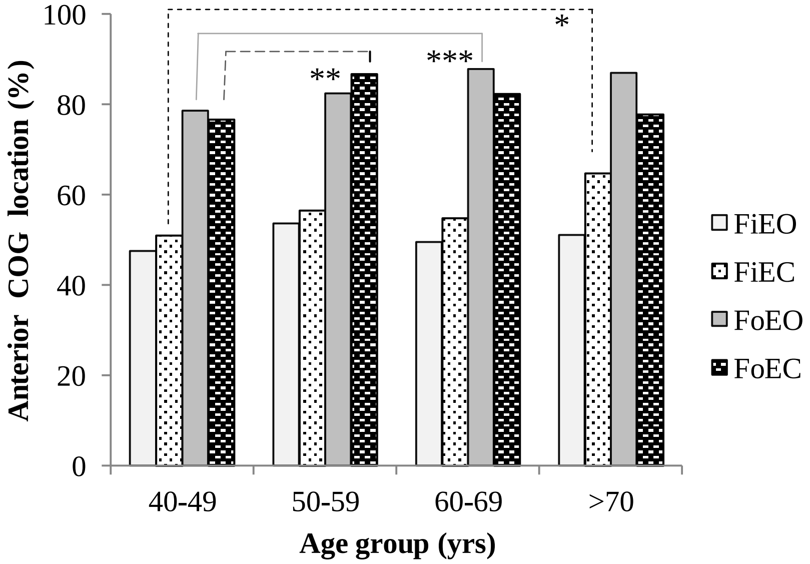


Figure 6.6 Observed proportions of participants with an anterior COG location for modified Clinical Test of Sensory Interaction on Balance.
FiEO= Firm surface, eyes open; FiEC= Firm surface, eyes closed; FoEO= Foam surface, eyes open; FoEC= Foam surface, eyes closed; COG= centre of gravity.
*p=0.04; **p=0.05; ***p=0.07

Table 6.1 Proportions of participants with an anterior COG location for each of the four tests of the mCTSIB

Test	**Proportion with an anterior COG location (%) by age group**			
	40-49 years	50-59 years	60-69 years	70-80 years
FiEO	47.5	53.6	49.5	51.1
FiEC	60.0	56.5	54.9	64.8
FoEO	78.6	82.5	87.8	86.9
FoEC	76.7	86.8	82.4	77.8

COG=Centre of gravity; mCTSIB=modified Clinical Test of Sensory Interaction in Balance; FiEO=Firm surface, eyes open; FiEC=Firm surface, eyes closed; FoEO=Foam surface, eyes open; FoEC=Foam surface, eyes closed.

6.5 Discussion

The use of the start location of the COG in the mCTSIB in this study provides the clinician with an objective measure of COG location in the antero-posterior plane in order to record changes in COG location. The focus on healthy community dwelling women aged from 40-80 years in this study has highlighted the adjustments made to COG location by healthy older women when there are changes in visual and proprioceptive inputs. The mCTSIB is frequently used in the assessment of balance to better understand the separate contributions of the visual, proprioceptive and vestibular systems to the individual's balance integrity. When vision is removed (FiEC) there is greater reliance on proprioception and vestibular systems to retain balance. When the surface is manipulated by using a foam surface to stand on (FoEO), proprioception is confounded so that reliance is on the visual and vestibular systems for balance. When both vision and surface are manipulated in the FoEC condition only vestibular function is not confounded. Older adults have been found to be more reliant on inputs from proprioception than on the visual and vestibular systems as balance is challenged (Wiesmeier et al., 2015). Proprioceptive acuity may be predictive of dorsi- and plantar-flexor muscle function for antero-posterior motor control in older adults (Craig, Goble, & Doumas, 2016) and has been found to be associated with both subjective and objective measures of balance (Deshpande et al., 2016).

In this study no significant difference was found between younger and older adults in the preferred anterior/posterior start location of the COG for stance on a firm surface with the eyes open (FiE0) using a categorical method of recording COG location. When test difficulty progressed from vision obscured on a firm surface (FiEC) to stance on a foam surface with vision (FoEO), a significantly greater proportion of participants started the test in an anterior location relative to the predicted centre of balance. However, for stance on a foam surface when vision is obscured (FoEC) compared to the FoEO condition, there was a lesser proportion of participants with a preferred anterior COG location in the older age groups. These findings suggest that for healthy women, a more anterior starting position of the COG is preferred with each progression in difficulty as test difficulty increases from FiEO to FiEC to FoEO but with a further increase in difficulty as sensory input is further reduced (FoEC), fewer women preferred an anterior starting position compared to the FoEO test condition. These findings need to be taken into consideration when training patients under altered surface and vision conditions to ensure safety.

Few studies consider the antero-posterior COG location in steady state stance in healthy adults. Those which have studied the COG location report the mean location (Geiger et al., 2007; Murray et al., 1975; Schwab et al., 2006) for tests. None of these studies report on the effect of manipulating vision and surface simultaneously. Some similarities have been identified between the mean location results for the above studies (based on distance measures) and the results of this study of the start location of COG using the categorical method to record COG location. Results from this study (Study 3) agree with other authors who have found that the mean location of the COG within BOS does not significantly change across age groups when subjects stand on a firm surface with eyes open (Murray et al., 1975; Schwab et al., 2006). The comparison between groups in the current study also identified that the proportions of adults with an anterior COG location were similar for all four age groups in the study (Table 6.1).

There were significant differences found in this study (Study3) for the COG start location between the vision and no vision test conditions and also between the firm surface and foam surface test conditions irrespective of age. Nichols et al. (1995) found that in young adults (mean age 23.6 years) the mean COG location was found to be more anterior as test difficulty increased with, for example, the removal of vision when standing on a firm surface. The findings for the start location of COG in Study 3 also suggest a similar effect for stance on a firm surface in the older participants (ages 40-80 years) when COG location is compared between the vision and no-vision tests on a firm surface. In this study as test difficulty increased from vision enabled to vision obscured on a firm surface a significantly greater proportion of participants started the test with the COG in an anterior location.

There was a further significant increase in the proportion of participants whose COG start position was anterior when the surface was changed from a firm to a foam surface with eyes open. However, when standing on a foam surface with eyes closed (which is a more difficult test condition due to multiple sensory inputs being confounded) there was no further increase in the proportion of subjects starting the test with an anterior location of COG. In fact, except for the 50-59 years group, the opposite tendency was evident with a smaller proportion of subjects demonstrating a start COG positioned anteriorly compared with stance on foam with eyes open. The greatest variability between the eyes open and eyes closed conditions on both surface types occurred in the 70-79 years group possibly reflecting the decline in sensory acuity previously reported (Low Choy et al., 2008).

The greater propensity to start tests with an anterior start COG location as test condition difficulty increases may relate to a greater need to be ready to respond to a possible loss of balance in more difficult test circumstances by facilitating a stepping response or the grabbing of a rail should the need arise (Merlo et al., 2012). This might explain the greater proportion of subjects with an anterior COG start location when standing on a foam (less stable) surface as it may provide more options for protective strategies. The reason for fewer women in the older age groups choosing an anterior COG start location for the most difficult test (FoEC) is less clear. In this test, both vision and proprioception are confounded thus the individual must rely to a greater extent on information from the vestibular system. However, there is evidence that the integrity of the vestibular system declines in older adults (Illing et al., 2010; Park et al., 2001) perhaps impacting on the reliability of this system when it must play a larger role under reduced visual and proprioceptive conditions.

Colledge et al. (1994) found that in subjects with an age range of 20-80 years, sway path length increases both with age and as test difficulty increases with the greatest sway path length evident for the FoEC test condition in subjects older than 70 years. In addition to this, both young and older adults spend a greater time away from the mean COG location as test difficulty increases (Teasdale, et al., 1991) with the difference again being more marked in those over 70 years of age. A significant factor in the ability to control anterior displacement is toe flexor strength. Endo et al. (2002) identified reduced toe flexor strength in conjunction with reduced anterior displacement in older (>60 years) adults. Reduced toe flexor strength has also been found to be a contributor to falls in older adults (Kim et al., 2011; Mickle, Munro, Lord, Menz, & Steele, 2009). The combination of increased sway path length, increased time away from the mean COG location and reduced control with anterior displacement in older adults in conjunction with reduced vestibular function, suggest that to retain an anterior COG location when standing on a compliant surface in the absence of vision would pose a greater risk to safety for this age group.

A pair-wise comparison between the 40-49 years group and each of the other age groups in this study showed significant differences with age for the FoEC (50-59 years group) and the FiEC (70-79 years group) test conditions. It is difficult to offer concrete reasons for the significant results for age for these groups for the FoEC and FiEC test conditions and the tendency to significance for the 60-69 years group for the FoEO test condition when each was compared with the 40-49 year group. Previous studies reporting the same data set as the current study have shown reduced stability on a firm surface with the eyes closed and an increase in failure rate (an inability to maintain balance leading to a step to prevent a fall) for the FoEC test condition for women in their fifties (Low Choy et al., 2003). The increases in the proportion of a preferred anterior COG start location for these age groups compared with the younger women might provide some explanation for this reduced stability. Furthermore, in conjunction with activity level and number of medical conditions, this instability seen in these older women has been shown to be a predictor for falls (Nitz et al., 2013).

Clinically, the management of clients presenting with balance difficulties begins with a comprehensive assessment. This ensures that all of the systems that are implicated in normal balance function are tested. An understanding of COG location particularly under a range of altered sensory or environmental circumstances, forms part of this detailed assessment of balance. The interpretation of which system or systems might be contributing to the balance difficulties is the basis of determining which treatment strategies are likely to be effective. When treatment choices are being made for older adults with balance deficits consideration needs to be given to the conflict that arises between a need to have the COG more anterior in more challenging balance conditions and the reduced ability to control the more anterior COG in those circumstances. Conversely, the preference for the COG to be positioned less anteriorly might also pose falls risks in a posterior direction should challenges additional to surface and vision manipulation be introduced to treatment. The ability to adjust the COG location appropriately for different environmental demands may be a factor that needs to be addressed more specifically in older adults. The findings of this study reinforce the need for an objective measure of COG location in the clinical setting.

The categorized BM outputs from the mCTSIB that were used in this study might be considered to be indicative of COG start positions that reflect healthy women between 40 and 80 years of age. Because of the ability to interpret these data provided by the BM from the perspective of sensory function, the current study results might facilitate the monitoring of COG changes for both assessment and treatment purposes in the clinical setting, particularly for groups of subjects with various pathologies by providing here a benchmark for women without serious pathology.

One of the strengths of this study is the large number of participants in each age decade. Further, this would seem to be the first time that an existing protocol (mCTSIB on the BM) has been explored to enable an enhanced understanding of COG location for use in the clinical setting. While outcomes in this study may have been hampered by a lack of sensitivity from using just the start position when analysing the COG location, the results show promising agreement with other studies. Limitations of this study include: (i) the inclusion of women only, (ii) the inability to identify the sources for the differences found, and (iii) due to the cross-sectional design, predicting how an individual's COG start location might change over time was not possible.

Further research using this method of COG analysis is warranted to investigate whether (i) similar changes can be identified in healthy, community-dwelling men, (ii) the COG start location differs in the presence of various pathologies, and, (iii) if it might be possible to differentiate between fallers and non-fallers. The ability to monitor COG location in assessment and in treatment will provide the clinician with additional information in the management of clients with balance impairments.

CHAPTER 7

Does start location of centre of gravity change as base of support configuration changes and as age increases? (Study 4)

The novel categorical method of recording centre of gravity location was able to demonstrate variations in antero-posterior location between test conditions of the modified Clinical Test of Sensory Interaction on Balance and between age decades in a large group of women. Further exploration is warranted to determine whether the method of categorization of the start location for COG in each of the mCTSIB test conditions can also demonstrate variability as base of support configuration is altered and age increases.

7.1 Abstract

Background/Purpose: A novel categorical method has been developed to record centre of gravity (COG) location from force plate data. The purpose of this study was to determine whether this novel method was sensitive enough to detect changes in COG location, similar to those described in the literature for other methods of recording, when the base of support (BOS) configuration is altered. The impact of increasing age was also evaluated.

Method: Eighty-one healthy participants (Men = 31; age range 30-80 years) were recruited from the community and divided into three age groups (30-49yrs, 50-64yrs, 65-80yrs). In one session participants were tested for three trials for each of six test conditions (Feet apart, with eyes open then closed (FAEO, FAEC); Feet together with eyes open then closed (FTEO, FTEC) and single limb stance on both the left (LSLS) and right (RSLS) foot). Using a Kistler force plate system the COG location was recorded at the commencement of each test trial and this location was then allocated to an anterior or posterior location based on the frequency of location from the 3 trials.

Results: Pearson's chi square was used to determine the difference in proportion of participants who had an anterior COG location for each of the six tests. There were increasing proportions of participants with an anterior COG location as test difficulty increased from FAEO to FTEO ($p<0.001$) with the proportion with an anterior COG location rising from 42% for FAEO to 52% for FTEO. This increase in the proportion with an anterior COG location also was evident between the FIEC and FTEC tests ($p<0.01$) with 48% being anterior for the FIEC and 55% being anterior for the FTEC test. The transition to RSLS from FTEO was trended to significance ($p<0.08$) with 95% of participants having an anterior COG location in the RSLS compared with 42% in the FTEO. The comparison between the LSLS (97% with an anterior COG location) and FTEO (42% with an anterior COG location) tests was not significant. When age was considered there was a significant difference ($p=0.03$) in the proportion of participants with an anterior COG location between the 50-64 year group (100% anterior) and the 65-80 year group (86% anterior). There was also a significant difference ($p=0.05$) between the proportion with an anterior COG location between the 30-49 year group (43% anterior) and the 65-80 year group (57% anterior) for the FTEC test condition.

Conclusions: The novel categorical method of recording COG location in the antero-posterior plane is able to demonstrate significant increases in the proportions of participants with an anterior COG location as test difficulty increases.

7.2 Introduction

Assessment of clients with balance impairments requires an understanding of balance under different sensory and base of support (BOS) size conditions as well as changes that may occur as age increases in the normal population. This allows assessment of the adaptability of balance to the challenges that may be encountered within daily function. Such challenges include the need to adapt to narrow walkways or areas in which lightning is poor as well as the need to balance on alternate limbs when climbing or descending stairs. While there are many objective measures available to clinicians that relate to balance competency there is still no objective method available to monitor centre of gravity (COG) location within BOS and limited data on the impact of increasing age on COG in the antero-posterior plane when there is a change in the size or configuration of the BOS.

The location of the COG within the BOS is an important element in balance. When the size and/or shape of the BOS changes, the proximity of the COG to some BOS boundaries may be reduced, leaving less leeway for sway error. Reduction in the medio-lateral boundaries (for example, standing with feet together or on one foot) impacts on medio-lateral stability while reduction in the antero-posterior boundaries (for example, standing on the balls of the feet) impacts on antero-posterior stability. The impact of such reductions may be more critical in older adults than in younger adults as the former typically demonstrate greater sway path length (Amiridis et al., 2003; Murray et al., 1975) and greater sway velocity (Berger et al., 2005a; Low Choy et al., 2003) even for comfortable stance (feet apart) on a firm surface and with eyes open.

Centre of gravity location changes for the medio-lateral plane have been studied under altered BOS conditions (Danis et al., 1998; Mouzat, Dabonneville, & Bertrand, 2004) and in gait preparation (Azuma et al., 2007; Mille & Mouchnino, 1998). However, there is limited evidence relating to antero-posterior changes in COG location under different BOS size and configuration test conditions particularly as age increases. There is also little evidence on whether COG location is different for men and women under the same test conditions. Studies in a young adult population have found that COG location is more anterior for stance on one leg compared to stance with feet apart or feet together (Byl & Sinnott, 1991; Teranishi et al., 2013) and that it becomes more posterior in tandem stance compared to stance with feet apart or feet together (Nichols et al., 1995; Teranishi et al., 2013). These studies all related to groups of mixed gender. Murray et al. (1975) compared antero-posterior COG mean location for feet-apart stance and stance on one leg in three age groups in men (20-29 years (N=8), 40-49 years (N=8), 60-69 years (N=8)) finding that the mean location in each stance position did not change as age increased. However, it was noted that the oldest group (60-69 years) exhibited greater distances away from the mean COG location during sway than the younger two groups. These findings suggest that in older men the COG may have more episodes ‘close to the boundary’ thus increasing the risk of a loss of balance but due to the small number studied in each age group, such generalities might not reflect a larger population. Whether these findings are also the case for older women is unknown. Acquisition of additional information on the behaviour of the COG under differing bases of support separately for men and women across various ages may therefore be useful to clinicians in directing treatment choices thereby potentially enhancing outcomes from intervention in clients with balance impairments.

Researchers have used a variety of measures to identify COG location. Such measures include mean distance from the centre of the ankle joint (Danis et al., 1998), percentage of foot length (Maki et al., 1994; Teranishi et al., 2013), and percentage change in body weight distribution (Nichols et al., 1995). Thus there is currently no consistent method being used to document COG location in research. With the increased use of commercially available force plate systems in clinical settings there is the possibility of providing clinicians with a consistent objective method by which to record COG location in clients. One commercial system, the Basic Balance Master®, Oregon (BM), provides a diagrammatic record of COG location at the commencement of each test condition in the modified Clinical Test of Sensory Interaction on Balance (mCTSIB) with test conditions for firm surface and foam surface with and without vision. Based on the information from the BM mCTSIB output, a novel method has been developed (Chapter 4) to identify COG location (Boughen, et al., 2013). Work has been completed using this method to compare COG start location when sensory inputs are altered and as age increases in women (Chapter 6).

The aims of this study when using this novel categorical method were to explore whether, (i) variability could be detected for antero-posterior COG start location under different BOS configurations (feet apart, feet together and single limb stance) for healthy adults aged between 30 and 80 years, and, (ii) this variability differed between age groups.

7.3 Method

7.3.1 Participants

This cross-sectional observation study was designed to collect data from 89 participants between the ages of 30-80 years with equal gender and age distributions. However, the time scale for the study resulted in a reduced recruitment number (N=81). All participants were required to be independently mobile within the community with no mobility aids or devices. The main exclusion criterion was that they should have no known pathology that might impact on balance, such as neurological diagnoses or current problems with dizziness, known sensory or vision loss, or joint pain. Of the 92 responders who agreed to participate in the study, 11 were ineligible due to ill-health (N=3) or lack of availability (N=8) for testing. This resulted in 81 participants, 31 of whom were males. As the number of participants was reduced they were divided into three age groups (30-49, 50-64, 65-80 years) instead of the five age decades originally planned. These age groupings covered an age group prior to changes in balance (30-49 years), an age group during which changes have been demonstrated (Low Choy et al., 2003; Nolan et al., 2010) (50-64 years) and an age group following those balance changes (65-80 years). Participant characteristics are shown in Table 7.1. Ethical clearance for this study was obtained from the University of Queensland Medical Research Ethics Committee (Approval Number 2013001298) (Appendix 1). Each participant was provided with an information pamphlet about the study and provided signed consent prior to the commencement of testing.

Table 7.1 Participant characteristics

Age group	Participant characteristics	Gender	
		Male	Female
30 - 49 years	Number	11	15
	Age in years (SD)	37.45 (6.33)	39 (6.92)
	Height (cms) (SD)	173 (4.96)	163.27 (6.39)
	Weight (kgs) (SD)	76.14 (7.63)	58.21 (6.98)
	Physical Activity (≥4)	72%	67%
	Meds (≥4)	0	0
50 - 64 years	Number	11	26
	Age in years (SD)	57.54 (3.3)	58.12 (4.72)
	Height (cms) (SD)	177.73 (5.87)	162.65 (6.38)
	Weight (kgs) (SD)	80.98 (8.74)	65.64 (14.82)
	Physical Activity (≥4)	100%	73%
	Meds (≥4)	0	4%
65 - 80 years	Number	9	9
	Age in years (SD)	71.89 (3.98)	71.56 (4.93)
	Height (cms) (SD)	175.56 (4.88)	162.44 (8.53)
	Weight (kgs) (SD)	81.79 (11.51)	64.80 (8.13)
	Physical Activity (≥4)	89%	78%
	Meds (≥4)	44%	11%

SD = standard deviation; Meds= Prescription medications

7.3.2 Measurements

As discussed in Chapter 3, because of the BOS options being limited on the BM, an alternative force plate system was used for this study. Centre of pressure (COP) data were collected from a Kistler force plate (40 x 60cms) that utilised a specifically designed Matlab (MathWorks®) software programme for analysis. This COP data was converted by the software programme to provide COG locations within the various BOS configurations studied. Conducting the study on the Kistler force plate enabled the use of customized software and more flexibility of BOS size than is available on the BM. The tests conducted were standing with feet apart and eyes open (FAEO) then eyes closed (FAEC), feet together with eyes open (FTEO) then eyes closed (FTEC), and single limb stance for both the left (LSLS) and right (RSLS) feet with eyes open. Three, ten-second trials were conducted for each of the six tests. Tests were conducted on a firm surface only as the altered sensory test conditions of the mCTSIB were addressed in an earlier study (Chapter 6). The location of the COG was recorded at the commencement of each BOS condition test trial. Based on a method devised previously (Chapter 4) (Boughen et al., 2013) the COG location at the commencement of each test trial was designated as anterior or posterior of each participant's predicted centre of balance. The predicted centre of balance for each participant was derived by a formula based on the subject's height and the assumption that the centre of mass of the body in standing lies 2.3° anterior of the medial malleoli (previously discussed in section 3.3.5 of this thesis). At least two of the three trials for each condition of BOS were required to be anterior (or posterior) for the location to be allocated to an anterior or posterior category respectively.

