THE UNIVERSITY OF QUEENSLAND

AUSTRALIA

Exploring Technology for Clinical Applications and Analysis of Factors Associated with Postural Control in Older Adults with Idiopathic Neck Pain

June Mei Tse Quek

Diploma in Physiotherapy

Bachelor of Health Science (Physiotherapy)

Master of Physiotherapy (Manipulative Physiotherapy)

A thesis submitted for the degree of Doctor of Philosophy at

The University of Queensland in 2018

School of Health and Rehabilitation Sciences

Abstract

Neck pain in older adults is common and has been associated with reduced postural control. However, the mechanisms underlying neck pain-related postural control deficits remain unknown. Unravelling this complex clinical phenomenon is important given the fact that older adults with balance deficits are at risk of falls. Furthermore, falls in older adults may potentially lead to serious consequences and place a burden on public health. This thesis aimed to explore new measurement tools and technique related to cervical spine impairments and postural control that may be potentially useful in research and in the clinical setting, and sought to better understand the mechanisms underpinning neck pain-related postural control deficits in older adults. .

Studies 1, 2 and 3 investigated the use of technology, i.e. the smart phone, the Microsoft Kinect and the Nintendo Wii Board to measure cervical range-of-motion, thoracic kyphosis and hallux flexor strength respectively. The results of study 1 showed that the Android phone was valid and reliable in the sagittal and coronal plane but not in the transverse plane. In other words, range-of-motion testing of cervical flexion and extension and lateral flexion were valid and reliable but not rotation in sitting. Study 2 demonstrated that the Microsoft Kinect was valid and reliable to measure thoracic kyphosis and could potentially bridge the gap of accessibility and ease of use in current measurement tools to regularly assess this important dimension of spinal posture. Study 3 evaluated the reliability of the Nintendo Wii Board to measure hallux flexor strength and showed that it was reliable. Because big toe strength has been previously shown to be an independent factor for balance in older adults, this newly developed device using the Nintendo Wii Board provides an affordable and reliable tool for clinic use.

Studies 4, 5 and 6 were cross-sectional studies aimed to further develop our understanding of how neck pain or neck pain-related impairments may impact postural control. Specifically, study 4 explored standing postural control mechanisms using new measures of signal frequency (wavelet analysis) and complexity (sample entropy) in older adults with neck pain. This study highlighted the use of wavelet analysis to reveal new insights into postural control mechanisms and this analytical technique was then used in studies 5 & 6. However, no consistent results could be obtained when comparing the results of wavelet analysis between studies 4 and that of 5 & 6. It is clear that more research needs to be done to determine the usefulness of employing wavelet analysis in revealing mechanistic insights into postural control in older adults with neck pain.

Studies 5 and 6 shed light on previously unknown factors influencing postural control in older adults with neck pain. Study 5 investigated potential differences in known predictors of postural control between older adults with and without neck pain. In particular, physical activity levels, lower limb motor and sensory function, vestibular function and visual contrast sensitivity were no different in individuals with and without neck pain. Study 6 investigated the associations of cervical spine impairments with poor postural control in older adults with neck pain. This study highlighted that neck pain moderated the relationship between static postural sway and four variables: forward head posture angles, a positive Dix-hallpike test, age and higher levels of physical activity. In addition, poor dynamic postural control was associated with greater dizziness disability, fear of movement and age.

In summary, this thesis advocates the use of technology, specifically the Microsoft Kinect to measure thoracic kyphosis and the Wii Balance Board application to measure hallux flexor strength, but not the Android phone to measure seated cervical range-of-motion, in the clinical setting. There is great potential for these technologies to break the existent barriers that practitioners currently face such as affordability, inaccessibility and ease of use. Further, this thesis identified factors that contribute to neck pain-related postural control deficits. The findings suggest that the mechanisms underpinning postural control deficits in neck pain are complex and may serve as a basis for future neuro-imaging studies to explore the role of the central nervous system and its integration of somatosensory input in maintaining postural stability in older adults with neck pain. Having a greater understanding of these mechanisms is important for developing management strategies to improve postural stability and potentially reduce falls risk. Future interventional studies are also required to determine if improving head posture and vestibular function will improve standing postural stability, and if reducing dizziness and fear of movement will increase dynamic stability in older adults with neck pain.