In addition to details of height and weight of participants, data collection included information relating to physical activity level (Hirvensalo et al., 2000) (Table 7.1) and prescription medications currently being taken as these two parameters might vary across age groups and needed to be excluded as possible influences on COG position. The activity level categories (Hirvensalo et al., 2000) provided a categorical classification that was easy to use with participants and which has been shown to provide an accurate measure of activity levels (Webster et al., 2011). For older adults, the use of four or more prescription medications has been suggested to be a predictor of falls (Robbins et al., 1989). Furthermore, higher activity levels and lower use of prescription medications would be consistent with a healthy participant group.

Table 7.2 Description of Physical Activity Levels

Physical Activity Levels	Descriptor
1	Moving only for necessary chores
2	Participating in outdoor activities 1 or 2 times per week
3	Participating in outdoor activities several times per week
4	Exercising 1 or 2 times per week to the point of perspiring or puffing
5	Exercising several times per week to the point of perspiring or puffing
6	Keep-fit heavy exercising or sport several times per week

7.3.3 Procedure

All tests for this study were completed in a single test session. Participants stood in bare feet on the Kistler force plates. Testing order was FAEO, FAEC, SLS (the participant could choose whether to start on the left or the right foot) followed by FTEO and FTEC. Three, ten second trials were undertaken for each test condition. A template to replicate foot position used on the NeuroCom Basic Balance Master® was secured to the force plate to ensure consistent foot placement between subjects (Figure 7.1). The BM template was positioned on the Kistler force plate such that the zero point for the antero-posterior axis was aligned. This was used in order to facilitate comparison between force plate systems for other aspects of the study not reported here. Foot width for the FA tests was determined by the height of the participant with three possible widths: (i) Small (S) = 76-140cms (ii) Medium (M) = 141-165cms and, (iii) Tall (T) = 166-203cms. This resulted in distances between the lateral borders of the heels of 19cms, 26cms and 30.5cms respectively. The medial malleoli were positioned over the thick, horizontal line of the template. Prior to moving the feet after the FA tests, the participant was asked to nominate in which order, left or right, to do the SLS tests as it was considered that order was not a critical factor for this test. If the left foot was nominated, the participant was requested to leave that foot in place on the force plate following the FA tests. The alignment for the FT tests was with the feet side by side on the central double line of the template with left and right medial malleoli and first toe of the left and right feet in contact if possible. Again the medial malleoli were on the thick, horizontal line for the antero-posterior alignment. Instructions for the FA and FT tests were for the participant to stand with arms relaxed by the side and looking straight ahead. For the SLS tests an additional request was that the legs should not come into contact with each other during the test trial time (10 seconds). The raised foot was placed back down on the force plate at the end of each of the three test trials for the SLS tests.

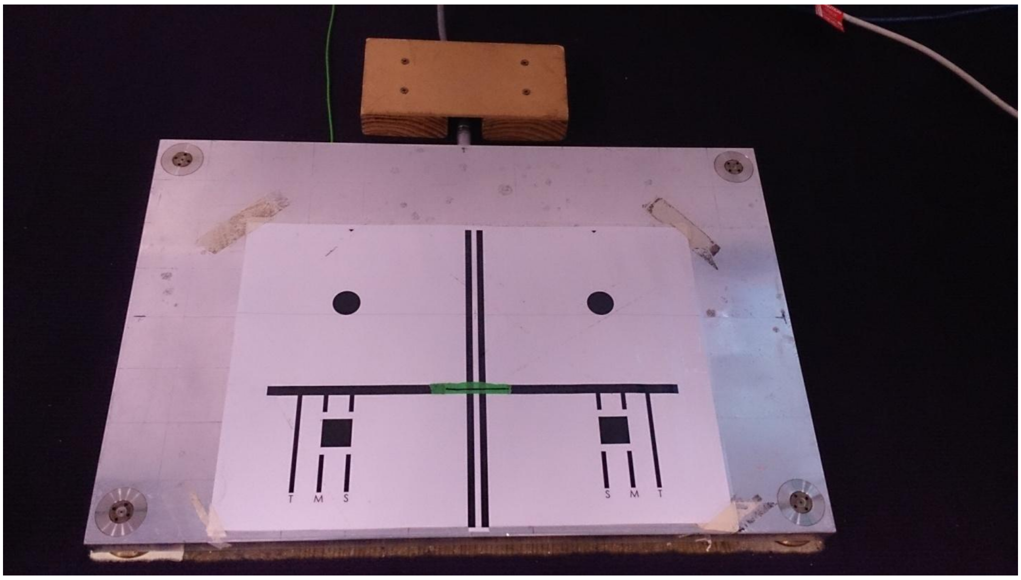


Figure 7.1 Template used for foot placement based on the positions used for the NeuroCom Balance Master (BM). T = Tall; M = Medium; S = Small.

7.3.4 Data Analysis

The proportion of participants with an anterior or posterior COG start location was recorded for each of the six test conditions. Pearson's Chi-square test was used to examine the association between tests for an anterior COG location when each test was compared to the FAEO test (that is, FAEO was compared separately with FTEO, RSLS and LSLS while FAEC was compared with FTEC). To ensure validity of the chi square test, expected cell frequency (≥5) was examined. For tests in which an expected cell frequency of ≥5 was not fulfilled, Fisher's exact test was applied. Furthermore, a pairwise comparison was conducted using Pearson's Chi-square, to compare the youngest to oldest and middle to oldest age groups for each of the six test conditions. All analyses were performed using Stata version 13.0 and significance was set at $p \leq 0.05$.

7.4 Results

Figure 7.2 shows the flow chart for participant recruitment. Results were not retrievable for all participants in all tests. In some tests (particularly the SLS tests) some participants in the older group were unable to achieve balance in this position (4 out of 18 participants) for the 10 second test duration. Participant characteristics are shown in Table 7.1. In addition, the majority of participants were right dominant. That is, the preferred skill limb for the majority of participants was the right lower limb. A preliminary analysis of data using Pearson's chi square showed no differences between genders for activity levels or prescription medications. There was also no significant difference for each of the test conditions based on gender. As a result, all subsequent analyses were of the whole group of participants rather than separately by gender. The proportion of participants with an anterior COG location for each test by age group is presented in Figure 7.3. This represents the observed proportions of participants with an anterior COG location relative to each individual's predicted centre of balance, for each test conditions in each of the three age groups. There was a significant difference ($p<0.01$) in the proportion adopting an anterior COG start location when the BOS was reduced from a feet apart position (FAEO) to a feet together position (FTEO) with significantly more participants having an anterior COG location for the FTEO test condition (51.9%) compared with the FAEO test condition (41.8%). When the eyes were closed in the feet apart (FAEC) and feet together (FTEC) tests there was also a significant increase ($p=0.01$) in the proportion of participants with an anterior COG location for the feet together test condition (48.1% for FAEC compared with 54.7% for FTEC).

No significant difference was demonstrated for the proportion of participants with an anterior COG location when FAEO and FTEO were compared separately with LSLS and RSLS. The observed proportions of participants with an anterior COG location were considerably larger in both right (94.5%) and left (97.4%) single limb stance compared with the feet apart (41.8%) and feet together (51.9%) tests with the eyes open (Figure 7.3). This was the case for all age groups. It is interesting to note the difference in anterior COG location between left and right single limb stance and particularly for the oldest group who were less likely to use an anterior COG location in left single limb stance.

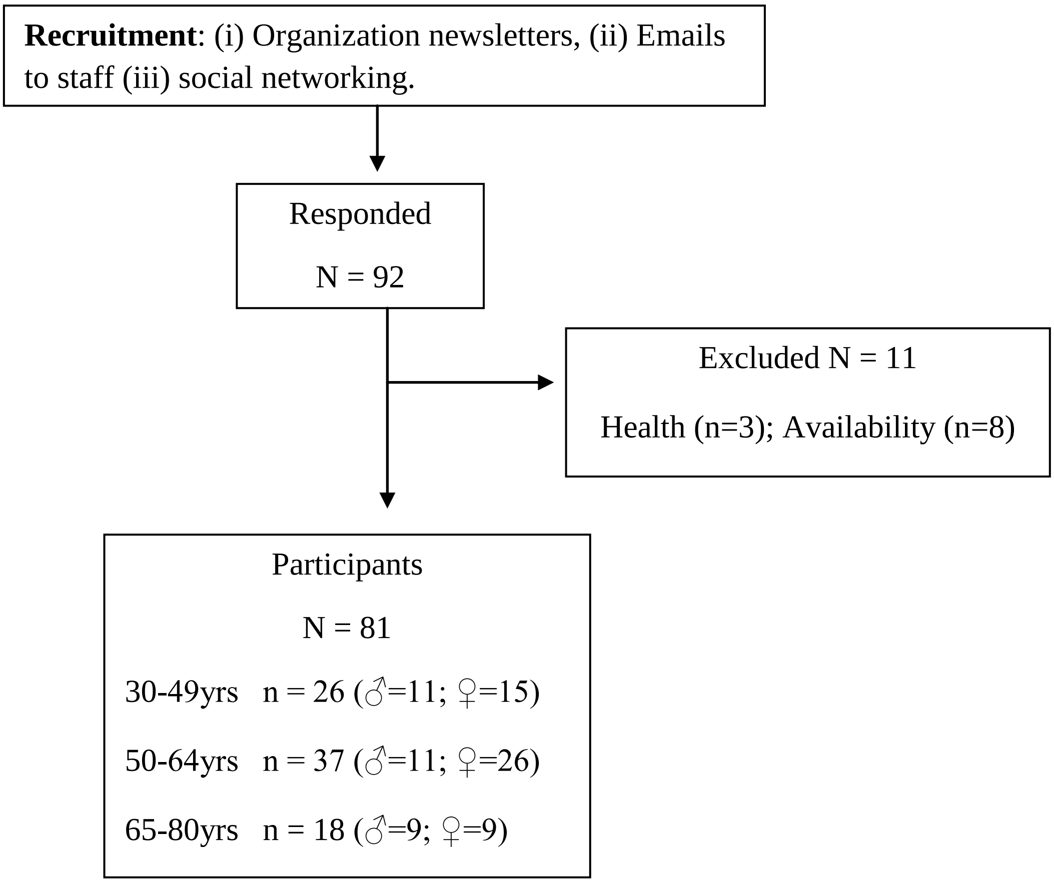
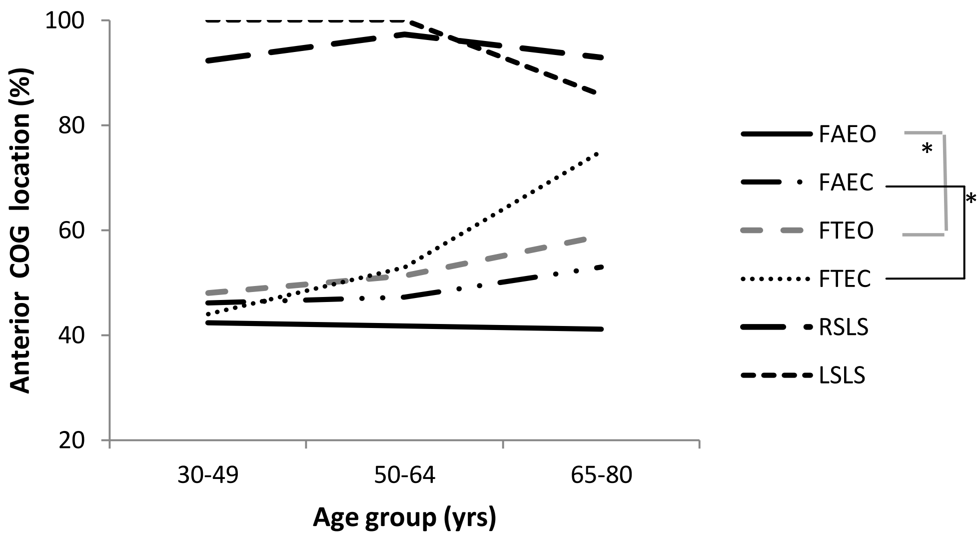


Figure 7.2 Flow chart of participant recruitment



*p ≤0.01

Figure 7.3 Proportions of participants with an anterior centre of gravity for six test conditions. FAEO = feet apart, eyes open; FAEC = feet apart, eyes closed; FTEO = feet together, eyes open; FTEC = feet together, eyes closed; RSLS = right single limb stance; LSLS = left single limb stance.

There was an interaction between age and the LSLS test (p=0.03). A pair-wise comparison showed a trend to significance (p=0.07) between the middle and oldest age groups for LSLS but not between the youngest and oldest groups. In this test a smaller proportion of participants in the oldest group had an anterior COG location compared with the middle group. There was also a significant difference (p=0.05) between the youngest and oldest groups for the FTEC test with a larger proportion of participants in the oldest group having an anterior COG location compared with the youngest group.

7.5 Discussion

This study found that a significantly greater proportion of participants had an anterior COG location (relative to the predicted centre of balance of each individual) when the medio-lateral dimensions of the BOS were reduced from stance with feet apart to stance with feet together for both the eyes open and eyes closed conditions. Although statistical significance was not demonstrated 95-97% of participants demonstrated an anterior COG location in the single limb stance tests compared with 42-48% in the feet apart tests. Significant shifts to a more anterior COG location for stance with feet together (Nichols et al., 1995) and for single limb stance in a mixed group of young men and women (Teranishi et al., 2013) and also for men alone across three age groups (Murray et al., 1975) have been reported in previous studies using other methods of recording COG location. These other methods consisted of percentage change of body weight distribution away from the centre of the BOS (Nichols et al., 1995), the location as a proportion of the participant's foot length measured from the heel (Teranishi et al., 2013) and the mean distance from the tubercle of the navicular bones of participants (Murray et al., 1975). The similar findings from this study when the categorical method is used to monitor COG location in the antero-posterior plane, lend support to the use of this method for group comparisons. When the BOS width was reduced from stance with feet apart to stance with feet together, there was a significant increase in the proportion of participants with an anterior COG location for the feet together test conditions. This result is similar to other studies which used different methods to record COG location (Danis et al., 1998; Nichols et al., 1995). Nichols et al. (1995) suggest that the anterior shift of the COG, when moving from feet apart to feet together stance, brings the COG closer to the geometric centre of the BOS thus increasing the distance from BOS boundaries and reducing risk of loss of balance as the test difficulty increases. The greater increase in the observed proportion of older participants (65-80 years) using this strategy of moving the COG more anteriorly might be a reflection of reduced balance competency for a narrowed BOS in this age group, particularly when the eyes are closed.

For all age groups a greater proportion of participants had an anterior COG location when the BOS changed from feet together to single limb stance. This is in agreement with other studies for both young adults (age range 19-32 years) (Teranishi et al., 2013) and also for older adults (age range 60-70 years) (Murray et al., 1975) using other methods to record COG location. In the latter study COG location was compared across three age groups (20-30 years, 40-50 years and 60-70 years) with each age group producing a similar result. The oldest group in the current study (Study 4) included participants up to 80 years of age and the same strategy of a more anterior COG location was evident also in this older group compared with the feet together stance.

It has been well established that the function of physiological systems declines as age increases. Declines have been demonstrated for vision (Foran et al., 2003; Haran et al., 2010), somatosensation (Choy et al., 2007; Lord et al., 1991), vestibular (Illing et al., 2010; Park et al., 2001) function as well as reduced central processing speeds (Lockhart et al., 2005; Yordanova et al., 2004). Study 4 has found that despite these physiological changes associated with ageing, the mean location of COG in the antero-posterior plane remains relatively consistent for the FAEO test across age groups in a healthy population. This is in agreement with the study by (Schwab et al., 2006) for a group of men and women for stance on a firm surface with the feet apart and eyes open.

The current study has found that this is also the case for the feet together test with eyes open and also when the eyes were closed for the feet-apart test. There were, however, significant differences between the youngest and oldest age groups for the FTEC test (an increase in proportion with an anterior COG location in the oldest group) and between the middle and oldest age groups for the LSLS test (a decrease in the proportion with an anterior COG location in the oldest group).

Older adults rely more on visual input for balance as the function of proprioceptive (Lord et al., 1991; Low Choy et al., 2008) and vestibular (Illing et al., 2010; Park et al., 2001) systems declines. As well as this, older adults demonstrate a smaller limits of stability area (Berger et al., 2005a; Slobounov et al., 1998) and larger sway path lengths (Patla et al., 1990; Slobounov et al., 1998) within that smaller area. It is not surprising then that the FTEC test in which vision was removed and the BOS reduced, resulted in a greater shift towards the centre of the BOS (that is, a shift anteriorly) for the oldest adults in this study.

It is difficult to interpret the different proportions of participants with an anterior COG location for left and right SLS as well as the significant reduction in those adopting an anterior COG location in the oldest age group compared to the middle group for the LSLS test even though the majority still preferred the anterior COG position. In young adults (Teranishi et al., 2013) found no difference in COG location between stance on the left or right foot. In a study of men across three age groups (young, middle and older) (Murray et al., 1975) also found no difference in the COG location between the dominant and non-dominant limbs for single limb stance for any group. However, other studies have observed some differences between dominant (preferred limb used for skilled activities) SLS and non-dominant (preferred stance limb) SLS in groups of young adults (Clifford & Holder-Powell, 2010; Vieira, Coelho, & Teixeira, 2014). These researchers found an increased range of COP sway in LSLS (Clifford & Holder-Powell, 2010) and greater stability in RSLS (Vieira et al., 2014) respectively. For the participants in both of these studies the left lower limb was the non-dominant limb and the right lower limb was the dominant limb.

The majority of participants in this study preferred the right lower limb for skilled actions such as kicking a ball, with the oldest group being older than those in the study by Murray et al. (1975). It may be that in older adults there is a change in COG location for single limb stance between the dominant (skill preferred) and non-dominant limbs (stance preferred) compared with younger groups. While those in the younger groups consistently adopted an anterior COG location for LSLS, the older participants did not. It is possible that the difference in control of the COG location between the dominant and non-dominant limb might be an indicator of altered balance competence in this older age group.

Adjustments to BOS size and shape are required throughout daily function. The ability to negotiate narrow walkways, stairs, small spaces and obstacles require a capacity to alter the BOS to accommodate the environment and the functional goal. The findings from this study highlight the changes that occur to the COG location when managing functional tasks that result in BOS narrowing. The ability to appropriately modify COG location in these contexts may be a critical factor in successful balance in such conditions. The use of this categorical method to identify COG location in clinics in which the BM or other force plate systems are used provides potential for additional information to assist clinicians in formulating optimal treatment plans for clients with compromised balance. It may help to clarify differences in adaptability between wider and narrower stance positions. It might also provide an objective method to document COG location for clients. The limitations of this study were the low participant numbers which did not enable gender differences to be considered for each age group, and, that the categorical measure lacks sensitivity to monitor small changes in COG location so its use might be limited to between-group comparisons rather than within-subject change.

Further research is warranted to explore whether the differences found for this study between LSLS and RSLS using the categorization method of recording COG location can be replicated for other participant groups of similar age and also whether the COG location under different BOS configurations differs with pathology.

CHAPTER 8

Levels of agreement between start and mean centre of gravity location under altered sensory and base of support conditions (Study 5)

The categorical method of recording centre of gravity start location in the antero-posterior plane has been shown to demonstrate differences in location as base of support surface and configuration change in Studies 3 and 4. It has also been shown, with few exceptions, to be relatively consistent across age groups. These findings are consistent with other researchers who use different methods of recording location based on the mean location of centre of gravity rather than the location at the start of a timed trial. However, the start and mean centre of gravity locations measured on force plates might not be interchangeable when the categorical method of recording COG location is used. Therefore further analysis is now required to determine the levels of agreement between the start location categories and the mean location categories for the different test conditions conducted in this thesis to provide confidence that if the start location is used to document centre of gravity location it might also be an indicator of the mean location.

8.1 Abstract

Background/Purpose: One commercial force plate system used in clinical settings provides information on the start location of centre of gravity (COG) for the four tests of the modified Clinical Test of Sensory Interaction in Balance (mCTSIB). Other research on COG location focuses on the mean location of COG. This study analysed the levels of agreement between the start and the mean locations of COG for a number of steady state balance tests using a categorical method to record COG location.

Method: Eighty-one adults (men = 31) aged 30-80 years (grouped 30-49 years; 50-64 years; 65-80 years) participated in the study. Start and mean locations of COG were categorized as forwards or backwards for the four tests of the mCTSIB and also stance with feet together (eyes open, then eyes closed) and single limb stance (left and right).

Results: There were substantial levels of observed agreement (>85%) between start and mean COG location for all test conditions. Levels of agreement (Kappa) were highest for the firm surface test conditions (both feet apart and feet together) with eyes open or closed. Kappa results were also moderate to high for the other test conditions (except for right single limb stance) although these also had wide confidence intervals. Agreements were less strong for the altered surface tests and single limb stance. There were some differences between age groups.

Conclusions: There are high levels of agreement between the start and mean locations of COG location particularly for the firm surface test conditions.

8.2 Introduction

Commercial force-plate systems are increasingly being used as part of the assessment process in clinical settings. The NeuroCom Basic Balance Master® (Oregon) (BM) is one such system which is designed for ease of use by clinicians to provide objective measures of both steady state (for example, the modified Clinical Test of Sensory Interaction on Balance (mCTSIB) and single limb stance (SLS)) and dynamic (for example, sit-to-stand and walking) balance. Sway velocity is the outcome variable used to quantify steadiness in the mCTSIB and SLS tests on the BM. In addition to the sway velocity, the software also provides a diagrammatic record of the centre of gravity (COG) location at the commencement of each test condition trial for the mCTSIB (previously shown in Figure 3.2., Chapter 3). However, most studies which consider COG location use the mean location of COG across the length of single or multiple trials (Carpenter et al., 2001; Geiger et al., 2007; Merlo et al., 2012). If the data provided by the BM is to be a useful record of COG location, the relationship between the start location and the mean location of COG must be considered. This additional knowledge may then provide clinicians with an objective method by which to monitor COG location in clients based on the information provided by the BM on COG location (refer to Chapter 3, Figure 3.2).

A search of the literature has been unable to identify any studies which consider the relationship between COG location for the start of test condition trials compared with the mean across all test condition trials, particularly for the antero-posterior plane. Researchers have found that the mean antero-posterior location of COG remains quite consistent for each individual regardless of the length of the test (Carpenter et al., 2001) and the age of the participant (Murray et al., 1975; Schwab et al., 2006). Two of these studies (Carpenter et al., 2001; Schwab et al., 2006) only considered stance on a firm surface with eyes open. The study by Murray et al. (1975) also studied the mean COG location for SLS and again found that the mean COG location remained relatively constant across the three (young, middle aged and older) age groups that they tested.

The purpose of this study was to identify the level of agreement between the start and the mean locations of COG under a range of sensory and base of BOS test conditions. The interaction between levels of agreement for start and mean COG location and age was also considered for each of the tests. Our hypothesis was that as test difficulty increased by successively confounding vision, proprioception and vestibular senses as well as BOS size, and as age increased there would be poorer agreement between the start and mean COG location measures.

8.3 Method

8.3.1 Participants

The study was designed to collect data from 89 subjects. Time limitations resulted in the recruitment of eighty-one healthy, independently mobile adults (31 males) with an age range of 30-80 years from the local community (previously discussed in Chapter 7, Section 7.3.1) for the study. Participants were grouped into three age groups (30-49 years (N=26), 50-64 years (N=37) and 65-80 years (N=18)). Respondents were excluded from participation if they had any known pathology (for example, diagnoses of neurological diseases, current problems with dizziness, known sensory or substantial vision loss, or joint pain) that might influence balance. In order to test H_0: Kappa = 0.06 against H_1: Kappa = 0.09 it was determined that 89 participants would be needed to achieve a power of 90% in a two-rater study.

8.3.2 Measurements

Testing was conducted on a Kistler force plate (40 x 60cms) as this allowed a greater range of data to be obtained than is possible on the BM (previously discussed in Chapter 3, section 3.3.1). We retained a protocol that was consistent with testing on the BM (Chapter 6). This included replication of the BM foot positions (Figure 8.1) for tests in which the feet were apart and calculation of each participant's predicted centre of balance (previously described in Chapter 3). The COG location was recorded at the start of each trial for all test conditions using Matlab software. In addition, this software calculated the mean COG location for each 10-second test trial. These start and mean locations were measured in millimetres from the medial malleoli. The start location was the distance in millimetres anterior to the medial malleoli at the commencement of the three test trials while the mean location, again recorded as the distance in millimetres anterior to the medial malleoli, was determined by the software based on multiple COG locations recorded during each ten-second trial. Each participant's predicted centre of balance was determined based on height and a forward lean of 2.3°. This distance (specific to each participant) was then subtracted from the measurements produced in data collection (distance from the malleoli which, based on BM outputs, was considered zero antero-posterior displacement) for each participant. When these calculations were completed, a positive number of millimetres represented an anterior COG location (category 5) while a negative number represented a posterior COG location (category 6). The rationale for applying this transformation to all COG data obtained from the Kistler force plates has been discussed in Chapter 3.

The COG locations were then categorized as being anterior or posterior relative to the centre of balance for each test trial (3 x 10sec trials per test) and then for each test (Boughen et al., 2013). At least two of the three results needed to be anterior (or posterior) to be allocated to a particular category (a full description of this method is provided in Chapter 4). The trials of test conditions conducted were: stance on a firm surface with feet apart eyes open (FiEO) then eyes closed (FiEC); stance on a foam surface, feet apart with eyes open (FoEO) then eyes closed (FoEC); stance on a firm surface, feet together with eyes open (FTEO) then eyes closed (FTEC); and, single limb stance on a firm surface on the left (LSLS) and right (RSLS) foot with eyes open.

8.3.3 Procedure

A single test session was used for data collection to gain a comparison between start and mean locations within a single test session. Participants were requested to remove all footwear prior to testing in order to eliminate between subject differences with different shoe-soles. The order of testing was FiEO, FiEC, LSLS and RSLS (the participant was able to choose preferred order for this test), FTEO, FTEC, FoEO and FoEC. Foot position was standardized by use of a template (Figure 8.1) based on that used for testing on the BM.

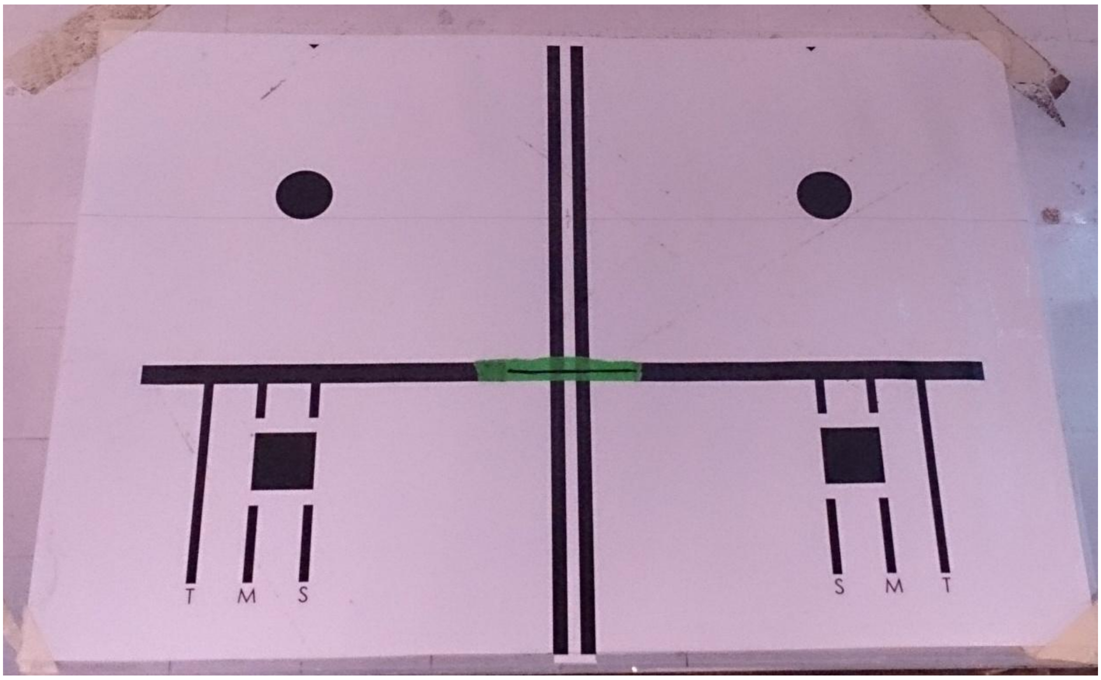


Figure 8.1 Template based on Basic Balance Master (BM) foot positions to standardise foot placement in tests on Kistler force plate.

The width of the feet apart for the FiEO, FiEC, FoEO and FoEC tests was determined by the height of the participant as per the BM protocol. Heights were categorized as small (S) (76-140cms), medium (M) (141-165cms) or tall (T) (166-203cms) with the distance between the lateral borders of the heels being 19, 26 and 30.5cms respectively. In the single limb stance tests the relevant foot was positioned again at the appropriate S, M or T heel position. The feet were aligned either side of the central vertical double lines for the feet together test with the first toe and the medial malleoli of both feet touching if possible. For all tests the medial malleoli were positioned above the thick horizontal line of the template. Participants were asked to stand quietly, looking straight ahead, with the arms relaxed by the side. Additionally, in the single limb stance tests an instruction was given that they should not allow the elevated limb to touch the stance limb during each test trial. The elevated limb was allowed to be placed down on the force plate at the end of each 10 second trial.

8.3.4 Data Analysis

Cohen's Kappa (κ) was used to determine the level of agreement between the proportions of participants who were categorized as anterior for both the start and mean COG locations for each test condition. This statistical test is appropriate for comparison of outcomes when categorical data is used. Stata version 13 was used for all statistical analyses. Interpretation of results was based on the method proposed by (Landis & Kock, 1977) which provides six classifications for strength of agreement: (i) ≤ 0 = poor, (ii) 0.01-0.02 = slight, (iii) 0.21-0.40 = fair, (iv) 0.41-0.60 = moderate, (v) 0.61-0.80 = substantial, and, (vi) 0.81-1.00 = almost perfect. As there are some limitations in the use of the Kappa statistic, the observed proportions are also presented. These limitations have been discussed previously in Chapter 3, Section 3.4. Analysis was conducted for the group as a whole rather than by age or gender. It was determined in Study 4 (Chapter 7) that there was no difference in activity level, or number of medications taken between the men and women included in this work which is the second of two aspects of studies utilising the Kistler force plate system.

8.4 Results

A sample of the data is provided in Table 8.1. The results from this study (Table 8.2) show that when using a categorical method to record COG location there is substantial to almost perfect agreement between the COG start location and COG mean location for the FiEO, FiEC, FTEO and FTEC tests, that is, for the firm surface test conditions standing on both feet with eyes open or with eyes closed. Observed agreements have been provided as further evidence of strength of agreement for these test conditions. Although both the observed agreement percentages and the Kappa values for the FoEO, FoEC and LSLS also show substantial levels of agreement, the wide confidence intervals reduce the strength of the results for these tests. The RSLS result had the weakest levels of agreement.

Table 8.1 Sample of the raw data from two participants showing recorded and adjusted distances from the medial malleoli as well as category allocations

File	htcms	sachtmms	adjzero (mms)	YmKist (mms)	adjYmtrial (mms)	YsKist (mms)	adjYstrial (mms)	Ymcat	Yscat
003_01_FOEO_01.mat	164	906.428	36.3477628	42.56469172	6.22	46.88666413	10.53890133		
003_01_FOEO_02.mat	164	906.428	36.3477628	40.63033423	4.28	52.9969479	16.6491851		
003_01_FOEO_03.mat	164	906.428	36.3477628	28.92265514	-7.43	25.2261156	-11.1216472	5	5
003_01_FOEC_01.mat	164	906.428	36.3477628	57.76201843	21.41	44.13191447	7.784151671		
003_01_FOEC_02.mat	164	906.428	36.3477628	30.74968158	-5.60	47.28098998	10.93322718		
003_01_FOEC_03.mat	164	906.428	36.3477628	46.32835298	9.98	46.45499877	10.10723597	5	5
003_01_FTEO_01.mat	164	906.428	36.3477628	45.20629175	8.86	42.02312899	5.675366191		
003_01_FTEO_02.mat	164	906.428	36.3477628	45.77150174	9.42	41.9633458	5.615582998		
003_01_FTEO_03.mat	164	906.428	36.3477628	41.1638653	4.82	40.50710463	4.159341835	5	5
003_01_FTEC_01.mat	164	906.428	36.3477628	39.69516447	3.35	39.57254233	3.224779526		
003_01_FTEC_02.mat	164	906.428	36.3477628	41.47391919	5.13	44.45744327	8.109680475		
003_01_FTEC_03.mat	164	906.428	36.3477628	45.53394516	9.19	46.63043682	10.28267402	5	5
003_01_RSLS_01.mat	164	906.428	36.3477628	46.67665287	10.33	62.34969055	26.00192775		
003_01_RSLS_02.mat	164	906.428	36.3477628	52.52544125	16.18	42.59457302	6.246810221		
003_01_RSLS_03.mat	164	906.428	36.3477628	47.6421206	11.29	49.35783197	13.01006917	5	5
003_01_LSLS_01.mat	164	906.428	36.3477628	46.00470244	9.66	33.60834186	-2.739420941		
003_01_LSLS_02.mat	164	906.428	36.3477628	48.16013969	11.81	56.25595205	19.90818925		
003_01_LSLS_03.mat	164	906.428	36.3477628	57.34513124	21.00	56.28178988	19.93402708	5	5

004_01_FIEO_01.mat	156	862.212	34.5747012	17.92352724	-16.65	14.7028902	-19.871811		
004_01_FIEO_02.mat	156	862.212	34.5747012	21.74554318	-12.83	20.4867926	-14.0879086		
004_01_FIEO_03.mat	156	862.212	34.5747012	23.06872155	-11.51	25.8674204	-8.707280803	6	6
004_01_FIEC_01.mat	156	862.212	34.5747012	23.74379943	-10.83	25.90577221	-8.668928987		
004_01_FIEC_02.mat	156	862.212	34.5747012	23.4065228	-11.17	19.57758909	-14.99711211		
004_01_FIEC_03.mat	156	862.212	34.5747012	23.20257525	-11.37	26.08786331	-8.486837894	6	6
004_01_FTEO_01.mat	156	862.212	34.5747012	25.47456134	-9.10	26.76729995	-7.807401246		
004_01_FTEO_02.mat	156	862.212	34.5747012	22.11280805	-12.46	24.21631271	-10.35838849		
004_01_FTEO_03.mat	156	862.212	34.5747012	22.58106289	-11.99	20.03774111	-14.53696009	6	6
004_01_LSLS_01.mat	156	862.212	34.5747012	40.89646849	6.32	46.3888944	11.8141932		
004_01_LSLS_02.mat	156	862.212	34.5747012	37.96688682	3.39	39.84026365	5.265562453		
004_01_LSLS_03.mat	156	862.212	34.5747012	38.19021251	3.62	30.48583119	-4.088870006	5	5
004_01_RSLS_01.mat	156	862.212	34.5747012	42.94508734	8.37	48.00516624	13.43046504		
004_01_RSLS_02.mat	156	862.212	34.5747012	45.75118988	11.18	49.71619218	15.14149098		
004_01_RSLS_03.mat	156	862.212	34.5747012	46.82154796	12.25	41.30576902	6.731067821	5	5
004_01_FOEO_01.mat	156	862.212	34.5747012	40.35712708	5.78	39.80641063	5.231709427		
004_01_FOEO_02.mat	156	862.212	34.5747012	41.8159994	7.24	38.74455931	4.169858109		
004_01_FOEO_03.mat	156	862.212	34.5747012	43.56645865	8.99	45.28649841	10.71179721	5	5
004_01_FOEC_01.mat	156	862.212	34.5747012	39.09148843	4.52	37.58690126	3.012200062		
004_01_FOEC_02.mat	156	862.212	34.5747012	39.79819634	5.22	37.98356049	3.408859295		
004_01_FOEC_03.mat	156	862.212	34.5747012	37.96895647	3.39	42.0493215	7.474620295	5	5

File=participant identification number_test session_test_trial number; htcms=participant height in centimetres; sachtmms=calculated sacral height in millimetres; adjzero=adjusted zero; YmKist= mean distance in millimetres; adjYmtrial=adjusted mean distance in millimetres; YsKist=start distance in millimetres; adjYstrial=adjusted start distance in millimetres; Ymcat=category of mean location; Yscat=category of start location; 5=anterior; 6=posterior.

Table 8.2 Levels of observed agreement and Kappa values between start and mean centre of gravity locations for all participants

Test	Observed agreement (%)	Kappa (κ) (CI 95%)
FiEO	92.4	0.84 (0.73 - 0.96)
FiEC	93.7	0.87 (0.77 - 0.98)
FoEO	95.0	0.72 (0.46 - 0.98)
FoEC	96.2	0.75 (0.48 - 1.00)
FTEO	89.9	0.80 (0.66 - 0.93)
FTEC	86.7	0.73 (0.57 - 0.80)
RSLS	93.5	0.41 (0.10 - 0.83)
LSLS	98.7	0.66 (0.04 - 1.00)

FiEO= Firm surface, eyes open; FiEC= Firm surface, eyes closed; FoEO= Foam surface, eyes open; FoEC= Foam surface, eyes closed; FTEO= Feet together, eyes open; FTEC= Feet together, eyes closed; RSLS= Right single limb stance; LSLS= Left single limb stance.

When age was considered (Table 8.2) the observed levels of agreement were, apart from two test conditions (80% for FTEC for the 30-49yrs group; 82% for FTEO for the 65-80yrs group), greater than 87%. The Kappa values were consistent for each of the three age groups for the FiEO and FiEC test conditions ranging from substantial to near perfect. When the BOS was narrowed to the feet together position the kappa values remained in the substantial to near perfect range in each of the age groups. However, the wide confidence intervals for the oldest group reduce the strength of the result for that group. Results for the SLS tests were also disappointing. Although it should be noted that for the LSLS all results (both for start location and mean location) were categorized as anterior in both the youngest and middle age groups. For tests in which the surface was altered, agreement was poor for both the youngest and oldest groups.

A Kappa result could not be achieved for the three results in which agreement was 100% between the start and mean locations. This is because in the 2 x 2 table upon which the statistical analysis is based there is a cell / or cells with no result. This produces the “too few ratings” result.

The Kappa results of zero for the RSLS test condition in the 50-64 years and 65-80 years groups, the FoEO test condition for the 65-80 year group and the FoEC test condition for the 30-49 years group suggest that agreement has occurred by chance only. However, in each of these tests the level of observed agreement exceeded 90%. The Kappa statistic is sensitive to the distribution of the marginal totals and this may limit its usefulness in this context. The only age group in which the Kappa values were consistently reliable for all tests (with the exception of RSLS) was the 50-65 years group. This group also had the highest number of participants.

Table 8.3 Levels of observed agreement and Kappa values by age group for comparison between start and mean centre of gravity location

Test	**30-49 years** (N = 26)		**50-64 years** (N = 37)		**65-80 years** (N = 18)	
	Observed agreement (%)	Kappa (κ) (95% CI)	Observed agreement (%)	Kappa (κ) (95% CI)	Observed agreement (%)	Kappa (κ) (95% CI)
FiEO	92	0.85 (0.64-1.00)	89	0.77 (0.56-0.98)	100	1
FiEC	96	0.93 (0.78-1.00)	92	0.83 (0.65-1.00)	94	0.88 (0.66-1.00)
FoEO	92	0.62 (0.14-1.00)	97	0.87 (0.63-1.00)	94	0
FoEC	92	0	97	0.89 (0.69-1.00)	100	**
FTEO	92	0.84 (0.63-1.00)	92	0.84 (0.66-1.00)	82	0.64 (0.28-1.00)
FTEC	80	0.61 (0.30-1.00)	91	0.82 (0.63-1.00)	88	0.67 (0.24-1.00)
RSLS	96	0.78 (0.37-1.00)	92	0	93	0
LSLS	100	**	100	**	93	0.63 (0-1.00)

CI = confidence interval; FiEO = feet apart, firm surface, eyes open; FiEC = feet apart, firm surface, eyes closed; FoEO = feet apart, foam surface, eyes open; FoEC = feet apart, foam surface, eyes closed; FTEO = feet together, firm surface, eyes open; FTEC = feet together, firm surface, eyes closed; RSLS = right single limb stance, firm surface, eyes open; LSLS = left single limb stance, firm surface, eyes open. ** too few rating categories (100% of participants were anterior for these tests)

8.5 Discussion

The comparison of the start and mean locations of COG in the antero-posterior plane based on the location of at least two out of three test trials (each trial lasting 10secs) has shown substantial to near perfect agreement for a range of balance test conditions conducted on Kistler force plates when participants aged 30-80 years, stood on a firm surface. These results lend strength to the findings in this study (Study 5) as other researchers also have noted the consistency of COG location of individuals in the antero-posterior plane for stance on a firm surface (Carpenter et al., 2001; Schwab et al., 2006) for healthy adults when using other methods to record COG location. While the Kappa results for the individual age groups were more variable, the levels of observed agreement remained high for all test conditions in each of the three age groups tested. We believe that this is the first time that a comparison has been made between start and mean locations of COG under a range of test conditions.

Carpenter et al. (2001) explored the impact of different test times on results for summary measures in a group of young adults. They found that for a test time of 120 seconds any subsection of the time (15, 30 or 60 seconds) yielded the same results for the mean antero-posterior location of COG. The consistency of this measure in healthy adults may provide the basis for a method to differentiate between pathologies. Certainly some differences in antero-posterior COG location have been identified in the presence of some pathologies. For example, a group of subjects with chronic low back pain have been shown to have a more posterior mean COG location (Byl & Sinnott, 1991) than controls. A link also has been found between COG location and older adults who have experienced a single fall (Merlo et al., 2012). In this instance, the COG location is more anterior.