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

Peer-reviewed papers

Quek J, Brauer SG, Treleaven J, Pua YH, Mentiplay B, Clark RA. Validity and intra-rater reliability of an Android phone application to measure cervical range-of-motion. *Journal of Neuroengineering and Rehabilitation* 2014; 11(1):65.

Quek J, Brauer SG, Clark R, Treleaven J. New insights into neck-pain-related postural control using measures of signal frequency and complexity in older adults. *Gait & Posture* 2014; 394: 1069-1073.

Quek J, Treleaven J, Brauer SG, O'Leary S, Clark RA. Intra-rater reliability of hallux flexor strength measures using the Nintendo Wii Balance Board. *Journal of Foot and Ankle Research.* 2015; 81:48.

Sarig Bahat H, Igbariya M, Quek J, Treleaven J. Cervical Kinematics of Fast Neck Motion across Age. *Journal of Novel Physiotherapies.* 2016; 6306:2.

Quek, J, Brauer, SG, Treleaven, J, & Clark, RA. The concurrent validity and intra-rater reliability of the Microsoft Kinect(TM) to measure thoracic kyphosis. *International Journal of Rehabilitation Research* 2017; 40(3): 279-284.

Quek J, Treleaven J, Clark R, Brauer SG. An exploratory study examining factors underpinning postural instability in older adults with idiopathic neck pain. *Gait & Posture* 2018; 60: 93-98.

Conference abstracts

Quek J, Brauer S, Clark R, Treleaven J. (2013). New insights into neck-pain-related postural control using measures of signal frequency and complexity in older adults. Presented at Australian Physiotherapy Conference, Melbourne, Australia. 17th Oct 2013.

Quek, J, Brauer, SG, Treleaven, J, & Clark, RA. (2015). Validity and reliability of an android phone application to measure cervical range-of-motion. *Physiotherapy*, 101, e1244. World Confederation for Physical Therapy, Singapore. 2 May 2015.

Quek, J, Brauer, SG, Treleaven, J, & Clark, RA. (2015). The use of the Microsoft Kinect to measure thoracic kyphosis. *Physiotherapy*, 101, e1243-e1244. World Confederation for Physical Therapy, Singapore. 2 May 2015.

Quek, J, Brauer, SG, Treleaven, J, & Clark, RA. (2015). Using the smart phone, Microsoft Kinect and the Wii Board to measure cervical range of motion, thoracic kyphosis and big toe strength. Presented at Australian Physiotherapy Conference, Gold Coast, Australia. 6th Oct 2015.

Publications included in this thesis

Quek J, Brauer SG, Treleaven J, Pua YH, Mentiplay B, Clark RA. Validity and intra-rater reliability of an Android phone application to measure cervical range-of-motion. *Journal of Neuroengineering and Rehabilitation* 2014;11(1):65.

Incorporated as Chapter 3.

Contributor	Statement of contribution
June Quek (Candidate)	Designed study (50%), Created the phone app (10%), Wrote and edited the paper (70%), Wrote ethics application (85%), Data Extraction (10%), Data analysis and interpretation (45%)
Sandy Brauer	Designed study (5%), Wrote and edited the paper (5%), Data analysis and interpretation (5%)
Julia Treleaven	Designed study (5%), Wrote and edited the paper (5%), Data analysis and interpretation (5%)
Yong-Hao Pua	Wrote and edited the paper (5%), Data analysis and interpretation (40%)
Benjamin Mentiplay	Wrote and edited the paper (5%), Data Extraction (90%)
Ross Clark	Designed study (40%), Created the phone app (90%), Wrote and edited the paper (10%), Wrote ethics application (15%) Data analysis and interpretation (5%)

Quek, J, Brauer, SG, Treleaven, J, & Clark, RA. The concurrent validity and intra-rater reliability of the Microsoft Kinect(TM) to measure thoracic kyphosis. *International Journal of Rehabilitation Research* 2017; 40(3): 279-284.

Incorporated as Chapter 4.