The hypothesis for Study 5 that agreement would be reduced as test difficultly increased, was supported as results of tests on the foam surface (FoEO and FoEC) and for reduced BOS (RSLS and LSLS) produced less proportional agreement. The hypothesis was based on the finding that participants have a longer sway path length as test difficulty increases (Amiridis et al., 2003; Gatev et al., 1999; Mouzat et al., 2004) and that this might result in more differences between start and mean COG location results when using an anterior/posterior categorization method. However, the agreement levels using the Kappa statistic do not necessarily support this argument due to the wide confidence intervals. The Kappa statistic is adjusted for the levels of agreement that might occur by chance and the wide confidence intervals suggest that the levels of agreement for the more difficult tests are impacted more by chance agreement than the firm surface tests. However, the way in which Kappa arrives at the ‘agreement by chance’ conclusion may not be appropriate in some research contexts (Sim & Wright, 2005; Viera & Garrett, 2005). This may also have influenced the confidence intervals in this study.

The participants in this study represented a relatively active sector of the community with most exercising at least once or twice each week to the point of perspiring or puffing. In addition, for the younger two groups (30-49 years and 50-64 years), the majority were on either no prescription medications or were taking just one. This suggests that the results in this study are indicative of performance for healthy community ambulant adults. Although the measure used in this study is categorical rather than continuous, the results may also lend support to other studies which have suggested that the antero-posterior location of COG is maintained within a small range (Carpenter, et al., 2001; Schwab, et al., 2006) in stance. This may also suggest that greater disparity between start and mean locations of COG may be an additional feature of compromised balance control. The limitations of the study are that this is a small sample of the population and that there were insufficient participant numbers to confidently compare performance based on gender for each age group. These relatively small numbers may also have affected the statistical analyses for each age group separately.

Based on the findings of Study 5, for clinics in which force plate systems such as the BM are being used, the results relating to COG start location for the firm surface tests displayed in the mCTSIB results diagram can be interpreted as providing almost perfect agreement with each individual's mean COG location for the antero-posterior plane. This then provides an objective method not previously available to clinicians, by which COG location may be documented in the clinical setting. Further study is warranted to explore whether there are differences in the level of agreement between start and mean COG location in groups with specific pathologies.

CHAPTER 9

Discussion

The final chapter presents the main findings of the five studies of this thesis. It also considers some of the possible applications of the work as well as limitations and directions for future research.

The overarching purpose of this work was to develop a novel method of recording centre of gravity location in bipedal stance within the base of support in healthy adults and determine its sensitivity to detect changes under different test conditions and age. Consideration was given to the primary objective in steady state balance which is to maintain the COG within the BOS. One of the factors implicated in successful balance is the distance of the COG from the boundaries of the BOS. Despite the increased use of force plate systems (for example, the BM) within rehabilitation settings, there is still no objective method available to clinicians to record COG location within BOS. Limited information was identified in the literature in relation to the understanding of COG location in the antero-posterior plane particularly in the contexts of increasing age and when balance is challenged by reduced sensory inputs or an altered BOS size for healthy adults. This limited information shows that the COG moves more anteriorly within the BOS when vision is reduced, when the surface is more compliant and as the medio-lateral dimensions of the BOS reduce. Clients who present for treatment of balance impairments, undergo a range of objective tests to assist the clinician to understand the source of the dysfunction. An objective measure of COG location should also be included in balance assessments particularly under different test conditions to better understand the capacity of the client to make appropriate adjustments to COG location in different environments. This suggests that there is a gap in the knowledge required to interpret steady state balance assessment outcomes (Study 1, Chapter 2).

The gap identified pertaining to knowledge on the location of COG in the antero-posterior plane during steady state stance has been addressed, in part, by the development of the objective, categorical method to record COG location for tests conducted on force plates. Once a method was developed (based on output provided in the mCTSIB on the BM force plate system), inter- and intra-rater reliability was assessed to be reliable (Study 2, Chapter 4). Pilot studies were also conducted to test the between-session repeatability of the new categorical method and also the comparability between two force plate systems for the COG location (Chapter 5). The ability of the devised categorical method to demonstrate changes in COG location under altered sensory (Study 3, Chapter 6) and BOS (Study 4, Chapter 7) test conditions and with increasing age (Studies 3 and 4) was then assessed. Finally, the COG location provided on the BM gives a record of the location at the start of each test condition trial yet most research has focused on the mean location of COG. Thus the levels of agreement between start and mean COG locations (Study 5, Chapter 8) were examined. The findings from these five studies are discussed below.

9.1 Discussion of findings

9.1.1 Review of the literature (Study 1, Chapter 2)

The first aim of this thesis was 'To explore the literature associated with centre of gravity behaviour and location in healthy adults when sensory inputs and base of support are altered'. This gave rise to a review of the literature (Study 1, Chapter 2) which identified considerable research demonstrating decline in all of the systems required to manage balance by controlling the COG within BOS, as age increases. There was also evidence of an increase in falls incidents with increasing age which might be related to failure to control COG within the BOS. While there was considerable evidence in relation to many of the factors implicated in compromised balance (for example, sway properties such as speed and area), there was less information on and understanding of, COG location, particularly in the antero-posterior plane, under different test conditions and across different ages in healthy adults. Furthermore, a range of methods have been used to record COG location in the published research making comparisons of findings difficult. Thus the purpose of this thesis was to address this dearth of information somewhat by developing a novel method of recording COG location in bipedal stance in healthy adults.

Research into changes in balance under altered sensory test conditions has mainly focused on outcomes of sway parameters (for example, sway velocity, sway path length or sway area) or the length of time a participant is able to hold a position. These previous studies consistently showed that when vision was decreased while standing on a firm surface there is an increase in sway velocity (Lazaro et al., 2011; Low Choy et al., 2003; Magnusson et al., 1990), sway path length (Colledge et al., 1994; Haibach et al., 2007) and sway area (Hageman et al., 1995). Similarly change from stance on a firm surface to stance on a foam, or unstable, surface results in increases in both sway velocity (Low Choy et al., 2003; Merlo et al., 2012; Schieppati et al., 1994) and sway path length (Haibach et al., 2007; Teasdale et al., 1991). These effects of reduced vision and/or use of a foam surface, on sway velocity, sway path length and sway area were evident regardless of the age of the participants although they were greater in older adults than in young adults.

At the same time as sway parameters were increasing, there was a reduction in the area of the BOS within which older adults were confident to move (Murray et al., 1975) for stance on a firm surface with eyes open. That is, the limit of controlled movement in all directions was reduced. This resulted in an increase in the ratio between sway movement measures, and the amount of space within which it is perceived to be safe to move. The combination of increased movement within a smaller available control area suggests that there is a greater risk of a loss of balance control in the older population. Objective information on the location of the COG around which an individual sways may also be a factor to consider when assessing balance particularly in older adults.

In clinical settings, the Clinical Test of Sensory Interaction in Balance (CTSIB) (Shumway-Cook & Horak, 1986) is commonly used to assess balance competency under altered sensory test conditions. Although the full CTSIB comprises six tests, a modified version (mCTSIB) is frequently used. This consists of four tests: firm surface with eyes open (FiEO) then closed (FiEC) and a foam surface with the eyes open (FoEO) then closed (FoEC). The manipulation of visual inputs (eyes open or eyes closed) and somatosensory inputs (firm surface or foam surface) as well as a combination of reduced vision and foam surface, provides information about which sensory systems are most relied upon by each individual. When force plates are used for these tests the sway velocity has been shown to be the most reliable of the sway parameters to show changes in sway in the different test conditions.

Contrary to anecdotal evidence there did not appear to be a change in COG location in the antero-posterior plane as age increases when individuals were tested on a firm surface with the eyes open (Murray et al., 1975; Schwab et al., 2006). However, there was little information available for tests of stance with the eyes closed on a firm surface and for stance on a foam surface with the eyes open or closed for healthy adults across a range of ages. Similarly there were few studies into the behaviour of COG location as BOS size changes and as age increases. Clinical tests in which the size and shape of the BOS are altered assist in understanding the circumstances in which an individual might be at risk of loss of balance. For example, a narrower BOS is required when walking between on a narrow path and is a necessity on stairs when no handrail is available.

In addition to the altered responses induced by manipulation of sensory inputs, changes in measures of sway also were evident when the size of the BOS was reduced (Study 1, Chapter 2). For stance in which the BOS was reduced from feet apart to feet together there was an increase in sway path length (Gatev et al., 1999; Mouzat et al., 2004). When stance changed from feet apart to stance on one leg, increases in both sway length (Amiridis et al., 2003; Byl & Sinnott, 1991) and sway velocity (Slobounov et al., 1997) have been demonstrated. There also was evidence that there is an anterior shift in COG location when the stance position changes from feet apart to feet together (Danis et al., 1998; Nichols et al., 1995) or from feet apart to single limb stance (Teranishi, et al., 2013). These studies recorded the mean COG location as distance from the ankle joint (Danis, et al., 1998), as an expression of body weight at the centre of balance (Nichols et al., 1995), or as a percentage of foot length measured from the heel (Teranishi et al., 2013). Such a range of measures limits the ability to compare studies in order to understand consistency in results between research groups.

From this review of the literature it became evident that an enhanced understanding of COG location within BOS for healthy young and healthy older adults, particularly when balance is challenged under altered sensory test conditions, was needed. Furthermore, if clinicians are to recognize the changes that occur in people with different pathologies compared with healthy adults, then the method of representation of the COG is needed. It also needs to be simple to use and have the potential to be sensitive to changes that might be achieved through treatment interventions designed to improve COG control over BOS. The use of force plate technologies within clinical settings facilitates monitoring of this process.

9.1.2 Development of the centre of gravity location measure (Study 2, Chapter 4)

This study addresses Aim 2: to develop a method for categorizing COG location based on the BM results output and assess tester reliability for this method. A method has been developed and reported in this thesis that provided an objective record of COG location (Study 2, Chapter 4). The hypothesis that the method would be reliable was supported.

Commercial force plate systems such as the BM are being used increasingly in clinical settings for assessment to gain objective measurements of balance. Such measures assist with the interpretation of the possible reasons for balance impairment and provide the basis upon which treatment choices can be made. In particular the output provided for the mCTSIB tests on the BM form the basis for the categorical method of location of the COG over the BOS in this thesis. This was the first time that a method has been proposed to record COG location which might be used in treatment facilities. In particular, for those facilities which use the BM, the use of this categorical method for COG location will provide a user-friendly method so that COG location can be considered in the interpretation of mCTSIB test results in addition to the usual observational measures.

The development of this measure allowed COG location to be recorded for both the medio-lateral and antero-posterior planes. However, for all studies reported in this thesis the focus was limited to the antero-posterior plane. The reliability of the COG measure was found to be substantial between two independent raters and also on two occasions for each individual rater (Study 2, Chapter 4). The categorical measure was easy to use with the second rater requiring just one fifteen-minute training session prior to rating the COG location as anterior or posterior. Although the categorical method was based on results for the mCTSIB on the BM, the same method used by the BM software to calculate the predicted centre of balance for each individual (Chapter 3, Section 3.3. 4) was used for all testing conducted on the Kistler force plates. On both force plate systems the COG location was categorised as being anterior or posterior to the predicted centre of balance of each participant. This allowed the same method of antero-posterior categorization to be adapted for use on other force plate systems thereby allowing analysis of COG location in a wider range of BOS stance tests not catered to by the BM software. When the medial malleolus is used as the reference point on the foot, this correction to identify the predicted centre of balance may be applied to any force plate system for which software can be customized. This may also allow for the pooling of data for meta-analysis from across facilities where different force plate systems are in use.

9.1.3 Studies to identify between test repeatability on the Balance Master and comparability between the Balance Master and the Kistler force plate systems (Chapter 5)

These pilot studies addressed Aim 3 of the thesis: to test the new categorical method of recording COG location for (i) between-session repeatability (Chapter 5, Section 5.1) and, (ii) comparability between different force plate systems (Chapter 5, Section 5.2). No studies were identified in the literature which considered the repeatability of the COG location on the BM. Consequently a pilot study was conducted to assess the repeatability of COG location for the four test conditions of the mCTSIB (Chapter 5, Section 5.1). Testing was conducted on two occasions separated by 24 hours. The results of this small study showed high levels of observed agreement although agreement was better for the foam surface tests than for the firm surface tests. No other studies have been identified which have compared the repeatability of COG location for the mCTSIB conditions on the BM. The small number of participants in this study (N=14) may have influenced the statistical outcomes.

As this thesis used data from two force plate systems (the BM and the Kistler force plates) an understanding of the comparability between the two systems for the same tests (mCTSIB) was needed. This small comparative study (N=8) is also reported in Chapter 5 (Section 5.2). Although the statistical analysis produced variable results for this study, it is important when using Cohen's Kappa to also consider the observed levels of agreement particularly in health studies. These results show high levels of observed agreement and suggest that the adjustments made to data collected on the Kistler force plates in order to replicate data collected on the BM, were appropriate. Further study is required in order to validate this finding with a larger number of subjects.

9.1.4 Changes to centre of gravity location under altered sensory test conditions (Study 3, Chapter 6)

Aim 4 of this thesis was to test whether the data obtained when applying the method of categorizing COG location is sensitive to changes under mCTSIB test conditions and with age in a healthy adults population. The findings related to age for this study are discussed separately in Section 9.1.6. Reduced sensory inputs (for example, vision or somatosensation) result in less information being available to the individual to generate effective motor outputs and, potentially, increase the risk of a loss of balance through failing to control COG over the BOS. While tests such as the mCTSIB, in which the visual and somatosensory inputs are manipulated, are commonly used in the assessment of individuals with compromised balance, there is limited understanding of the COG location behaviour in the antero-posterior plane under such test conditions in healthy adults.

There was some evidence (Study 1, Chapter 2) that the antero-posterior mean location of the COG changes as test difficulty increased from stance on a firm surface with, then without, vision (Nichols et al., 1995) to stance on a foam surface with and without vision (Merlo et al., 2012) when the distance of the mean COG was measured. However, these studies did not compare different age groups with the former study using only young subjects (age range 21-47 years) and the latter using only elderly subjects (mean age 79 ± 5 years). In each of these studies, that is, for both young and old subjects, there was an anterior shift of the COG as the test difficulty increased. Whether the anterior shift was similar in these two age groups is not known. Therefore this investigation of the impact of age on COG category in the antero-posterior plane under the conditions of the mCTSIB would provide new data to enhance knowledge in this area.

The results of Study 3 (Chapter 6) that looked at manipulation of sensory input have demonstrated, for a large group of women (age range 40-80 years), an increase in the proportion of participants with an anterior COG start location when the newly-developed method of recording COG location was used. There were statistically significant differences between the vision and no vision tests on both the firm and foam surfaces in the mCTSIB. There was also a significant difference between the firm and foam surface conditions. However, in the current study (Study 3) instead of a further increase in the proportion of participants with an anterior COG location for the FoEC test, (with the exception of the 50-59 years group) a reduction in the proportion of women with an anterior COG location was identified. These results suggest that for this test (FoEC), rather than moving their COG anteriorly there was a tendency to hold their COG more posteriorly for three of the four age groups. Thus the hypothesis for Study 3, that the method of categorization of COG location was sensitive to show differences due to the mCTSIB conditions and age, was supported.

The ability of the new categorical method to demonstrate this anterior preference for COG as test difficulty increased for groups of healthy adults suggests that this method of recording COG location may be useful in demonstrating between-group differences in those presenting with different pathologies. The additional knowledge on how pathology impacts on the location of COG within the BOS may then contribute to decisions for tailoring treatment for the management of balance impairment. Understanding the adjustments made by healthy individuals of different ages to retain balance when sensory inputs are reduced, facilitates the interpretation of test results in those with balance difficulties. It also helps to identify the circumstances in which an individual might be at risk of loss of balance in the community. The FiEO and FiEC tests attempt to replicate instances in which vision might be reduced, for example finding your seat at a cinema or when moving from bright sunlight to a darker foyer. The FoEO and FoEC tests replicate circumstances in which proprioceptive input and/or vision might be reduced, for example when walking on lawns or on plush carpets.

9.1.5 Changes evident with altered base of support configuration (Study 4, Chapter 7)

Study 4 (Chapter 7) addressed Aim 5: to test whether this categorisation of COG location is sensitive to the varying BOS test conditions of FA, FT and SLS. , Thus a study was designed to consider the sensitivity of the categorization method to demonstrate changes in COG location in the antero-posterior plane under three different BOS conditions, namely, feet apart, feet together and single limb stance and age (Study 4, Chapter 7). Evidence in the literature suggested that the COG shifts to a more anterior location when the BOS changes from feet apart to feet together (Nichols et al., 1995) and from feet apart to single limb stance (Teranishi et al., 2013) in young adults.

In this study the results for a mixed group of men and women (age range 30-80 years) who were divided into three age cohorts, also found that the categorical method of recording COG location demonstrated increased proportions of participants with an anterior start COG location when stance was changed from feet apart to feet together for both eyes open and eyes closed conditions. Although the relationship between the FAEO and SLS was not statistically significant (both for stance on a firm surface), the proportion of participants with an anterior COG in SLS (for both left and right stance) was more than double that for FAEO. This was the case for each of the young, middle and older age groups. Clinically this suggests that, for healthy adults, there is an anterior shift of COG in SLS tests. This result agrees with the significant findings in the study by Teranishi et al (2013) for their group of young participants. The hypothesis for Study 4 addressing Aim 5 was supported for BOS configuration. The differences found for COG location in the antero-posterior plane between RSLS and LSLS in this study raise questions about the use of different strategies for balance on the left and right feet. While there is limited information on this in relation to COG location some researchers have noted different characteristics between dominant and non-dominant SLS. For young adults there is some evidence showing increased COP sway for left SLS compared with the right foot (Clifford & Holder-Powell, 2010) and greater stability in right SLS compared with the left (Vieira et al., 2014). This may have implications for gait performance particularly in patients who have had a stroke. Further study is needed to explore the consistency of these findings for different participant groups and across different ages.

9.1.6 Centre of gravity location as age increases (Studies 3 and 4, Chapters 6 and 7)

To fulfil the second aspect of Aim 4 of this thesis sensitivity to the impact of increasing age on the location of COG when under altered BOS size test conditions was tested. The literature review (Study 1, Chapter 2) identified that, contrary to popular belief, the antero-posterior location of COG remains remarkably consistent regardless of age in healthy adults when compared with young adults, for stance on a firm surface with eyes open (Schwab et al., 2006) and also for single limb stance with eyes open (Murray et al., 1975). These studies both used the distance from the posterior border of the heels to quantify the COG location.

Similar consistency of COG location across age groups also was found using the new categorical method for COG location for the feet apart tests on a firm surface with eyes open in Studies 3 (Chapter 6) and 4 (Chapter 7). In both Studies 3 and 4 there was no significant difference in the proportion of participants with an anterior COG location for stance on a firm surface with eyes open, when younger and older age groups were compared. However, when sensory input (Study 3) or BOS size (Study 4) was manipulated there were significant differences with age for some tests. Thus proving this aspect of the hypothesis for Aim 4 where age related sensitivity was found.

In Study 3 there was a significant difference between the 40-49 year and the 50-59 year groups for the FoEC test. A greater proportion of participants utilised an anterior COG in the older group while for the other age groups there was a lesser proportion of participants with an anterior COG location compared with the FoEO test. There was also a trend to significance for the 60-69 year old group compared with the youngest group in the FoEO test where a higher proportion of participants utilised an anterior COG to balance. The anterior preference was not as evident in the 60s for FoEC or in the 70s for FoEO. Also in Study 3 the result for the 70-80 year old group differed significantly from the 40-49 years old group for the FiEC test.

It is interesting to note in Study 3 that there was a spike in the proportion of participants with an anterior COG location in the 50s when both surface and vision were manipulated (the most challenging test), while the spike in anterior COG location in the 60s was also with the surface alteration but in the presence of vision (a less challenging test) and in the 70s the spike was evident for the firm surface when vision was compromised (the least challenging of these three tests). Reduced stability (measured as inability to complete all three trials of the test) has also been identified for these altered surface test conditions in the 50s and 60s for this group of women in an earlier study (Low Choy et al., 2003). The persistence of a preferred anterior COG location may be linked to the reduced stability for women in the 60s for the FoEO test condition and for women in the 50s for the FoEC test condition.

Age was also a factor for some tests under reduced BOS conditions. In Study 4 (Chapter 7) there was a significant interaction between the LSLS test and age group. However, there was only a trend to significance when the younger age group (30-49 years) was compared to the older age group (65-80 years). Some studies have identified differences between the dominant and non-dominant limbs for SLS in younger groups (Clifford & Holder-Powell, 2010; Vieira et al., 2014) while in another study of adults in three age groups no difference was found (Murray et al., 1975). In the current study 100% of the participants in the young and middle age groups had an anterior COG for LSLS compared with 85% in the oldest group. In RSLS the proportions were very similar for each of the three age groups (92-97%). This does seem to agree with Vieira et al. (2014) who found, in young adults, greater stability for stance on the dominant lower limb. If, as Nichols et al. (1995) have suggested, an anterior shift occurs to position the COG closer to the centre of the BOS to increase the distance of the COG from the BOS boundaries and enhance stability, the greater proportions of anterior location in the LSLS for the young and middle groups may indicate less confidence in control for stance on the non-dominant foot and therefore a need to be closer to the centre of the BOS. In the oldest group, there may be other factors which interfere with the ability to control a more anterior COG location in the less skilful foot.

Firstly, strong toe flexors (particularly of the first toe) are needed to limit forward trajectory. Older adults have been shown to have reduced strength in the toes flexors (Endo et al., 2002) and this has been shown to be a significant predictor of balance and function (Menz et al., 2005). Reduced toe flexor strength also has been shown to be linked to falls incidence (Kim et al., 2011; Mickle et al., 2009). Secondly, older adults have a longer sway path than younger adults (Amiridis et al., 2003) and a longer sway path has been demonstrated for LSLS compared with RSLS even in young adults (Clifford & Holder-Powell, 2010). This suggests that the more anteriorly the mean COG is located within the BOS, the greater the likelihood that the anterior stability boundary will be exceeded with antero-posterior sway in older adults. Thirdly, processing speeds and response times have been shown to be reduced even in healthy older adults (Lockhart et al., 2005; Yordanova et al., 2004). This may impact on the speed with which the direction of movement might be reversed when approaching the limit of stability. These factors suggest that it may be less safe for older adults to position the COG quite as far forward particularly in LSLS and so might help to explain our findings.

9.1.7 Relationship between start and mean centre of gravity locations (Study 5, Chapter 8)

This study addresses Aim 6 of the thesis: to compare the start location and mean location of COG obtained simultaneously for the mCTSIB conditions and the varying BOS test conditions.

The data used in Studies 2 and 3 was collected on the BM. The BM provided a record of the start location of COG, that is, the location at the commencement of each of three test trials for the four test conditions of the mCTSIB. However, studies identified in the literature which record the COG location in the antero-posterior plane, were based on the mean location of COG rather than the start location. Thus it was important to look at the levels of agreement between start and mean locations of COG in steady state stance for the categorical method and this was Aim 5 of this work. We are unaware of other studies that have looked at levels of agreement between start and mean locations of COG.

The use of Kistler force plates in conjunction with Matlab software (MathWorks(R)) in Studies 4 and 5 (Chapters 7 and 8) allowed for the recording of both the start location and the mean location for each test trial for a larger range of tests than offered by the BM. For Study 5 the levels of agreement between the start and mean locations of COG in the antero-posterior plane were considered in eight test conditions: firm surface, feet apart with eyes open then closed (FiEO, FiEC); foam surface, feet apart with eyes open then closed (FoEO, FoEC); firm surface, feet together with eyes open then closed (FTEO, FTEC) and finally, single limb stance on the left or right leg with eyes open (LSLS, RSLS).

The levels of agreement between the start location and the mean location were substantial (κ=0.61-0.80) to almost perfect (κ=0.81-1.00) for all tests except for RSLS (κ=0.41). However, the lower limits of the confidence intervals ranged from substantial for the less difficult tests (FiEO, FiEC and FTEO) to moderate for the more difficult tests (FoEO, FoEC, FTEC and LSLS). This suggests that for the firm surface tests a record of the start location of COG which is categorized as anterior or posterior provides a reliable indication of the mean COG location. Based on the lower limit of the confidence intervals, the FoEO, FoEC and FTEC tests show less convincing levels of agreement while the SLS tests are slight to fair although the high observed levels of agreement for these tests should be considered in conjunction with the Kappa results. It is unclear why the result for RSLS was so low (κ=0.41 (CI = 0.01-0.83)). Participants were allowed to choose the order in which RSLS and LSLS were tested with the majority choosing to start with LSLS. Therefore the hypothesis for Aim 5, that the start and mean COG locations would be similar for the least complex test conditions but would show less agreement as the tests became more complex, was proven.

Clinically, the implication of these results is that the COG start location provided in results on the BM can be considered to be representative of the COG mean location for the firm surface tests of the mCTSIB (FiEO and FiEC).

9.2 Implications of thesis findings

The use of this novel, objective method devised to record COG location in this thesis has been sensitive enough to identify specific patterns of change in the antero-posterior plane within a group of healthy adults under a range of test conditions where sensory input and BOS were manipulated. Notably, for stance on a firm surface with the eyes open, the COG location does not change in the antero-posterior plane as age increases. Previously, estimates of antero-posterior COG location within the BOS based on the posture of a person (for example, differing degrees of thoracic kyphosis or anterior pelvic tilt) have been shown to be unreliable (Geiger et al., 2007; Schwab et al., 2006). Equally anecdotal evidence that the COG moves more posteriorly as age increases has been shown to be incorrect in healthy adults (Murray et al., 1975; Schwab et al., 2006). Such unsubstantiated and erroneous observations and beliefs have an impact on clinical reasoning and thus impact treatment choices.

Under usual clinical conditions, when testing steady state balance competency a range of tests with increasing degrees of difficulty is used by the clinician. These tests aim to challenge balance when vision (FiEO and FiEC) and/or surface compliance (FoEO and FoEC) (mCTSIB) is manipulated or when the size of the BOS is progressively reduced (FA, FT and SLS tests). The purpose of these tests is to identify circumstances in an individual's daily environments in which balance may be compromised. Changes in environments from hard surfaces such as tiled floors or footpaths, to softer surfaces such as carpets or lawns or from well-lit to more dimly-lit areas alter the sensory inputs available to an individual.

In order to identify the impact of pathology in a client, the characteristics of COG location in the antero-posterior plane must be clearly understood for these different test conditions in healthy adults. The use of the categorical method of recording COG location developed in this thesis provides one more piece of information relating to balance response under different test conditions in standing. The categorical method has demonstrated an anterior shift for preferred COG location when test difficulty progresses from FiEO to FiEC and a further anterior shift between FiEC and FoEO. This is the case for each of the age decade groups from 40 to 80 years of age. There was also a higher proportion of people preferring an anterior COG location when feet-apart stance was compared to feet together stance and a more marked anterior COG preference when feet together stance was compared to single limb stance when the eyes are open. Again this was true for all age groups. The expectation then is that healthy subjects, regardless of age, will compensate for reduced sensory input (either visual or somatosensory) or a smaller BOS size by preferentially locating their COG more anteriorly to approach more closely the geometric centre of the BOS. The ability to record COG location provides additional information on an individual's responses to balance challenges that may be encountered in daily function.

The fact that a more anterior COG location occurs in healthy adults as test challenges increase, raises questions about the attributes that are needed to control a more anterior COG location. The primary strategy used for feet apart and feet together stance is the ankle strategy (Byl & Sinnott, 1991; Winter et al., 1996). That is, movement alternates between ankle dorsi- and plantar flexion. Factors which may impact on this capacity are somatosensory integrity, joint range of movement (particularly of the talocrural joint) and strength of the dorsiflexor and plantar flexor muscles.

Detection of sway for small range movements (for example for stance on a firm surface with the feet apart) in standing is primarily achieved via the slight movement of the COG stimulating the mechano-receptors on the plantar surface of the feet. When sway range increases (for example in single limb stance) there is additional input from the muscle stretch receptors and possibly Golgi apparatus of the tendons. Recovery from sway in a particular direction requires muscle activation within a limited timeframe which in turn relies on efficient recruitment of appropriate muscle contraction force. Larger sway ranges are associated with greater movement velocities resulting in shorter times within which to act to maintain the COG within the BOS. Thus sensory and motor nerve conduction speed and central processing times are important factors contributing to antero-posterior COG control. Greater forces also need to be generated by the muscles in order to change sway direction particularly for higher velocity movements and are crucial for maintaining balance and preventing a fall. Adequate strength then is required in such muscles as the Tibialis Anterior, Tibialis Posterior and Soleus as well as the Flexor Digitorum, Lumbrical and Interosseous muscles of the feet.

Declines in somatosensation (Choy et al., 2007), nerve conduction speed, central processing speed (Lockhart et al., 2005; Yordanova et al., 2004), joint flexibility (Gehlsen & Whaley, 1990) and strength (Choy et al., 2007; Gehlsen & Whaley, 1990) have been demonstrated in older adults. There is also evidence of an increased incidence of falls in those with reduced somatosensation (Melzer et al., 2004; Menz et al., 2006), reduced ankle range of movement (specifically for dorsi-flexion range) (Chiacchiero et al., 2010; Menz et al., 2006; Nitz & Low Choy, 2004) and reduced strength (Allet, Kim, Ashton-Miller, De Mott, & Richardson, 2012; Gehlsen & Whaley, 1990; Kim et al., 2011; Thelen, Schultz, Alexander, & AshtonMiller, 1996). However, the number of systems and the extent of the decline in each system is highly variable between individuals as they age.

Associations have been found between COG location and fallers when surface and vision conditions were manipulated. In a study to differentiate between non-fallers, single fallers and repeat fallers Merlo et al. (2012) found an association between antero-posterior COG location and falls history for stance on a firm surface with eyes closed and also for stance on a foam surface with eyes open. In particular, the single fallers had a more anterior COG location for stance on a firm surface both with the eyes open and with the eyes closed. This was also the case for stance on a foam surface with the eyes open. These findings along with those from the studies reported in this thesis provide a greater understanding of COG location adjustments under different test conditions in healthy adults. This knowledge may then provide a basis for comparison for individuals whose balance is compromised as a result of pathology and guide intervention choices as well as a benchmark for evaluation of treatment efficacy.

Given the extent of the physiological and biomechanical changes that accompany ageing, it was surprising that there were so few age-related differences in preferred COG location in the antero-posterior plane between tests in which sensory and BOS components are manipulated particularly in the oldest group of participants in our studies. Our findings found that only in the oldest groups the FiEC in women (compared with the 40-49yrs age group), the FTEC for a combined group of men and women (compared with the 30-49yrs age group) and the LSLS for a combined group of men and women (compared with the 30-49yrs age group) showed a COG location that was significantly different for age. These tests represent the individual responses to reductions in vision alone (FiEC), in both BOS size and vision (FTEC) and in BOS size alone (LSLS) so might reflect the subtle age related decline in sensory acuity that has been demonstrated previously (Choy, et al., 2007; Illing, et al., 2010).

There is some evidence which points to changes in the location of the antero-posterior COG in the presence of pathology in a range of age groups for stance on a firm surface with the eyes open. For example, teenagers with scoliosis have been found to exhibit a more posterior COG location than controls (Dalleau et al., 2007). However there were conflicting results for older adults with low back pain. Two research groups have found a more posterior COG location for the eyes open tests for stance on a firm surface with the feet apart, in young adults with a mixture of chronic and acute low back pain (Byl & Sinnott, 1991) and chronic low back pain (Mientjes & Frank, 1999) for stance on a firm surface (feet apart). In another study the antero-posterior COG location of patients (mean age 55yrs) with low back pain (again with a mix of acute and chronic diagnoses) was found to be very similar to a group of controls (mean age 32.9 yrs) for stance on a firm surface with eyes open (Geiger et al., 2007). Of these three studies, only one of them (Mientjes & Frank, 1999) considered stance on a foam surface with eyes open. This study found no difference between the control and low back pain groups for stance on a foam surface with eyes open.

The new categorical method of recording COG location devised and tested for reliability and sensitivity to various sensory and BOS test conditions may prove useful as a tool to explore whether COG location in different in people with other pathologies compared with healthy groups. It may also prove to be a useful tool in conjunction with other measures to predict those at greater risk of loss of balance and increased risk of a fall.

9.3 Strengths and Limitations

9.3.1 Strengths

This thesis presents the development of a method for recording COG location which provides the practitioner with an objective assessment of COG location. This is an important addition to assessment as the location of the COG within the BOS may impact on a person's stability. The closer the COG is to any boundary of the BOS, the greater the risk of a loss of balance. Furthermore subjective assessments of COG location have been found to be unreliable. As treatment choices are based on the findings in the assessment of each client, it is important to incorporate all aspects which may impact on balance in the assessment process. This should include an objective evaluation of COG location.

The high number of participants, particularly for Studies 2 (756 test conditions analysed) and 3 (481 test conditions analysed) is one of the strengths of this thesis. Such numbers add strength to the findings in Studies 2 and 3. In addition, the range of ages incorporated into Studies 2-5 has allowed for consideration of the impact of age (young, middle-aged and older adults) on the behaviour of COG location in the antero-posterior plane for the test conditions examined which are frequently used in steady state balance assessments. This has allowed the identification of the few differences in responses exhibited in older age groups. The agreement between the findings in the studies in this thesis and those of researchers using other methods of recording COG location for the antero-posterior plane add support to the ability of this method to demonstrate change under different test conditions. The use of the simple categorization method devised in this thesis, particularly for those clinicians and researchers who use the BM, provides an easy option to document COG location without the need for complicated analyses. It is a method which can be applied with minimal training and thus is user-friendly. Furthermore, this may then facilitate the sharing of de-identified data between treatment facilities and add valuable insights to research on balance impairments in people with different pathologies.

9.3.2 Limitations

There are several limitations to this thesis.

While the BM was used for Studies 2 and 3, data for Studies 4 and 5 were collected on a different force plate system. Some difficulties presented with the replication of the zero reference point for the anterior or posterior location of COG on the second (Kistler) force plate system. It is possible that this replication did not fully match that on the BM. The small (N=8) pilot study undertaken to compare COG location on the BM and Kistler force plates for the mCTSIB test conditions (Chapter

4) showed only 75% observed agreement for two of the test conditions (FiEO and FoEC test conditions) although observed agreement of 88% was found for the other two (FiEC and FoEO test conditions). Results for tests on the BM may not then be repeatable on other force plate systems using customized software. Additional research to compare results on the BM with those from other force plate systems is needed to determine whether there can be agreement between systems. This would also require larger subject numbers.

The participants in Studies 2 and 3 were all women while those in Studies 4 and 5 included both men and women. The intention in Studies 4 and 5 was to analyse men and women separately for each age decade. However, because of recruitment difficulties, it was not possible to achieve the number of participants of each gender in each age decade within the timeframe available. Despite this, an initial comparison between the results for the men and women for each test showed no significant differences between the two genders overall. Previously there has been some suggestion that there are gender differences in balance (based on measures of sway velocity) as age increases. While changes in stability have been identified in women from the 40s and 50s (Low Choy et al., 2003; Low Choy et al., 2008), similar changes in men seem to occur later (Nolan et al., 2010). A further result of reduced participant numbers was that instead of categorizing age in decades (30-39 through to 70-80 years) it was necessary to group the ages into younger (30-49 years), middle (50-64 years) and older (65-80 years) groups. Analysis of results for age decades may have delivered different outcomes.

Although this categorical method for recording COG location demonstrates clear differences between test conditions in groups of people, it lacks the sensitivity to measure small differences in individuals. The participants in Studies 4 and 5 were a healthy, active group. In older adults associations have been identified between activity levels and hip fracture (Hoidrup et al., 2001; Nitz et al., 2013). There are interactions also between polypharmacy (≥4 medications) and falls (Richardson et al., 2015; Zia, Kamaruzzaman, & Tan, 2015) in older adults. The use of multiple medications (that is ≥4 drugs) with or without the use of drugs which are known to increase risk of falls (for example, antipsychotics, anti-parkinsonian drugs and narcotic analgesics) is a significant factor in increasing the risk of falls (Zia et al., 2015). As these factors impact on balance, it is possible that different results might have been found if the study participants had been a less active group. .

Further research is needed to determine whether gender differences can be demonstrated across age decades in healthy adults for COG location when the categorical method is used and whether these results can be replicated in participant samples other than those who are healthy. However, this method would seem to provide a promising method by which COG location can be recorded (particularly for clinics in which the BM is used) to provide comparisons between participant groups. The method may also prove to be a useful tool to compare COG location in people who have different pathological conditions such as Parkinson's Disease and Multiple Sclerosis for example. The level of sensitivity to change in the measure with an intervention also warrants investigation.

9.4 Directions for future research

There are a number of aspects arising from the studies reported in this thesis which warrant further research.

The results found in this thesis need to be compared with those from different participant groups nationally to confirm uniformity of findings both for the BM and other force plate systems. This would provide greater flexibility in the force- or pressure-plate (for example, the WiiFit pressure plate) systems which might be used in the field to identify COG location with an objective measure. Although our inter- and intra-rater reliability study (Study 2) showed substantial to near perfect reliability, only two assessors were used. The uniformity of results from the BM also needs to be evaluated across a greater number of assessors.

This research has looked only at healthy adults. Further research is needed to evaluate whether COG location is a contributing factor in falls and to investigate possible interactions between COG location and other factors such as strength (particularly for the toe flexors), ankle joint range of movement and gait speed. Gait requires a forward progression of the centre of gravity in single limb stance. This may have implications in those who prefer a posterior COG location in the single limb stance tests. There may also be cultural differences in stance which may provide opportunities for international collaborations.

As adults age and become increasingly frail, they are more likely to be sedentary for longer periods of the day, and may be supported in a semi-reclined position. Investigation of the effect this might have on antero-posterior COG location when these adults stand as well as links this might have with falls is another area of research that has not previously been explored. An altered COG location within the BOS might also apply to those who have been bed bound for long periods of time, for example, in Intensive Care units.

Further exploration of the use of this method for evaluating treatment outcomes may also provide useful information on the effectiveness of treatment protocols particularly for use in the comparison between treatment groups.

9.5 Conclusions

The purpose of this thesis was to develop a novel method of recording COG location within the BOS in bipedal stance. The ability of the method to demonstrate changes in preferred COG location in some commonly used clinical tests of balance was then tested. Healthy adults show a preference for an anterior COG location as test difficulty increases (except when both surface compliance and vision are simultaneously compromised) when more adults (although less than 50%) prefer a position that is more posterior than that adopted when standing on a firm surface using vision. Incorporating an objective measurement of COG location in steady state balance testing allows additional understanding of the compensations that are made in different environmental contexts and may assist in decisions relating to treatment delivery for those individuals with compromised balance function.

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Appendices

Appendix 1

Ethics Approval

The title of this thesis was altered during the course of the programme -

From:

Can the start location of the centre of gravity be used to reflect the mean location of the centre of gravity in standing balance tests? Does this location change with age and under different sensory conditions?

To:

The development of a novel method of recording centre of gravity location in bipedal stance in healthy adults.

THE UNIVERSITY OF QUEENSLAND

Institutional Human Research Ethics Approval

Project Title: Can The Start Position Of The Centre Of Gravity Be Used To Reflect The Mean Position Of The Centre Of Gravity In Standing Balance Tests? Does This Change With Age And Under Different Test Conditions?

Chief Investigator: Mrs Jill Boughen

Supervisor: Dr Jennifer Nitz, Dr Venerina Johnston, Dr Asad Khan

Co-Investigator(s): None

School(s): School of Health and Rehabilitation Sciences, Division of Physiotherapy

Approval Number: 2013001298

Granting Agency/Degree: PhD

Duration: 31st October 2015

Comments/Conditions:

Participant Information Sheet – Additional Information – 2nd last sentence – please change to: "An incident report will be made to UQ Occupational Health & Safety Division and the Ethics Office".

Note: if this approval is for amendments to an already approved protocol for which a UQ Clinical Trials Protection/Insurance Form was originally submitted, then the researchers must directly notify the UQ Insurance Office of any changes to that Form and Participant Information Sheets & Consent Forms as a result of the amendments, before action.

Name of responsible Committee:
Medical Research Ethics Committee
This project complies with the provisions contained in the *National Statement on Ethical Conduct in Human Research* and complies with the regulations governing experimentation on humans.

Name of Ethics Committee representative:
Professor Bill Vicenzino
Chairperson
Medical Research Ethics Committee

Signature ______________________ Date 20/11/2013

Appendix 2

Forms for:

- **Participant information**
- **Participant consent**

School of Health and
Rehabilitation Sciences

Head of School
Professor Louise Hickson
BSpThy(Hons), MAud, PhD

CRICOS PROVIDER NUMBER 00025B

PARTICIPANT INFORMATION FORM
Research Project

Title of the Project: Can the start position of the Centre of Gravity be used to reflect the mean location of the Centre of Gravity in standing balance tests?

Chief Investigators:
Mrs Jill Boughen, PhD Candidate in the School of Health and Rehabilitation Sciences
Dr Jennifer Nitz
Dr Venerina Johnston
Dr Asad Khan,

Background and Aims of the Study
Falls are a common problem in the older population. We know that poor balance is a risk for falls so we need to have accurate methods of measuring balance. This study is exploring the accuracy of one method of measuring balance under different conditions and also whether age impacts on results. A better understanding of balance will help with the development of more specific treatment programmes for individual patients who are experiencing problems with their balance.

Your participation:
Your participation in this study is voluntary. While we would appreciate your participation in this study, we respect your right to decline.
If you would like to proceed as a participant in this study you will be asked to sign a consent form.
All testing will be conducted in the School of Health and Rehabilitation Sciences at The University of Queensland St Lucia Campus.
We expect that all testing will be completed in one session which will last no longer than one-and-a-half hours.
Appointments will be made by telephone and at that time some questions will be asked to determine your suitability for this study – for example, your age and current medications.

The tests in this study will look at:
(i) your ability to feel touch on your feet,
(ii) the strength of your legs and upper back,
(iii) the range of movement at your ankles,
(iv) your vision,
(v) your balance when you are standing on your two feet and
(vi) your balance standing on one foot.

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The standing balance tests will be conducted with your eyes open and then with your eyes closed and they may need to be repeated on two separate pieces of equipment.
These tests are commonly performed in balance assessments conducted by Physiotherapists. The tests are not painful and your safety will be monitored at all times.