Contributor	**Statement of contribution**
June Quek (Candidate)	Designed study (50%), Wrote and edited the paper (70%), Wrote ethics application (85%), Data Extraction (90%), Data analysis and interpretation (85%)
Sandy Brauer	Designed study (5%), Wrote and edited the paper (10%), Wrote ethics application (5%), Data analysis and interpretation (5%)
Julia Treleaven	Designed study (5%), Wrote and edited the paper (10%), Wrote ethics application (5%), Data analysis and interpretation (5%)
Ross Clark	Designed study (40%), Created the Kinect software (100%), Wrote and edited the paper (10%), Wrote ethics application (5%), Data Extraction (10%), Data analysis and interpretation (5%)

Quek J, Treleaven J, Brauer SG, O'Leary S, Clark RA. Intra-rater reliability of hallux flexor strength measures using the Nintendo Wii Balance Board. *Journal of foot and ankle research* 2015; 81:48.

Incorporated as Chapter 5.

Contributor	**Statement of contribution**
June Quek (Candidate)	Designed study (50%), Wrote and edited the paper (70%), Wrote ethics application (85%), Data Extraction (70%), Data analysis and interpretation (70%) Designed and built wooden device (20%)
Julia Treleaven	Designed study (10%), Wrote and edited paper (5%), Wrote ethics application (5%), Data analysis and interpretation (10%)
Sandy Brauer	Designed study (10%), Wrote and edited paper (5%), Wrote ethics application (5%), Data analysis and interpretation (10%)
Shaun O'Leary	Wrote and edited paper (5%), Designed and built wooden device (80%)
Ross Clark	Designed study (30%), Wrote and edited paper (15%), Wrote ethics application (5%), Data Extraction (30%), Data analysis and interpretation (10%) Created the software for data acquisition (100%)

Quek J, Brauer S, Clark R, Treleaven J. New insights into neck-pain-related postural control using measures of signal frequency and complexity in older adults. *Gait & Posture* 2014; 394: 1069-1073.

Incorporated as Chapter 6.

Contributor	**Statement of contribution**
June Quek (Candidate)	Designed study (70%), Wrote and edited the paper (70%), Wrote ethics application (85%), Data Extraction (70%), Data analysis and interpretation (70%)
Sandy Brauer	Designed study (10%), Wrote and edited paper (10%), Wrote ethics application (5%), Data analysis and interpretation (10%)
Ross Clark	Designed study (10%), Wrote and edited paper (10%), Wrote ethics application (5%), Data Extraction (20%), Data analysis and interpretation (10%)
Julia Treleaven	Designed study (10%), Wrote and edited paper (10%), Data Extraction (10%), Wrote ethics application (5%), Data analysis and interpretation (10%)

Quek J, Treleaven J, Clark R, Brauer S. An exploratory study examining factors underpinning postural instability in older adults with idiopathic neck pain. *Gait & Posture* 2018; 60:93-98.

Incorporated as Chapter 7.

Contributor	**Statement of contribution**
June Quek (Candidate)	Designed study (70%), Wrote and edited the paper (60%), Wrote ethics application (85%), Data Extraction (70%), Data analysis and interpretation (70%)
Julia Treleaven	Designed study (10%), Wrote and edited paper (15%), Wrote ethics application (5%), Data Extraction (10%), Data analysis and interpretation (10%)
Ross Clark	Designed study (10%), Wrote and edited paper (15%), Wrote ethics application (5%), Data Extraction (10%), Data analysis and interpretation (10%)
Sandy Brauer	Designed study (10%), Wrote and edited paper (10%), Wrote ethics application (5%), Data Extraction (10%), Data analysis and interpretation (10%)

Contributions by others to the thesis

Professor Sandy Brauer, Dr Julia Treleaven and Dr Ross Clark made large contributions to all aspects of this research. This included research question design, study design, implementation of the methods, implementation, analysis and interpretation of the data, oversight, review and guidance on manuscript/thesis chapters, and design of tables and figures. In addition Dr Ross Clark played a key role in the development and implementation of the software required for studies 2, 3, 4, 5 and 6.

Dr Shaun O'Leary played a key role in the design and building of the equipment used for strength testing in study 4.

Dr Pua Yong Hao played a significant role in statistical analysis and interpretation of data for studies 1 and 2 as well as manuscript drafting in study 2.

Dr Michael David played a significant role in statistical analysis and modelling in study 6.

Dr Peter Baker assisted with data analysis in study 1.

Dr Alan Huang assisted with statistical analysis for study 3.

Dr Dion Scott provided assistance with equipment needs for studies 5 and 6.

Dr Benjamin Mentiplay played a role in data collection for study 2.

Mrs Katrina Williams contributed her expertise as a vestibular specialist in the interpretation of results in study 6.