Additional information:
Expected benefits: As this study will constitute a limited assessment of balance and no treatment will be applied, it is not expected that there will be benefits to balance function for participants.
Unexpected events during testing: We have conducted a risk assessment for the tasks to be completed in this research and all measures will be taken to ensure your safety while participating in this research. However, should any injury be sustained an initial triage would be undertaken followed by appropriate referral as indicated for management. An incident report would be written with a copy sent to the RRID.
Access to result: The results of your tests will be available to you at the completion of the study upon request.

What if I change my mind?
If you should decide to participate in the study you are free to withdraw from the study at any time without giving a reason.
Your confidentiality and privacy will be maintained at all times. Identifying information (eg name and contact details) will not be connected with data storage.

Who do I contact for further information?
If you would like further information about this project please contact the chief investigator whose details appear below.
This study has been cleared by the Medical Research Ethics Committee in The University of Queensland in accordance with the National Health and Medical Research Council's guidelines. You are, of course, free to discuss your participation in this study with project staff. Dr Venerina Johnston is contactable on (07) 3365 2124. If required, an incident report will be made to UQ Occupational Health & Safety Division and the Ethics Office.

We would like to thank you for considering participating in this study.
Yours sincerely,

Mrs Jill Boughen

Email: j.boughen@uq.edu.au

Telephone or SMS: 0408 007 156

School of Health and Rehabilitation Sciences

Head of School
Professor Louise Hickson
BSpThy(Hons), MAud, PhD

CRICOS PROVIDER NUMBER 00025B

CONSENT FORM
Research Project

Title: Can the position of the centre of gravity at the start of a test be used to reflect the average position of the centre of gravity in standing balance tests? Does this change with age and for different balance tests?

Chief Investigator: Mrs Jill Boughen
Division of Physiotherapy
School of Health and Rehabilitation Sciences
The University of Queensland
Email: j.boughen@uq.edu.au

1. I ____ (PLEASE PRINT) hereby consent to participate in this project.

2. I have read and understand the information leaflet provided for me in relation to this study.

3. I consent to the use of information obtained from me for the purposes of this project and all papers that may arise from it.

4. I understand that all information obtained from me, including results from tests conducted, will remain confidential to the research team and that all information will be securely stored with all identifying information removed and stored separately in a password protected file on computer.

5. I understand that none of the information that I provide will be described or portrayed in any way that will identify me in any report of the study.

6. I understand that I may ask any further questions about the research study at any time.

7. I understand that I am free to withdraw from this study at any time without giving a reason.

8. I understand that this project is not a treatment programme and that there is no benefit for participation.

Signature of Participant: ___________________________________

Date: ________________

Signature of Witness: _____________________________________

Date: ________________

Appendix 3

Published manuscripts

Boughen J, Nitz J, Johnston V. Centre of gravity: relevance of behaviour and location in bipedal stance in older adults. *Physical Therapy Reviews.* 2017 doi: 10.1080/10833196.2017.1283831

Abstract

Background: The purpose of this review paper is to draw together the large body of literature on steady-state balance and the changes that occur as age increases to enable clinicians to access and interpret this literature and to integrate the findings into their daily practice.

Objectives: As there is increasing use of force plate technology in the clinical setting for both assessment and treatment of steady state stance in people with balance problems, clinicians need a clear understanding of not only the relationship between centre of gravity and base of support but also the impact of age and different test conditions.

Major findings: This review presents basic balance concepts relating to both the sway characteristics and location of the COG within BOS and the changes that occur as age increases. The impact of changes in the BOS, such as size and compliance, are also addressed in the context of the ageing client. It is possible that the location of COG within BOS in conjunction with sway characteristics may be more critical in older age groups than in the young as all body systems (sensory, central and musculoskeletal) show declines with increasing age.

Conclusions: This paper will assist clinicians to understand characteristics of sway in quiet stance and changes associated with altered test conditions with particular reference to the effects of ageing.

Keywords: centre of gravity, location, sway, ageing, standing balance

1. Introduction

Research on balance control over the last sixty years has resulted in a substantial volume of literature. In the last three decades exploration of the additional effects of ageing on balance control and falls incidence has added further to this volume of information. For clinicians working with older clients, accessing and integrating this array of information is both time-consuming and, at times, confusing. Different research interests result in the use of different measurement parameters and different methods of analysis to impact on how findings are presented. For example, those interested in technical aspects of equipment used in balance research may take a more mathematical approach than those interested in behavioural aspects of balance. This paper uses a descriptive approach to interpret the research findings that are relevant to changes which occur in quiet stance as age increases. Such findings might be utilised by clinicians when tailoring treatment for clients with poor balance who have fallen or are at risk of falling owing to their reduced capacity to control the body mass over the base of support.

The management of older clients with balance anomalies requires an understanding not only of the declining function of sensory and motor systems but also an awareness of the characteristics of and relationships between the body and its base of support (BOS) which is represented by the feet on the ground for standing balance. Normal balance control requires competency in most, if not all, of the systems involved in maintaining balance but as people age there is a progressive decline in all of the systems needed for successful balance (Horak, Henry, & Shumway-Cook, 1997; Lord, Clark, & Webster, 1991; Shumway-Cook & Woollacott, 2007). Studies of men (Allum, Carpenter, Honegger, Adkin, & Bloem, 2002; Illing, Choy, Nitz, & Nolan, 2010; Nolan, Nitz, Low Choy, & Illing, 2010) and women (Low Choy, Brauer, & Nitz, 2003; Low Choy, Brauer, & Nitz, 2008; Nitz & Low Choy, 2004) of different ages have shown that balance declines are measurable by the seventh and sixth decade respectively. While some researchers believe that balance decline is an inevitable consequence of ageing, Imms and Endholm (1981) have proposed that reduced balance is not inevitable but rather, is a secondary effect related to the onset of pathologies. There is, however, considerable evidence of reduced function in both peripheral and central systems (Low Choy et al., 2008; Mecagni, Smith, Roberts, & O'Sullivan, 2000; Menz, Morris, & Lord, 2005; Tanaka, Noriyasu, Ino, Ifukube, & Nakata, 1996; Yordanova, Kolev, Hohnsbein, & Falkenstein, 2004) as people age. Reduced performance has been demonstrated in a wide range of attributes such as somatosensation and strength (Lord et al., 1991; Low Choy et al., 2008), flexibility (Chiacchiero, Dresely, Silva, DeLosReyes, & Vorik, 2010; Nolan et al., 2010), vision (Foran, Mitchell, & Wang, 2003; Haran et al., 2010), vestibular function (Illing et al., 2010; Park, Tang, Lopez, & Ishiyama, 2001) and reduced central processing speeds (Lockhart, Smith, & Woldstad, 2005; Yordanova, et al., 2004) in older adults. All of these have been implicated in reduced balance function.

There is ample evidence of the impact of peripheral and central changes with ageing on body sway characteristics such as sway area (Berger, Buisson, Chuzel, & Rougier, 2005; Era et al., 2006; Slobounov, Moss, Slobounova, & Newell, 1998), sway path length (Lord et al., 1991) and sway velocity (Berger et al., 2005; Era et al., 2006; Low Choy, Brauer, & Nitz, 2007). The centre of pressure (COP) is the parameter which is frequently used to study sway behaviours. The COP represents the ground reaction (or upwards) forces resulting from the activation of the motor responses required to control movement of a body and can be recorded through the use of force plate technology (Winter, Prince, Frank, Powell, & Zabjek, 1996). The centre of gravity (COG) on the other hand represents the gravitational (or downward) forces acting on the centre of mass (COM) of a body over its BOS (Winter et al., 1996) and is subject to change based on alterations of postural alignment. As analysis of COP data can provide information on COG, researchers are able to gain an indirect representation of the movement of the body in stance via this method. Further discussion of these terms is provided in a later section of this paper.

While there has been considerable research on sway parameters, less attention has been paid to the mean location of the COG within the BOS and whether this changes with ageing or under different balance conditions. Location of COG, in conjunction with the speed and direction of movement, determines the time within which a subject must react to retain balance (Pai & Patton, 1997; Slobounov et al., 1998). This review aims to provide a summary for clinicians of basic balance concepts that may be studied when tests of quiet stance (also known as static balance) are conducted on force plates. In addition, changes that occur with ageing are considered. Table 1 provides a summary of terms used in this paper.

Table 1 Common balance terms

Term	Definition	Effect with ageing
Base of support	Area contained within the outer borders of the feet	
Feasible stability boundary	Area within the outer borders of the limits of stability	Area size decreases
Functional base of support	Length of maximum forwards / backwards sway for stance on two feet	Length decreases
Sway area	Area over which the centre of pressure moves during the time-span of a test	Area size increases
Sway length	Length of sway path in a particular movement plane - may be antero-posterior or medio-lateral. This may be given as a total path length or the maximal path length for antero-posterior or medio-lateral directions	Length increases total path length increases maximal length increases
Sway velocity	Total distance moved divided by test time	Velocity increases

2. Components of balance

The basic elements which impact on the balance of a body are the mass of the body, the height of the COM, the movement characteristics and location of the COG with respect to the BOS (LeVeau, 2011) and the size, configuration and compliance of the BOS. Changes in the location and the velocity of COG displacement as well as changes in the size and shape of the BOS will impact on stability and changes in all of these elements have been demonstrated with ageing.

2.1 Centres of mass, gravity and pressure

The COM of a body is defined as 'the point that is at the centre of the total body mass' (Shumway-Cook & Woollacott, 2007) (p158) representing the central point of equilibrium of a body. For the multi-segmented human body this point is the weighted average of the centres of mass of all of the segments (Winter, 1995) and its location varies according to the organization and size of the segments. Although the BOS remains constant in quiet stance, there are continual small oscillatory movements of the COM (Spaepen, Vranken, & Willems, 1976). These small movements are referred to as body sway. Three factors contribute to this perpetual movement: (i) respiration with its rise and fall of the diaphragm and movement of the rib cage results in constant shifts of COM (Roberts & Stenhouse, 1975), (ii) changes in body alignment also contribute through changes in the gravitational forces which act to destabilize COM (Woodhull, Maltrud, & Mello, 1985), and (iii) the muscles involved in resisting the effects of gravity produce phasic rather than constant forces (De Luca, Lefever, McCue, & Xenakis, 1982). Other destabilizing features in bipedal quiet stance include the relatively high COM of the human body (two-thirds of the body mass is located two-thirds of the height from the ground (Winter, 1995)) and the relatively small BOS. The position of COM is an estimate for each individual and cannot be measured directly (Hasan et al., 1996a). However, the gravitational force on the COM (represented by the COG within the BOS) must be countered by muscle activity if the body is to remain upright in stance. The forces generated by the muscles produce ground reaction forces which are measured through force plates as COP parameters and COG can be estimated from this data.

Force plates have been used by researchers in the study of balance control since the 1950s and more recently have been used in some rehabilitation centres for the assessment and treatment of people with balance problems. Force plates provide multiple measures of the ground reaction forces (or COP) through the feet as the body's neuromuscular system responds to the continual movements of the body. When dual force plates are used, both the horizontal, or shear, forces (representing antero-posterior and medio-lateral components) and the vertical forces (Rougier, 2008) are measured. The software used to process the data may produce a trace or stabilogram (this is a record of COP movements throughout the test time) to provide a two dimensional (antero-posterior and medio-lateral) visual representation of the COP path recorded over a series of time points (Figure 1). The position of the COG (the downwards forces), the point at which a plumb line from the COM intersects with the BOS, can be estimated from the COP data to provide an indirect method by which to track movements of body sway.

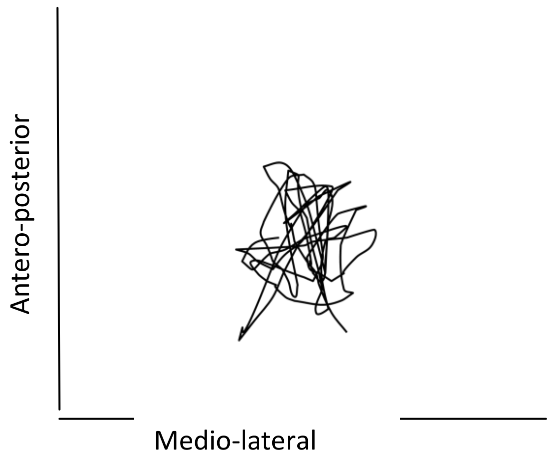

Figure 1 An example of a trace of sway from centre of pressure data for stance on two feet.

While COG and COP are frequently used interchangeably in the literature and although they are both measures of displacement, they are not identical measures (Winter et al., 1996). The COG represents the 'vertical vector' from the COM (Winter et al., 1996) to the BOS and represents real movement of the body. Its position is influenced by both change in the position of body segments and by the moment of the body's inertia (Rougier, 2008). The COG is quite distinct from the COP which is a reflection of the motor or net neuromuscular responses that are required to control COG (Baratto, Morasso, Re, & Spada, 2002; Berger et al., 2005; Patla, Frank, & Winter, 1990) i.e. COP is the resultant ground reaction force vector on the force platform (Winter et al., 1996). A number of researchers have shown that movements of COG and COP are not equal and that the size and frequency of movements of COP are larger than COG (Hasan et al., 1996b; Patla et al., 1990; Roberts & Stenhouse, 1975; Spaepen et al., 1976; Winter et al., 1996). These differences between COP and COG locations are particularly evident towards limits of stability ranges such as in the outer range of anterior or posterior displacement but are much more synchronous through middle ranges of movement. Despite these differences, if enough points are plotted for both COG and COP the mean locations are considered to be approximately equivalent (Rougier, 2008) with an increase in movement of COP reflecting an increase in movement of COG (Hasan et al., 1996b). The greater accessibility of COP, via force plate technology, makes it a more objective and convenient measure for researchers and clinicians to use (Hasan et al., 1996a).

The high cost of force plates means that they are not available to many researchers and clinicians. The development of less expensive pressure platforms such as the Wii balance board (Wii Fit ® platform, Nintendo, Japan) has resulted in much greater access to COP data in both research and clinical settings. The Wii balance board has been demonstrated to have excellent reliability and validity for tests of quiet stance (on two feet with the eyes open, then closed, and stance on one foot with the eyes open) in both older (Chang, Chang, Lee, & Feng, 2013) and young (Clark et al., 2010) adults when compared to testing on force plates. Not only are pressure plates a less expensive option to force plates, they are also more portable. Despite this, force plates are still considered as the 'gold standard' of these technologies (Huurnink, Fransz, Kingma, & van Dieen, 2013).

The continual movements that occur in stance are referred to as 'sway'. Analysis of the features of body sway such as area of sway, sway path length and sway velocity via the use of COP data has been used by researchers to gain insight into characteristics of balance under static or dynamic test conditions. Stance tests in which the participant adopts a fixed stance position (for example, standing with the feet apart or together and with the eyes either open or closed) may be referred to as static stance (Baratto et al., 2002; Geldhof et al., 2006; Granacher, Muehlbauer, Gollhofer, Kressig, & Zahner, 2011), quiet stance (Fujiwara, Asai, Kiyota, & Mammadova, 2010; Gatev, Thomas, Thomas, & Hallett, 1999) or unperturbed stance (Pinsault & Vuillerme, 2009). The term 'static', in the context of posturography, has been defined as tests in which the surface is flat and unperturbed. That is, disturbance of the body is internal and predictable (Baratto et al., 2002). It has also been defined as a test in which the BOS and the ground remain still (Granacher et al., 2011) while the COM is free to move through sway. These tests provide information on spontaneous sway under fixed, predictable conditions. Dynamic tests may be defined as those in which the position of the participant is subjected to different types of unpredictable stimuli (Baratto et al., 2002) thus resulting in reactive responses. This use of the term 'dynamic' implies the presence of an unexpected external stimulus such as a movable stance surface or a destabilizing force applied to the body and gives information on reactive strategies. It is used in this context particularly in posturographic studies. However, Granacher et al. (2011) use the term 'dynamic' to denote tests in which both the BOS and the COM shift. This broader interpretation of the term encompasses both anticipatory (there is no unexpected perturbation – for example functional tests such as sit-to-stand or walking tests) and reactive (presence of an unexpected perturbation – for example movement of the platform) tests.

Although some researchers suggest that analysis of dynamic movement is more relevant to normal function, Baratto et al. (2002) note that static (or quiet stance) and dynamic studies address different aspects of postural control and produce different types of information. Static tests provide information on spontaneous sway and, in this context, the control system has the advantage of anticipatory feedback loops to manage the balance (Baratto et al., 2002). Dynamic tests require the systems to respond to unexpected stimuli, that is, there must be reactive strategies, such as taking a step, to maintain a position of balance. These reactive strategies are dependent on reflex responses. Both approaches remain useful to researchers and clinicians although the use of quiet (or static) stance assessments with or without the use of force plates, is more common in the clinical context.

2.2 Changes with ageing

Changes in sway attributes for tests in quiet stance have been noted as people age and have been linked to declines in both sensory and motor function. Increased sway, when standing on a firm surface, is associated with reduced tactile thresholds, reduced joint position sense (Lord et al., 1991; Low Choy et al., 2008) and increased vibration thresholds (Low Choy et al., 2008). Cutaneous sensation (or tactile sensitivity) is implicated in the regulation of small oscillations around the vertical axis whereas proprioceptive input from muscles (evidenced by vibration thresholds) is more involved in larger body sway (Kavounoudias, Roll, & Roll, 2001) or larger velocity movements (Fitzpatrick & McCloskey, 1994). Tactile sensitivity (Choy, Brauer, & Nitz, 2007; Menz et al., 2005), vibration thresholds (Baloh, Ying, & Jacobson, 2003; Low Choy et al., 2008), and joint position sense (Choy et al., 2007; Lord et al., 1991) have all been shown to decline with ageing.

Sway area is the total area over which the COP moves during the time of a test. It is often reported as the area covered by 95% of all COP positions during the test time (Bauer, Groger, Rupprecht, & Gassmann, 2008). Sway area has been shown to increase for healthy older adults compared with younger adults (Berger et al., 2005; Slobounov et al., 1998) reflecting greater COP movement within the BOS in quiet stance. Studies have shown associations between reduced sensation and reduced vision and an increase in sway area (Lord et al., 1991; Tanaka et al., 1996). Conversely there is a reduction in sway area when somatosensation is enhanced through the use of spike insoles (Palluel, Nougier, & Olivier, 2008) which further reinforces the importance of somatosensory function to sway area. Older adults have reduced function of both tactile sensitivity (Choy et al., 2007; Lord et al., 1991; Melzer, Benjuya, & Kaplanski, 2004; Tanaka et al., 1996) and joint position sense (Choy et al., 2007; Lord et al., 1991) in the lower limbs. This reduced sensory function is thought to be a contributing factor to postural instability (Tanaka et al., 1996) and falls (Melzer et al., 2004).

Another factor which may affect sway area is body somatotype. This has been implicated in altered sway area in a group of primary and secondary age girls (Allard, Nault, Hinse, LeBlanc, & Labelle, 2001). These researchers found that body weight and height influence sway area with ectomorphs (those with low weight and small musculature) having a larger sway area than other body types. This combination of low weight and small musculature may also be a factor to consider when assessing sway area in older adults as muscle cross-sectional area is reduced in this group (Doherty, 2003; Frontera et al., 2000).

Sway path length also increases with ageing (Colledge et al., 1994; Laughton et al., 2003; Slobounov et al., 1998). It also increases in both young and old when tests become more challenging (for example, standing on a soft surface with eyes open or closed). However, the sway path length increases in older adults are greater than those in young adults under more challenging test conditions (Colledge et al., 1994). Fallers, when standing with their feet together, show greater COP path length in the medio-lateral plane than non-fallers (Melzer, Benjuya, Kaplanski, & Alexander, 2009). Reduced strength, particularly of the ankle muscles is also associated with greater sway path length in the antero-posterior plane. Butler et al. (2008) found that subjects (aged 60-69 years) with weak dorsi-flexor muscles but equivalent sensory function (N=17) when compared to controls (N=34 in this group), showed increased maximal sway length in the antero-posterior direction in the eyes closed condition in quiet stance. Based on these findings, they suggest a link between reduced dorsi-flexor strength and reduced proprioceptive control of balance in quiet stance. However, there needs to be some caution when considering these results as subject numbers were small.

Alterations in body position also affect sway path length. Buckley et al. (2005) found that COP displacements in the antero-posterior plane increased to a similar degree for both head-flexed and head-extended positions when elderly subjects (N=12; age 72.1 ± 2.5 years) stood on a firm surface with eyes open. However, although there is an increase in sway distances associated with spontaneous sway in older adults, the *maximal* excursion distances, or limits of stability (that is the maximal COP distance in each direction), for older people have been shown to reduce both when tested on force plates (Cavanaugh et al., 1999; King, Judge, & Wolfson, 1994) and in a functional test of reach (Functional Reach test (Duncan, Weiner, Chandler, & Studenski, 1990)). In this latter test the distance of maximal forward reach is measured at the finger tips when the subject leans forwards with one arm outstretched while standing on a firm surface with feet apart. This reach distance is also related to maximal COP anterior path length – a decrease in Functional Reach is accompanied by a decrease in path length anteriorly (Duncan et al., 1990).