Ms Tan Jia Ling assisted with data collection for studies 5 and 6.

Statement of parts of the thesis submitted to qualify for the award of another degree

None.

Acknowledgements

To my Heavenly Father, thank you for the incredible, invaluable gift of life you have given me through Jesus Christ and communion through the Spirit. Your wisdom, strength and power have sustained me. Thank you for showing me that your ways are not of this world, that being weak is strong, and that being poor is rich. What I have gained during this PhD journey has surpassed my wildest imagination. All I have is yours.

To my supervisors, Sandy, Julia and Ross, I couldn't have asked for a better advisory team! Thank you for all your support and advice throughout my candidature. I especially appreciated your care and concern and understanding during my recovery post TBI.

Sandy, your brilliance is amazing and your capacity to thrive under the numerous competing demands for your time is incredible. It has been such a privilege to be supervised by you. Thank you for giving me many opportunities to teach and to explore different career options.

Julia, you never fail to offer a listening ear and you are always ready to give of your time. For that, I'm very grateful. Your humility and unassuming ways are refreshing and endearing, especially when being a leading expert in your field.

Ross, I'm continuously amazed by your cleverness and creativity. I love your work ethic and have enjoyed working with you. Although you may appear to be tough on me (sometimes), underneath you have such a tender heart. Thank you for caring, especially after my accident.

To my mum, thank you for always being so supportive over the choices I have made in my life. The sacrifices you have made and hardships you have gone through, have not gone unnoticed. I would not be where I am without all that you have done. Thank you, and I love you.

To my only blood sister, thank you for your love and support throughout my life. Thank you for always welcoming me home, that means a lot.

To my extended Quek family, I cannot thank you enough, especially to my uncles and aunties for the love and support you have given to me after dad passed away. I am deeply grateful.

To Jo and Jennie monkeys, I have only realised how much you mean to me during our last official gathering in Brisbane. I love how God used trials to prune us, and that we could be there to support, encourage and pray for each other. Thank you for being the pillars of support for me during this journey. I'm so glad that our friendship is not bound by physical means but is one that is eternal. I'm excited to see what's next in our lives!

To my SLE church family, thank you for being my family away from home. It has been such a privilege to journey with you all in the ups and downs of our lives. Thank you Steven Tran and Benjamin Ho for teaching me God's Word faithfully. I treasure very much the spiritual food that sustains me every week.

To my Zion BP church family back home, thank you for your prayers during my ordeal. I'm looking forward to reuniting with and serving alongside you.

To the Nation family, thank you for welcoming me into your family wholeheartedly and loving me despite my intolerance to screams and bodily fluids :). Most importantly, thank you for showing me what it means to live for, and to love Jesus. I don't think I can express how much my life has been impacted by your family.

To Yvonne, thank you for your support, your prayers and visiting me when I had my accident. I'm very touched by your love and I am very thankful for our many years of friendship.

To Irene Toh, "one of the most beautiful qualities of true friendship is to understand and to be understood". I'm so grateful for our friendship.

To Karen Koh, thank you for your support and encouragement throughout this PhD journey. It has been such a blessing to have you alongside.

To Hoon and Miran, it has been such a wonderful time getting to know you both. Thank you for all your support, encouragement and company. Life in Seddon would be quite lonely without you!

To my Seddon prayer warriors, Viana, Katelyn, Grace, thank you for journeying alongside with me, praying with me, loving and encouraging me. It has been such a privilege to be partners with you in the Gospel.

To Dr Pua Yong Hao, thank you for personally mentoring me in my research career. I would never have dared to venture into research if not for your guidance. Your passion for your work exemplified through relentless hard work is inspiring.

Last but not least, I'm grateful to my company, Singapore General Hospital for the PhD scholarship. I would never have been able to do my PhD without this scholarship. I'm thankful to my colleagues, with special mention of Bee Yee, Jennifer, Agnes, Si Min, Yan Qin. Thank you for your support and kind understanding during my unanticipated and unexpected delay in completing my PhD.

Keywords

Neck pain, postural control, balance, kyphosis, forward head posture, wavelet analysis, range of motion, older adults.