Velocity of sway also increases as age increases (Berger et al., 2005; Cavalheiro, Almeida, Pereira, & Andrade, 2009; Low Choy et al., 2007; Slobounov et al., 1998) particularly in the medio-lateral plane (Berger et al., 2005; Lajoie & Gallagher, 2004). In their study of COM velocity-position predictions Pai and Patton (1997) found that as the COP moves closer to the boundary of the BOS the feasible velocities that can be controlled without loss of balance must reduce. Sway velocity has been found to be higher in fallers than non-fallers of similar ages for stance on a firm surface (Lajoie & Gallagher, 2004; Lazaro, Gonzalez, Latorre, Fernandez, & Ribera, 2011; Melzer et al., 2004) and increases further in the absence of vision (Melzer et al., 2004; Slobounov et al., 1998). It should be noted, however, that even in young adults sway velocity increases in the absence of vision and also when the size of the BOS decreases (for example stance with feet together as opposed to feet apart) (Slobounov, Slobounova, & Newell, 1997). Vision is one of the sensory systems that declines with increasing age (Baloh et al., 2003; Foran et al., 2003). There is also a reduction in the functional size of the BOS which is thought to be as a result of reduced strength of the foot (Endo, Ashton-Miller, & Alexander, 2002; Mickle, Munro, Lord, Menz, & Steele, 2009), ankle (Melzer et al., 2009; Menz et al., 2005) and hip muscles (Choy et al., 2007). That is, older adults have a restricted maximum range (limits of stability) over which they may sway without loss of balance compared with young adults. These changes in vision and usable BOS size may in part, explain the increased sway velocity in older adults compared with young adults in eyes open tests. In effect, the older adults are not being tested under equivalent test conditions as vision and usable BOS are already diminished.

The number of degrees of freedom may also impact on sway velocity results. In a study to compare 'freeze' stance (subjects instructed to prevent movement at hip and knee joints as much as able) with 'free' stance (no instruction to limit movement at any joint), Slobounov et al. (1997) found significantly reduced sway velocity in the freeze condition. This condition effectively limits movement to the ankle joint resulting in fewer degrees of freedom of movement than when movement at other lower limb joints and the trunk is unrestricted. This suggests that the instructions given to subjects can impact on findings. Some researchers request that the subject stand as still as possible while others do not include this in the instructions. In a comparison between two instructions, 'stand quietly' and 'stand as still as possible', Zok et al. (2008) found that the different instructions produced different results in all measured parameters. The 'stand quietly' instruction was also associated with greater variability producing higher standard deviation values. In the clinical setting, adherence to 'standard procedural instructions' is vital so that repeated measurement of intervention effect, as well as the accuracy of data retrieved from various studies employed in meta-analyses, can be reflective of a true result.

The length of time for which a position is required to be maintained may also impact on test results particularly in inter-session reliability. In a systematic review of the literature to investigate evidence for test-retest reliability of COP summary measures when non-specific low back pain subjects were compared with controls, Ruhe et al. (2010) found a number of factors which influence reliability. They recommend that duration of testing should be at least ninety seconds when using summary measures as outcomes. However, in a clinical context, quiet stance tests, including those in which the BOS is changed (for example, stance with the feet apart then feet together then single limb stance) or sensory conditions are altered (as in closing the eyes or standing on a compliant surface), test times are usually limited to thirty seconds. Although a longer test time may be feasible for research on subjects who are not presenting with specific balance deficits, it may not be realistic in some subject groups (for example, those with neurological pathologies) who have compromised balance function (Doyle, Hsiao-Wecksler, Ragan, & Rosengren, 2007).

While many researchers have used COP summary statistics such as sway path area, length and velocity to differentiate between age groups (Berger et al., 2005; Cavalheiro et al., 2009; Patla et al., 1990; Slobounov et al., 1998), between fallers and non-fallers (Melzer, Kurz, & Oddsson, 2010) and between test conditions (Lord et al., 1991; Tanaka et al., 1996) in the study of balance, there seems to be no single parameter of sway that is considered the most sensitive for determining changes in balance related to ageing. Sway velocity has been shown to have the highest test-retest reliability of the commonly used sway parameters (Lafond, Corriveau, Hebert, & Prince, 2004; Moghadam et al., 2011; Ruhe et al., 2010; Salavati et al., 2009) while both sway velocity (Lafond, et al., 2004) and medio-lateral sway amplitude (Maki, Holliday, & Topper, 1994; Melzer et al., 2010) have been found to be sensitive measures for predicting future falls. However, in a group of subjects with hemiparesis in which sway velocity was the outcome parameter, Liston et al. (1996) found that stance on a firm surface with the eyes closed had only moderate test-retest reliability while in the eyes open test reliability was poor. In this study there was no assessment for tests of altered BOS size or surface. It may be that different outcome parameters are needed for different pathologies.

Although COP summary measures are frequently used as outcomes in research, some researchers question whether larger excursions of COP are indicative of reduced balance control in older adults or whether this increased movement serves to provide the elderly with a greater sensory input, particularly from the ankle joint, which is then used to successfully manage their balance (Patla, et al., 1990). Other researchers contend that COP summary measures do not provide the best interpretation of performance. These researchers believe that more sophisticated methods of analysis of COP traces such as stabilogram diffusion analysis (Collins & De Luca, 1993; Vette, Masani, Sin, & Popovic, 2010) and fractal measures (Duarte & Zatsiorsky, 2000; Thurner, Mittermaier, & Ehrenberger, 2002) offer better insights into the control strategies for balance and give a more sensitive analysis of data. Thurner et al. (2002) in comparing healthy young (N=57, aged 30.5 ± 5.0 years) and older (N=19, aged 62.9 ± 10.9 years) adults found that the COP movement patterns of the healthy young were highly complex while the older group showed much less complexity. They suggest that complex movement patterns allow better adaptation to rapidly changing environmental conditions with more regular, or less complex, patterns resulting in less stability. While these more complex analyses are useful in a research environment, they are less accessible to clinicians in a treatment environment. Furthermore, as the number of subjects in the younger group was three times the number in the older group, the findings for the older group are inconclusive.

2.3 COG location

The location of COG (the resultant downward force representation of the COM) within the BOS is one of the factors which influences stability (LeVeau, 2011). Maintenance of balance in quiet stance is dependent on preservation of the COG within the BOS and although there is continual movement of the COG it generally remains towards the centre of the BOS (Spaepen et al., 1976). This gives the greatest freedom of movement within the area of the base without impinging on the boundaries. The closer the COG is to any of the BOS boundaries, the shorter the distance before the COG is at risk of exceeding the BOS requiring action to avert a loss of balance and a fall.

Location of COG is particularly relevant for older adults because of the changes in many of the systems involved in managing the body's response to movement. There is ample evidence of reduced inputs from sensory systems (Baloh et al., 2003; Lord et al., 1991; Menz et al., 2005) and slowed central processing (Lockhart et al., 2005; Yordanova et al., 2004) as well as deficiencies in the musculoskeletal system (Endo et al., 2002; Johnson, Mille, Martinez, Crombie, & Rogers, 2004; Low Choy et al., 2008) with ageing. When multiple systems become compromised, a COG which is located closer to the boundary has the potential to be associated with a higher risk of instability. Although COG location was not identified, Teasdale et al. (1991) found, in their study to compare postural sway characteristics of young (N=10; mean age=21.5 years) and elderly (N=18; mean age=74 years) subjects under different test conditions, that a greater proportion of time was spent in sectors that were further away from the mean COG position in the older group than in the young. This characteristic was more marked in stance on a compliant surface both with and without vision. The greater the distances away from the centre of sway, the greater the risk of loss of balance as there is less time to reverse the direction of sway back towards the central, more stable position. The risk to loss of balance is greater in older adults than in young due to the longer central processing times in older adults (Lockhart et al., 2005; Yordanova et al., 2004) and the reduced capacity to generate the appropriate muscle torques in the shorter timeframe (Johnson et al., 2004).

In a group of young adults used as controls, COG has been found to be located anterior to the ankle joint at approximately 61% of foot length measured from the first toe (Geiger, Muller, Niemeyer, & Kluba, 2007). Schwab et al. (2006) compared simultaneous radiographic and force plate data to study changes in the gravity line location in relation to the vertebral column and the feet in three, healthy groups each with twenty-five subjects – young (29.8 ± 5.8 years), middle (47.3 ± 6.2 years) and elder (70.8 ± 5.2 years). They found that with increasing age, while the distance between the gravity line and the vertebral column increased (the vertebral column moved more posteriorly), the location of the gravity line with respect to the heels remained relatively constant. The posterior shift of the thoracic and lumbar vertebrae may explain the perception of a posterior shift of COG with respect to BOS by clinicians. These researchers suggest that the mobility of the pelvis through anterior or posterior tilt and antero-posterior translation is an important factor in preserving the gravity line position in relation to the BOS. Participants in this study were required to stand with the arms in 45° of shoulder flexion potentially impacting on COG location (reflective of the alteration in the organisation of the body segments) in relation to both BOS and vertebral column. Also in this study the 'heel' was defined as the posterior most triggered force-plate sensor so that actual location of COG relative to anatomical landmarks of the feet was not identified. Although the COG location may need to be interpreted with some caution, the study does point to postural adjustments to balance that are needed to accommodate for age-related vertebral pathologies.

The influence of increasing trunk flexion has also been found to cause no change in the mean COP location in a group of young adults (Saha, Gard, Fatone, & Ondra, 2007). Despite the increase in trunk flexion, mean COP location within BOS was preserved through an increase in plantar flexion and hip flexion ranges. However a change in the position of the cervical spine has been found to have an effect on COG location with a head flexed position resulting in a more posterior COG within the BOS (Buckley et al., 2005). Clinically in older people in whom there are reduced somatosensory inputs, there is likely to be a more persistent neck-flexed posture when walking so as to enhance visual inputs of the environment and for foot placement especially when walking in complex environments. The presence of a head-flexed posture in this group may impact on COG location. Further, if there is an unexpected shift of the COG to an even more posterior position, there may not be the spatial or temporal capacity in older adults to avert a backwards loss of balance resulting in a fall.

Flexibility of the ankle joint, particularly for dorsiflexion range of movement, may also impact on location of the COG within the BOS. In a study looking at the response to prolonged stretch to the calf muscles, Rougier, Burdet and Genthon (2006) found that increased calf length as a result of prolonged stretch of the plantar flexor muscles, results in an anterior shift of the mean COP.

Conversely the mean COP moves more posteriorly in subjects in whom the triceps surae has been fatigued (Berger, Regueme, & Forestier, 2011). Decreased dorsiflexion range has been implicated in reduced functional balance (Mecagni et al., 2000; Menz, Morris, & Lord, 2006) and in falls (Menz et al., 2005; Nitz & Low Choy, 2004) in older adults although there has been no specific connection made with altered average COG location in these studies.

Others have considered loading in the medio-lateral direction. Two studies found increased loading on the right foot (Haddad et al., 2011; Schwab et al., 2006) when standing on a firm surface with feet comfortably apart. Another group considered the pressure under the plantar surface of the left and right great toes in both older (mean age 71.4 years) and younger (mean age 21 years) adults, when standing on a firm surface but with feet together (Romberg position) and observed greater pressures under the great toe of the non-dominant (left) foot (Tanaka et al., 1996). In a study to assess postural preparation for movement, Mille and Mouchnino (1998) looked at anticipatory postural adjustments for three different initial COG positions in the medio-lateral direction prior to lifting one leg in standing in a group of young (21-37 years) adults. They found that the location of the initial COG was linked to the duration of the anticipatory postural adjustments and the duration of the initial COP thrust with a longer duration of COP thrust for a larger distance of COG movement. Centre of pressure thrust in this study was considered to be the early displacement of the COP towards the moving leg to initiate the shift of the COG to the supporting leg. A longer COP thrust duration may present problems for older adults. In a study of platform perturbations at varying velocities, Inglis et al. (1994) found that in the presence of reduced somatosensation there is altered ability to scale magnitude of response to magnitude of perturbation in both velocity and amplitude. Although this study design related to surface perturbation it raises the question as to whether there may be similar difficulties for older adults for internal perturbations. Further research to validate these findings is needed as the results were based on only small subject numbers (reduced somatosensation N=9; age-matched controls N=8).

2.4 Base of Support

There are three concepts which have been studied that relate to the base of support in bipedal stance. The first is usually referred to simply as the BOS although it may be referred to more specifically as the geometric BOS. This is ‘the area defined by the outer boundaries of the feet at the surface of contact’ (Slobounov et al., 1998) and is related to the size and position of the feet. The second is the area over which the COP moves in quiet stance which is referred to as the sway area. Finally there is the concept of the area representing the maximum limits within which the COP can move without loss of balance. Slobounov et al. (1998) tracked the limits of stability in anterior, posterior, lateral and diagonal movements of the COP to provide an estimate of the functional boundaries of the BOS. They refer to this area as the functional stability boundary (FSB). It has been found that, for all age groups, the area of the FSB is less than the BOS area when standing on a firm surface.

Another term used in relation to the BOS is the functional base of support (FBOS) (King et al., 1994). This is defined as the proportion of the antero-posterior distance which is used during sustained maximal movement in forward then backward lean divided by the subject's foot length. In contrast to the FSB, the FBOS represents movement in just one plane and is a measure of distance rather than area of movement. The area of the BOS is an important consideration in postural stability as it determines the available space within which the COG can move (Horak, 2006). When the area of the BOS is reduced, for example standing on one foot compared with standing on two feet, sway velocity (Low Choy et al., 2003) and path length (Amiridis, Hatzitaki, & Arabatzi, 2003; Era et al., 2006) both increase. These increases are greater in older than in younger subjects. Other aspects of BOS such as the shape and the surface compliance can also influence sway parameters in both young and old adults.

The shape of the BOS has implications for the available path length. For example, stance with the feet comfortably apart results in a reasonably long medio-lateral path dimension while the antero-posterior path length is limited to the length of the foot. However, for stance with the feet heel-to-toe (sharpened Romberg or tandem stance) the medio-lateral path length is reduced to approximately the width of one foot while the antero-posterior length is related to the length of the two feet end to end. The feet-apart position has greater stability in the medio-lateral direction while the tandem position has greater stability in the antero-posterior direction (Hasan et al., 1996b).

It has been proposed that a change in the BOS shape also results in a change in strategy to maintain balance, that is, different control mechanisms are required. When standing with the feet apart the strategy employed to control movement in the antero-posterior direction is the ankle strategy while control of sway in the medio-lateral direction is achieved using the hip load/unload strategy (Winter, Prince, Stergiou, & Powell, 1993). However, the use of these strategies to control antero-posterior and medio-lateral movements changes when the foot position is changed. Winter et al. (1996) noted that stance in the tandem position resulted in a change to these strategies with an ankle strategy being used more for the medio-lateral direction and the hip load/unload used for control of antero-posterior movement.

An additional feature to include when considering BOS is the surface compliance. Researchers have found that a more compliant surface results in increased velocity of sway for both young (Haibach, Slobounov, Slobounova, & Newell, 2007) and old (Illing et al., 2010; Low Choy et al., 2003) adults. A more compliant surface also impacts on the FSB even in young adults with reduced boundaries evident when standing on a surface which has greater compliance (Haibach et al., 2007). Patel et al. (2008) compared torque variance when subjects stood on three different foam densities (firm, medium and soft) with eyes open and eyes closed. They found that there was greater instability when standing on firm foam than on soft foam and that there was greater variance in the lateral direction than in the antero-posterior direction. From both a clinical and research perspective, as stance on firm foam is less stable than on soft foam (Patel et al., 2008), the degree of compliance of the surface of the BOS also needs to be considered when interpreting or comparing test results in assessment as well as in designing treatments.

2.5 Base of support and ageing

Several studies have shown decreases in FBOS with ageing (King et al., 1994; Slobounov et al., 1998; Tanaka, Takeda, Izumi, Ino, & Ifukube, 1999) for stance on a firm surface. King, Judge and Wolfson (1994) found that subjects under the age of 60 years (N=23, age range 21-59 years) used a mean sway path length of 60% of available foot length while those over 60 years (N=90, age range 60-91 years) used a mean of only 42%. They also noted much greater variability of results for the older group although this greater variability may have been due to the wide age range in this older group. Endo et al. (2002) also found reduced FBOS in older compared with younger subjects although in this study the findings were reported as a percentage of functional toe length. They found that older adults used 28.3% less of the available length of the first toe than younger adults when performing the Functional Reach Test (Duncan et al., 1990) and linked this finding to a reduction in toe-flexor strength. In their study on FSB, Slobounov et al. (1998) found that the area within the FSB decreases with age and that there is a further reduction in area in the absence of vision.

A reduction in the size of the BOS in older adults (Berger et al., 2005; Tanaka et al., 1999) also impacts on the area or space available for movement of the COG. For example, stance on just one foot, results in higher COG movement velocities and poorer balance performance in older adults (Amiridis et al., 2003; Illing et al., 2010; Low Choy et al., 2003). This is also the case when there is a change in the shape of the BOS (such as in tandem stance) (Amiridis et al., 2003; Era et al., 2006). In addition to higher sway velocity, as the size of the BOS decreases (e.g. from feet apart to Romberg to single limb stance) sway path length increases. This is the case in both young and old subjects but the increase and variability is greater in older subjects than in the young (Amiridis et al., 2003).

In standing, the size and shape of the BOS is affected by physical deformities such as bunions, hammer and mallet toes which are more common in older feet (Menz & Lord, 2001). These deformities influence the size and shape of the forefoot in particular. Older age groups show difficulty in using the forefoot (especially the toes) in maintaining balance on two feet (King et al., 1994; Tanaka et al., 1999) which effectively reduces the FBOS (that is, maximal antero-posterior movement). They also seem to be more hesitant to use a smaller BOS, for example, standing on one foot or rising on to the toes when reaching forward (Cavanaugh et al., 1999). In their study on ageing feet, Menz and Lord (2001) found that 87% of the 135 men and women tested (aged 75-93 years) had at least one foot problem ranging from toe deformities to ulcers, corns and deformed nails. While physical deformities may alter the BOS, the presence of other pathologies and the presence of pain also will impact on the FSB (the area representing limits of movement in all directions without loss of balance).

At the same time as the FSB is decreasing in older people, the area over which the COP moves in quiet stance increases (Berger et al., 2005; Slobounov et al., 1998) producing a higher ratio between the COP sway area of quiet stance and the area of the FSB. This may then result in a higher frequency of COP ‘close-to-boundary’ incidents (Slobounov et al., 1998). The higher ratio between COP sway area and the FSB results in greater control requirements in a group whose systems are less able to manage that control. Reduced somatosensory (Baloh et al., 2003), visual (Cummings et al., 1995; Ivers, Cumming, Mitchell, Simpson, & Peduto, 2003) and vestibular (Paige, 1994; Park et al., 2001) function as well as longer response times (Allum et al., 2002; Lockhart et al., 2005) in older adults, mean that the COG has moved much closer to the boundary before action can be taken. An additional problem is that the necessary corrective action is produced by a motor system which has reduced force production capacity available (Lockhart et al., 2005), to arrest movement. Pai et al. (1998) found, in their studies of predictive models of loss of balance and the need to take a step to recover balance, that a step became imminent when the COM came within 10% of the boundary of the BOS. This might suggest that for older adults with a reduced FSB and greater sway path displacements, the need to step occurs sooner when an anterior shift of COG is required such as in forward reach.

Increased surface compliance also results in changes in balance for older adults. It is associated with a greater sway area (Lord et al., 1991) and a greater proportion of time is spent further from the mean COP location compared with young adults (Teasdale et al., 1991). In men, there is a significant reduction in stability evident by the seventh decade when standing on a compliant surface with eyes closed (Illing et al., 2010) while in women reduced stability for this condition is evident in the sixth decade (Low Choy et al., 2003).

Changes of context in balance require response adaptation and a re-weighting of sensory inputs (Horak, 2006). Kluzik et al. (2005) found that when subjects (N=51, age 20-49) stood on a sloped surface for 2.5 minutes, they adapted by leaning into the surface. For example, if the slope had the feet angled upwards (effectively more dorsi-flexed ankles) the trunk leant forwards. However, this adaptation persisted for up to four minutes in some subjects after they were returned to a level surface. This suggests that recalibration takes time to adapt to the initial change and then also to adapt on return to the start position. In another study Jonsson et al. (2004) found that for single limb stance it was the first five seconds that were the most critical if balance was to be maintained. These findings suggest that older adults might be at greater risk in transition stages – for example, when stepping onto or off a compliant surface or closing their eyes or adapting to a narrowed BOS.

When considering whether the implications of the studies discussed here can be generalized to the broader population, it is important to note that while some studies reported on data collected from fewer than 15 subjects (Buckley et al., 2005; Haibach et al., 2007; Hasan et al., 1996b; Huurnink et al., 2013; Inglis et al., 1994; Mille & Mouchnino, 1998), others had numbers that were in excess of 100 participants (Choy et al., 2007; Duncan et al., 1990; Era et al., 2006; King et al., 1994; Lord et al., 1991; Low Choy et al., 2003; Low Choy et al., 2007; Menz & Lord, 2001; Nitz & Low Choy, 2004). These large samples are more representative of the community and their results are more able to be safely translated to practice. Apart from this variability in study quality, a number of recommendations for practice can be made.

In clinical practice, tests of balance competence in quiet stance must include assessments of altered BOS size and shape as well as the ability of the individual to adapt to altered surface compliance and vision conditions. The size, shape and surface of the BOS become relevant to the function of older adults in a range of contexts in daily function. Altered size and shape of the BOS is necessary when there is a requirement to reduce width of BOS such as in crowded or cluttered environments or when reaching for items on shelves. Changes in surface include moving from a tiled (firm) surface to a carpeted (soft) surface or when walking on grass. Function under these conditions may be further compromised if vision is poor such as in the presence of reduced lighting.