Australian and New Zealand Standard Research Classifications (ANZSRC)

ANZSRC code: 110317, Physiotherapy, 40%
ANZSRC code: 110308, Geriatrics and Gerontology, 30%
ANZSRC code: 100499: Medical Biotechnology not elsewhere classified, 30%

Fields of Research (FoR) Classification

FoR code: 1103, Clinical Sciences, 70%
FoR code: 1099, Other Technology, 30%

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List of Abbreviations

3DMA: Three-dimensional motion analysis

ABC: Activities-specific Balance Confidence

AP: Anteriorposterior

BMI: Body Mass Index

BPPV: Benign Paroxysmal Positional Vertigo

C: Compliant

CI: Confidence Interval

CoP: Centre of Pressure

CROM: Cervical range-of-motion

DGI: Dynamic Gait Index

DHI: Dizziness Handicap Inventory

DV: Dependent Variable

DVA: Dynamic Visual Acuity

EO: Eyes Open

EC: Eyes Closed

FHB: Flexor Hallucis Brevis

f: female

F: Firm

HHD: Hand-Held Dynamometry

HIT: Head Impulse Test

ICC: Intra-class correlation coefficient

JPE: Joint Position Error

LOA: Limits of agreement

MDC: Minimal Detectable Change

ML: Mediolateral

MTP: Metatarsophalangeal

n: Sample size

N: No

NDI: Neck Disability Index

NP: Neck pain

NRS: Numeric Rating Scale

NWBB: Nintendo Wii Balance Board

OA: Osteoarthritis

OLP: Ordinary least products

PFActS-C: Pictorial Fear of Activity Scale- Cervical

Prop Bias: Proportional Bias

RMS: Root Mean Square

ROM: Range-of-motion

SD: Standard Deviation

SE: Standard Error

SEM: Standard error of measurement

TUG: Timed Up and Go

Y: Yes

Chapter 1: Introduction

The lifetime prevalence of neck pain (NP) is high in adults (18-84 years) – ranging from 14.2% to 71% with a mean of 48.5% (Fejer et al., 2006). Specifically, in the older population, NP is amongst the most common complaints and affects 20% of the population on a monthly basis (Hartvigsen et al., 2004). Importantly, 7% of older adults had modified or diminished their physical activities as a result of NP and those who reported NP of more than 30 days of pain duration had significantly lower general physical body strength scores compared to those who reported no pain (Hartvigsen et al., 2006). Therefore, NP may impose a significant impact on the lives of those affected.

Noteworthy in recent research, is the growing evidence implicating the role of the cervical spine in influencing postural control. There is substantial evidence to indicate that those with cervical spine dysfunction demonstrate poorer postural control compared to healthy controls (Ruhe et al., 2011; Silva & Cruz, 2012). Even in the absence of trauma, individuals with idiopathic NP are reported to demonstrate increased postural sway in standing compared to age-matched controls (Field et al., 2008; Poole et al., 2008; Uthaikhup et al., 2012). These studies included both older and younger adults, indicating that NP-related postural control impairment is a phenomenon observed across all ages. However, it is important to highlight that older adults have a higher risk of falls (Campbell et al., 1990) leading to severe consequences (Murray & Lopez, 1996). In particular, NP in older adults is associated with increased concerns for falling (Kendall et al., 2016) and has been identified as a risk factor for falls, (Kendall et al., 2015). Therefore, it is essential to identify the mechanisms linking NP and postural control changes in older adults. To begin, an understanding of postural control and balance is required.

1.1 Basic definitions of postural control, balance and associated terms

The terminology related to balance and postural control can be confusing, and these terms are often used synonymously. This section defines the various terms related to postural control used throughout this thesis. Understanding what each term represents may help clarify the nomenclature used in the literature.

1.1.1 Balance and postural control

Balance, also known as postural stability, is defined as one's ability to maintain the centre-of-gravity (COG) or also known as centre of mass, within the base of support (D'Anna et al., 2015; Shumway-Cook & Woollacott, 2001) and is achieved via the complex interaction and integration of the visual, vestibular, and somatorsensory systems and alterations in cognitive and motor output (Melzer et al., 2001). On the other hand, although no specific definition exists for postural control, it is commonly described as "the act of maintaining, achieving or restoring a state of balance during any posture or activity" (Pollock et al., 2000). Optimal postural control when standing not only involves accurate perception of environmental stimuli, but also responding appropriately to alterations in the body's orientation within the environment to maintain the body's centre of gravity within the base of support (Carr & Shepherd, 2000; Shumway-Cook & Woollacott, 2001).

1.1.2 Postural sway, centre of pressure and centre of gravity

Physiological postural sway in static upright standing is defined as the continuous corrective movements around the COG of a body designed to maintain postural control (Shumway-Cook & Woollacott). It is typically thought that in static standing, postural sway can be quantified by describing the centre of pressure (CoP) movement over time (Chagdes et al., 2009). CoP marks the point location of the resultant vertical ground reaction force (Winter, D. A., 1995) and is calculated from these ground reaction forces. CoP is an indication of the trajectory of the center of body mass and the amount of torque applied at the support surface to control body-mass acceleration (Winter et al., 1990). The difference between the COG and the CoP is that the COG is a passive variable guided by the postural control system (and cannot be directly derived from a force platform) (Winter, David A, 1995) whereas the CoP is the weighted average of all pressures resulting from the area of contact with the support surface and is obtained from a force platform (Winter et al., 1990).

1.1.3 Parameters of CoP

Various CoP parameters have been used to quantify postural control and the selection of which measure to use is controversial. This is because conflicting opinions exist as to which measure is the most sensitive and best characterizes the changes within the postural control system (Palmieri et al., 2002). Commonly used standard CoP parameters include CoP displacement (Palmgren et al., 2009), velocity (mean rate of change of sway)(Boucher et al., 2008) and root mean square (RMS) amplitude (standard deviation of CoP displacement) (Field et al., 2008), Higher measures of CoP sway are traditionally

interpreted as poorer postural control but recent research suggests that an increase in sway may be exploratory to obtain information about the environment (Carpenter et al., 2010). More information regarding the application of these parameters and the gaps in the literature in the NP population is included in section 1.4.1.

1.1.4 Sensory systems in postural control

An effective postural control system requires the normal functioning of the visual, vestibular and somatosensory systems to detect the peripheral sensory inputs of the body's position and movement in space relative to gravity and the environment (Paulus et al 1984). Information from each of these systems is integrated and interpreted by the central nervous system, and together with prior experience, plans appropriate responses to achieve optimal postural control (Allum & Hulliger, 1989, Massion 1994). Each of these systems provides different sensory information for postural control and will be discussed below.

1.1.4.1 Visual Input

The visual system provides information on the position and motion of the head with respect to surrounding objects and is a reference for verticality (Shumway-Cook & Woollacott, 2017). Postural control in standing can be maintained without visual information due to reliance on the other systems, but deprivation of visual input leads to significant increase in CoP motion during quiet standing (Black et al., 1982; Diener, H.C. et al., 1984; Friedrich et al., 2008; Riley & Clark, 2003). Although vision is not absolutely necessary for postural control, it may become crucial for individuals with suboptimal ability to process other information such as the elderly population (Haibach et al., 2007; Sundermier et al., 1996) and those with vestibular (Black et al., 1988) or somatosensory impairments.

1.4.1.2 Vestibular Input

The vestibular system provides a gravitoinertial frame of reference for postural control by detecting the position and movement of the head with respect to gravity and inertial forces (Shumway-Cook & Woollacott, 2017). During postural disturbances, the vestibular system indicates the direction and velocity of sudden changes to head movement and these vestibular signals are thought to trigger and modulate automatic postural responses according to the amplitude of the disturbances (Allum et al., 1994; Horak et al., 1990; Horak et al., 1994; Macpherson & Inglis, 1993). Although a loss of vestibular input can be easily compensated by the other sensory systems in quiet stance (Horak et al., 1990), it is clear that the vestibular system contributes to postural control when experimental stimulation of

vestibular system evokes an increase in body sway (Hlavacka & Njiokiktjien, 1985; Johansson et al., 1995). Further, there is evidence that gait kinematics such as timing and magnitude of foot displacement is regulated by vestibular feedback (Bent et al., 2004). Accordingly, previous studies have demonstrated gait deviations towards the lesioned side in individuals with unilateral vestibular deficits (Brandt et al., 2001; Jahn et al., 2000).