It is evident that declines in function of sensorimotor and central systems in older adults have significant effects on sway parameters. The impact of these declines becomes more apparent as test difficulty increases by reducing BOS size or shape or by reducing the available sensory information by changing surface compliance or altering visual inputs. However, as many of these age-related factors are modifiable in older adults, the ability to interpret the implications of responses under different balance test conditions by the clinician will impact on treatment choices for each individual.

3. Conclusion

The characteristics of COG in relation to BOS are always of relevance to clinicians when considering stability in standing. Just as competent balance is the result of the interaction of multiple systems, intervention to reduce risk of loss of balance, or falls, also needs to be multifaceted. In the clinical setting an understanding of balance is derived in part through assessment of steady state balance incorporating changes in BOS size (e.g. tandem stance, or single leg stance positions), altered somatosensory (via a compliant surface) and altered visual (open or closed eyes) conditions.

Movement characteristics of COG are well studied yet there are still gaps in understanding balance responses particularly in older adults under more challenging test conditions. Furthermore, many of the studies which have been conducted rely on results from small numbers of subjects. In addition, there is little comment on the location of COG within BOS particularly in quiet stance in older adults and under altered test conditions. For older adults, the reduced sensory inputs, reduced central processing speeds, increased reaction times and compromised musculoskeletal system in combination with increased sway velocity and reduced, usable BOS all contribute to greater vulnerability to loss of balance if the COG is habitually located nearer any boundary of the BOS. Further research might consider whether average location of COG in bipedal stance changes with ageing and in the context of the standing surface and use of vision to determine whether sensory decline is contributing to changes in COG location within BOS and risk of falling with ageing.

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Boughen J, Dunn K, Nitz J, Johnston V, Khan A. A new method of interpreting the centre of gravity location using the modified Clinical Test of Sensory Interaction on Balance: A reliability study. *Hong Kong Physiotherapy Journal.* 2013;31:64-8 doi:
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Abstract

This study tests the inter- and intra-rater reliability of a new method of interpreting centre of gravity (COG) location results of the modified Clinical Test of Sensory Interaction on Balance (mCTSIB) tested on the NeuroCOM Balance Master™ (BM). Sixty-three women (40-80 years) were randomly selected from a cohort of 500 women from the Longitudinal Assessment of Women (LAW) study. Start location of COG, as provided diagrammatically in the BM test results, for each of the four tests (firm surface, eyes open and closed; foam surface, eyes open and closed) was subjectively allocated by two raters (blinded to one another) to one of nine location categories on two occasions separated by at least 2 weeks. Kappa (κ) analysis of the data showed a substantial level of both inter-rater [κ=0.84 (95% CI = 0.82-0.86)] and intra-rater [rater 1 κ = 0.78 (95% CI = 0.74-0.79), rater 2 κ = 0.88 (95% CI = 0.86-0.90)] reliability. The strong inter- and intra-rater reliability of this new interpretation of COG location in the mCTSIB test on the BM suggests that this may be an additional reliable method for clinicians to interpret results from steady state balance tests on the BM.

Key words: Centre of gravity, location, CTSIB, reliability

Introduction

Preservation of standing balance depends on the ability of an individual to control movement of the body's centre of mass (COM) within the base of support (BOS) (Hasan et al., 1996). There are several factors that influence the COM movement. These include: the location or position of the centre of gravity (COG) (the vertical projection of the COM) within the BOS, the velocity of COM (i.e. both the speed and direction of movement), and the size and configuration of the BOS. As force plate technology has become more available in rehabilitation settings, clinicians are now able to access more accurate information on the velocity of the COG in assessment of patients. In addition, the size of the BOS being used can be seen via limits of stability measures. However, it is still not possible to track the location of the COG in the clinical setting.

It has been shown that the proximity of COG location to the boundary of the BOS is linked with the need to take a protective step (Pai, Rogers, Patton, Cain, & Hanke, 1998). Also an association has been identified between the antero-posterior position of COG and fall incidence (Merlo et al., 2012) in a group of older adults who had fallen once or twice in the previous twelve months. Given these indications of the relevance of the location of COG in the preservation of balance stability a method by which COG location could be tracked would be of value to clinicians. It would provide additional information as part of the assessment process, particularly in those patients with pathology which affects the sensory systems, as well as being a useful indicator of the impact of therapeutic intervention.

The aim of this study is to examine the inter- and intra-rater reliability of a new method to monitor the location of the COG which has been developed by the authors. It is based on an analysis of the results produced by the NeuroCom Balance Master 6.0, Oregon (BM) for the modified Clinical Test of Sensory Interaction on Balance (mCTSIB) test battery. The BM software provides an average composite location of COG across all tests for the mCTSIB. In addition the location of the COG is recorded diagrammatically at the commencement of each trial (Figure 1). An average composite COG location is not useful clinically because it does not provide specific information for each of the surface and visual conditions. A reliable method of categorizing the COG location under the different test conditions of vision and surface is proposed based on the results provided by the BM. This will enable understanding of the behaviour of the COG in healthy adults under these different test conditions. Such a measure is necessary so that comparisons can be made for different age groups and different pathologies to inform focused treatments for balance deficits. An analysis of the separate diagrammatic COG recordings from the BM for each of the mCTSIB tests forms the basis for this original method of interpretation of COG location under different test conditions.

Method

Participants

Balance Master results printouts from sixty-three subjects were selected from a larger sample of five hundred independent, community-dwelling women (age range 40-80 years) who participated in the Longitudinal Assessment of Women (LAW) study (Khoo, O'Neill, Travers, & Oldenburg, 2008). Paper copies of results from participants were stored in seven, four-drawer filing cabinets. The first drawer in each cabinet housed data from the 40-49 years group, while the second, third and fourth drawers held data for the 50, 60 and 70 year age groups respectively. Modified systematic sampling was used such that every second file from a single drawer in each of the seven four-drawer filing cabinets was selected: (i) drawer one in cabinet one, (ii) draw two in cabinet two, (iii) drawer three in cabinet three, and so on, returning to drawer one for cabinet five. This method enabled an unbiased sample to be extracted and ensured that all age groups were represented in the sample (19 in their 40s, 19 in their 50s, 12 in their 60s and 13 in their 70s). Ethical approval for the LAW study was obtained from the ethics committees of the Royal Brisbane and Women's Hospital and The University of Queensland. All participants provided written consent prior to the start of the study (Khoo et al., 2008).

Measurements

The mCTSIB carried out on the BM consists of four test conditions to explore balance on different surface types with and without vision: (i) firm surface, eyes open (FiEO), (ii) firm surface, eyes closed (FiEC), (iii) foam surface, eyes open (FoEO), and, (iv) foam surface, eyes closed (FoEC). It is an abridged version of the Clinical Test of Sensory Interaction on Balance (Shumway-Cook & Horak, 1986) which allows clinicians to bias the three sensory (somatosensory, visual and vestibular) inputs involved in postural stability during a steady state balance assessment. The summary results provided by the BM software package give three measurements of COG : (i) the sway velocity (degrees/second) mean for each test condition as well as an average of the mean sway velocity across all four tests (twelve trials in total), (ii) the composite Limits of Stability across all four test conditions and (iii) the COG alignment, also calculated as a composite score across all four test conditions, which reflects an average of the subject's start positions relative to the centre of the BOS. A diagram (Figure 1) is also presented using symbols (o = FiEO, + = FiEC, * = FoEO, X = FoEC) to represent the location of the COG at the start of each trial. This reliability study is based on an interpretation of the location of the test symbols (described in the Categorization section) for each 10-second trial as depicted on the diagram.

Procedure

The test protocol for the mCTSIB on the BM requires that the subject stands on the force plate with their two feet apart. The stance width is determined by the BM software based on the height of the subject. The three possible widths (small (S), medium (M) and tall (T)) are marked on the force plate for the FiEO and FiEC tests. For the FoEO and FoEC tests they are marked on the square of foam. Three trials of each of the four conditions of the mCTSIB (FiEO x 3, FiEC x 3, FoEO x3, FoEC x 3) were conducted Each trial lasted 10 seconds (Low Choy, Brauer, & Nitz, 2003). This procedure was repeated on three occasions over the five-year time phase of the study. There was a minimum of one year between assessments. Altogether four tests on three occasions gave a total of twelve test conditions which were rated for each participant. A total of 756 test condition results for the sample were obtained from the 63 subject's files and were used in the reliability testing. Two raters scored the 756 test condition results on two separate occasions in order to calculate intra-rater as well as inter-rater reliability. There were at least two weeks separating the first and second rating allocation and the raters were blinded to one another.

Categorization

A new method of analyzing the output generated by the BM software was developed for the purposes of this study. No previous studies were located which have used this method of analyzing the BM software data. The BM software displays COG locations for the three trials of each test via the symbols o, +, *, X (Figure 1).

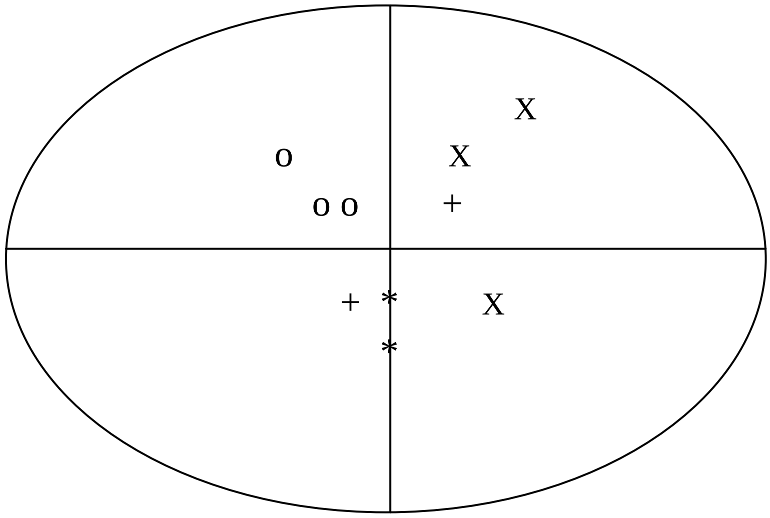

Figure 1: Example of COG location for each trial

FiEO “o” = sector 1; FiEC “+” = no allocation; FoEO “*” = sector 8 as the two visible symbols fall directly on the line; FoEC “X” = sector 2.

This display was used to determine the location of the COG for each condition and formed the basis for category allocation. Nine sectors were identified and these are shown in Figure 2. In order to be allocated to a particular sector at least two of the three symbols must occur in the same sector (Figure 1). In some cases the symbols could have been allocated to more than one sector and hence the sector numbers indicate the order of prioritization. In other words, quadrants take precedence over hemispheres and forward/backward hemispheres take precedence over left/right hemispheres. For example, “X” in Figure 1 could be allocated to sector 2 (right/forward quadrant) or to sectors 5 or 8 (forward or right hemisphere respectively) but since quadrants take precedence over hemispheres, the allocation is made to sector 2.

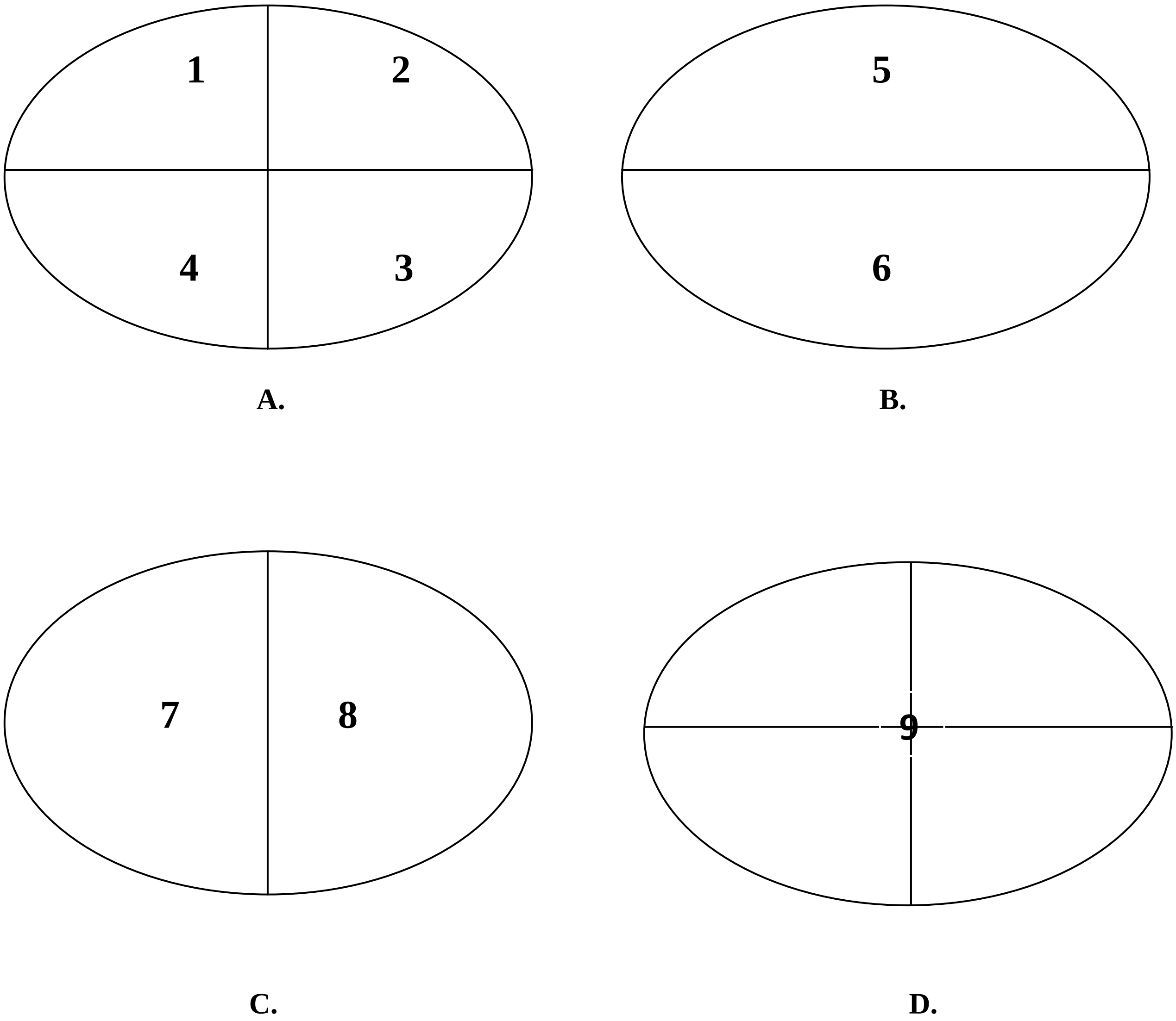

Figure 2: Explanation of categories

A. Quadrants: Left forward (1), Right forward (2), Right back (3), Left back (4); **B.** Forward (5) and back (6) hemispheres; **C.** Left (7) and right (8) hemispheres; **D.** Centre (9).

Where two symbols fall in different sectors (e.g.”+” in Figure 1) and the third is not visible, no allocation is made. Allocation to sector nine (9) occurs only when the symbols fall directly in the centre and cannot be allocated to any other sector. The terms “forward/backward” are used instead of “anterior/posterior” to conform with the terminology used in the BM output.

Statistical Analysis

A reliability analysis using the unweighted Kappa statistic was performed to determine the degree of consistency for both intra- and inter-rater reliability. Kappa was chosen for its ability to take into account agreement by chance and its applicability to the nominal, categorical data for just two raters. Scores for Kappa range between 0 (consistent with agreement by chance) and 1 (perfect agreement). A Kappa value of 0.61-0.80 represents substantial reliability while a value range of 0.81-0.99 represents almost perfect agreement (Landis & Kock, 1977)**.** A 95% confidence interval (CI) was also calculated for each kappa statistic to give further information regarding the strength of the reliability analysis. Inter- and intra-rater reliability was assessed for each test condition as well as for the reliability across the four test conditions. Statistical analysis was performed using Stata version 11.0 StataCorp LP.

Results

The results of the kappa analyses with a 95% CI are presented in Table 1.

An overall inter-rater reliability of 0.84 (95% CI 0.82-0.86) would be described as almost perfect agreement. The intra-rater reliability for rater 1 was substantial at 0.78 (95% CI 0.74 - 0-79) and for rater 2 was almost perfect agreement at 0.88 (95% CI 0.86 – 0.90) (Landis & Kock, 1977)**.** Analysis of each individual test showed inter-rater agreement ranged from substantial to almost perfect agreement and intra-rater agreement were substantial for rater 1 and almost perfect for rater 2. In addition to the strong Kappa values the CI range is small emphasizing the precision of the reliability coefficients.

Table 1 Intra- and inter-rater reliability using Kappa (κ) and 95% confidence interval (CI).

TEST	INTRA-RATER (Kappa (95% CI))		INTER-RATER (Kappa (95% CI))
	Rater 1	Rater 2	
FiEO	0.80 (0.76-0.81)	0.88 (0.84-0.91)	0.80 (0.77-0.84)
FiEC	0.78 (0.74-0.81)	0.89 (0.87-0.93)	0.85 (0.82-0.90)
FoEO	0.76 (0.73-0.78)	0.89 (0.87-0.91)	0.86 (0.80-0.90)
FoEC	0.73 (0.70-0.75)	0.87 (0.81-0.90)	0.82 (0.78-0.84)
Combined	0.78 (0.74-0.79)	0.88 (0.86-0.90)	0.84 (0.82-0.86)

FiEO = firm eyes open; FiEC = firm eyes closed; FoEO = foam eyes open; FoEC = foam eyes closed

Discussion

The usefulness of any outcome measure in the clinical assessment of patients relies on the capacity of the measure to be consistently applied by different clinicians. This study has assessed the reliability of a new method of monitoring the COG start location adapted from data produced in the mCTSIB test conditions on the BM. We have demonstrated levels of agreement ranging from substantial (κ 0.61-0.80) to perfect (κ 0.81-0.99) for both inter- and intra-rater reliability. The results from two raters for this method of categorization are in good agreement. This is the first time, to the best of our knowledge, that the start location of COG has been assessed in a defined, categorical way for each of the four test conditions of the mCTSIB on the BM.

The objective of devising this novel method of categorizing the COG location was, principally, to provide clinicians with a simple way to assess the COG location in the clinical setting. The mean COG position is a summary measure that is reported less often in research papers. In a study to assess sampling duration effects on the reliability of summary measures in a group of young adults, Carpenter, Frank, Winter and Peysar (2001) found that the mean COG position for the antero-posterior and medio-lateral planes showed high reliability. Subjects in this study were assessed standing on a firm surface with their eyes open. However a measure of the mean COG position across a number of tests to assess balance under different surface and vision conditions, as provided by the BM results, does not help clinicians to differentiate between responses for each test.

Further research is needed in order to show whether or not the COG location changes with ageing under different surface or visual conditions in healthy adults. Studies which identify the COG location within the BOS mostly test subjects on a firm surface only with the subjects standing with their feet apart (Carpenter et al., 2001; Danis, Krebs, Gill-Body, & Sahrmann, 1998). Low Choy, Brauer and Nitz (2007) reporting on the same data set used in the current study, found no changes to stability across ages when subjects stood with their feet apart on a firm surface with eyes open using sway velocity data. However, they were able to demonstrate changes for stance stability on a compliant surface as well as for stance with eyes closed. Merlo et al. (2012) found that the COG location in firm surface tests also showed no difference between groups of fallers and non-fallers. However, they found an association between COG location on a compliant surface with eyes open and the incidence of falls in older adults. These research findings support the need for a clinically reliable measure of COG location in tests which manipulate sensory inputs to be available to clinicians.

There is increasing information available on the behaviour of COG location in the presence of pathology. For example teenage girls with scoliosis had a more posterior location of COG than controls when standing on a firm surface with their eyes open (Dalleau, Allard, Beaulieu, Rivard, & Allard, 2007). This was also the case for subjects with chronic low back pain (Mientjes & Frank, 1999) although in this study the same posterior location of COG was also noted when these subjects were standing on foam with their eyes open. As knowledge of differences in COG location increases for subjects with different pathologies, there is a need for normative data against which to make comparisons. It would be useful for clinicians to be able to monitor COG location in the treatment setting and to be able to compare the results in the presence of pathology against the results for healthy adults. It may also be possible in the future for the location of COG to be used to evaluate treatment effectiveness.

In this preliminary reliability study we have investigated a new method by which the Centre of Gravity location can be monitored using the mCTSIB. Further work, including the use of more raters, is needed in order to assess the use of this categorising method as a valid measure of the location of COG in different patient groups. It should be noted that since, in this study, the COG location was measured only at the commencement of each test trial, the method does not purport to offer a true average of the COG location over the complete trial. In spite of these recognised limitations, it is hoped that these results will help to further research in this important field.

Conclusion

The location of the COG in stance warrants further investigation. This study has established the reliability for a novel method of categorising the location of COG, developed by the authors, under a range of test conditions using existing data from the mCTSIB on the BM. Its use will facilitate further exploration by clinicians of COG-within-BOS characteristics across different test conditions for different age groups and in the presence of pathologies.

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