1.4.1.3 Somatosensory Input

The somatosensory system plays a significant role in postural control by providing information regarding the position and motion of the different body segments with reference to the supporting surfaces (Shumway-Cook & Woollacott, 2017). A loss of lower limb somatosensory input has resulted in increased body sway in quiet stance (Diener, H. C. et al., 1984; Horak et al., 1990; Magnusson et al., 1990). Further, proprioceptive deficits induced experimentally in the neck and ankle muscles have demonstrated an increase in CoP motion during quiet stance (Kavounoudias et al., 1999; Patel et al., 2009). Likewise, the importance of somatosensory function in dynamic postural control has been shown in gait studies where reduction or loss in somatosensory inputs have resulted in detrimental changes to various aspects of walking kinematics such as walking speed, stride length, stride time, base width and double support duration (Allet et al., 2008; Courtemanche et al., 1996; Mueller et al., 1994).

1.1.5 Cognitive load

In addition to the sensory systems mentioned, it has been shown that cognitive load affects the regulation of posture in both healthy young and older adults (Dault et al., 2003; Melzer et al., 2001). No studies have shown an impact of cognitive load on individuals with NP to date. This issue would require extensive investigation and therefore is beyond the scope of this thesis.

1.1.6 The impact of aging on the sensory systems and central processing

Age-related changes in the sensory systems have been shown to adversely impact postural control (Goble et al., 2009; Shumway-Cook & Woollacott, 2017). Physiological and functional changes within these systems have been observed with increasing age. Specifically, the visual system shows a decline in visual acuity (Jack et al., 1995), contrast sensitivity (Lord et al., 1991c) and loss of visual field (Sturnieks et al., 2008) as age increases. A functional reduction in the vestibular system is observed via a loss of 40% of vestibular hair and nerve cells by age 70 and a 3% loss per decade of vestibular nucleus

cells beginning from age 40 to 90 years (Rosenhall & Rubin, 1975). Further, researchers have documented a decline in the quality and quantity of cutaneous receptors with aging (Shumway-Cook & Woollacott, 2017). As such, the vibratory sensation threshold increases with age (Kenshalo Sr, 1986) and tactile sensitivity increases with age as measured by threshold to touch stimuli (Kalisch et al., 2008).

In addition to considering the integrity of the individual sensory systems, it is also important to evaluate sensory organization and adaptation at the CNS during postural control (Shumway-Cook & Woollacott, 2017). This is because according to the sensory weighting theory, the CNS organizes and adapts sensory information for optimal postural control when changes in postural control responses occur, for example, when visual input becomes less reliable (Oie et al., 2002). Evidence is growing to implicate the role of a declining central nervous system together with that of the degenerative peripheral nervous system as co-mechanisms for age-related deterioration of postural control (Goble et al., 2009). Accordingly, it has been reported that age-related atrophy of the motor cortex and corpus callosum may be associated with balance and gait deficits (Papegaaij et al., 2014; Seidler et al., 2010).

1.2 Postural control and the cervical spine

There is considerable evidence that spinal pain affects standing postural control (Mok et al., 2004, 2011; Ruhe et al., 2011; Silva & Cruz, 2012). The underlying mechanisms of how dysfunction of the cervical spine could affect postural control are however unclear. It is postulated that due to the high density of mechanoreceptors found in the cervical spine (Boyd-Clark et al., 2002; Kulkarni et al., 2001) and the extensive connections the cervical spine has with the vestibular, visual and central nervous systems (Horak et al., 1989), postural control impairments associated with cervical spine dysfunction are due to aberrant afferent input from the cervical spine. It is then suggested that a mismatch from abnormal afferent input from the cervical spine and normal information from the vestibular and visual systems can result in postural control disturbance during standing (Treleaven, 2008). Despite these postulations, studies investigating the associations between NP-related impairments and postural control during standing remain scarce (Quek et al., 2013; Silva & Johnson, 2013; Treleaven, 2011; Treleaven et al., 2006).

1.3 Importance of identifying the correlates of postural control in NP in older adults

Older adults are at an increased risk of falls (Campbell et al., 1990; Tinetti & Williams, 1998), and the consequences are often severe – including physical injuries, associated

illness, loss of independence, and early death (Murray & Lopez, 1996). Poor balance is a primary risk factor for falls in older adults and ageing is characterised by an increased sway in unperturbed standing (Laughton et al., 2003). However, it is unclear how the process of ageing (above 60 years old) influences the somatosensory function of the cervical spine and how it could then link to poor balance.

Previous studies have demonstrated a positive correlation between age and joint position error in peripheral joints such as toe-matching (with significant reductions by age 60s and 70s) and weight bearing knee replication task (significant reduction by the 60s) (Low Choy et al., 2007). As such, it is biologically plausible that the proprioceptive function in the cervical spine may also deteriorate with age and could be an important link to postural control impairment in this population. In addition, age-related spinal changes such as increased thoracic kyphosis (Ostrowska et al., 2003) and cervicothoracic changes (cranial migration of the inflexion point between cervical lordosis and thoracic kyphosis) (Boyle et al., 2002) may reduce postural stability via a forward displacement of the trunk's centre of mass towards the limits of stability in older adults (Horak et al., 1989).

Furthermore, increased postural sway (Lajoie & Gallagher, 2004) and gait deficits (Rubenstein, 2006) have been demonstrated as risk factors for falls in older adults. Specifically, fallers were characterised by an increased postural sway at a higher frequency in static standing (Lajoie & Gallagher, 2004), increased time taken to complete the "Timed Up and Go test" (Shumway-Cook et al., 2000) and scoring 19 or less in the dynamic gait index (Shumway-Cook, A. et al., 1997). It is important to highlight that postural control and the underlying systems are potentially modifiable given that the central nervous system is highly plastic and adaptable (Walston et al., 2006). Therefore, as a first step to investigating correlates of postural control in NP, it is important to identify relevant and modifiable NP-related impairments that impact postural control during standing and functional tasks such as walking. Addressing factors that are potentially amenable to therapeutic intervention may help improve postural control, and potentially, reduce the risk of falls.

1.4 Identified gaps

In this next section, we highlight gaps in the understanding of the problem and discuss why exploring the associations between NP-related impairments and postural control during standing may constitute a worthy endeavour.

1.4.1 Balance measures

To facilitate understanding of the complexity involved in the use of balance measures, this section is divided into static and dynamic balance measures. In this this thesis, static

balance measures are those taken with the participant in quiet standing on a firm fixed base of support (Visser et al., 2008) and dynamic balance measures refer to those obtained when the aim is to maintain postural control during movement (Westcott et al., 1997).

1.4.1.1 Static balance measures.

Standing balance is commonly examined firstly under conditions of standing on a firm surface with eyes open, then increasing demand by removing input from the visual system by closing the eyes or providing altered somatosensory input by standing on soft surfaces. These tests have also considered foot positions such as comfortable, narrow and tandem stance that reduced the base of support. Previous studies have demonstrated reduced postural control in individuals with NP using various postural control measures with different visual conditions (eyes open and/or eyes closed) and foot positions (see table 1-1). These postural control measures include reduced sway energy (Poole et al., 2008), CoP RMS amplitude (Field et al., 2008), CoP velocity and CoP displacement (Boucher et al., 2008). Generally tests of eyes open (McPartland et al., 1997) or closed (Poole et al., 2008) on a firm surface in comfortable stance have proven sufficient to demonstrate balance deficits in NP, indicating that proprioception may be impaired in NP. Further, these changes seem to be more sensitive in the anterio-posterior than the medio-lateral direction (Ruhe et al., 2011) as this is the axis on which the majority of movement and postural control occurs due to inverted pendulum control of the hinge-like ankle joint (Karlsson & Frykberg, 2000).

Table 1-1 Study characteristics & selected CoP parameters comparing idiopathic neck pain versus healthy controls in adults & older adults

Study	Participants		Conditions	Duration (sec)/ Number of trials	CoP Parameter	Results
	Neck Pain	Controls				
Adults						
McPartland et al. (1997)	n=7 (6f) Age=39 yrs (no SD stated)	n=7 (4f) Age= 39 yrs (no SD stated)	Comfortable stance EO/EC/F Narrow stance EO/EC/F	30/6	Sway Area, Velocity, Torque (Did not differentiate AP or ML)	NP greater velocity sway in EO comfortable stance ($p<0.05$),higher torque in both EO & EC comfortable and narrow stance ($p<0.05$)
Michaelson et al. (2003)	n=9 (f) Age=40±9 yrs	n=16 (13f) Age=41±9 yrs	Narrow stance EO/EC/F Tandem stance EO/EC/F Single leg EO/F	20/1	Sway area (mm^2)	No statistical difference between groups ($p>0.05$)
Boucher et al. (2008)	Group 1: High OA/ n=9 (3f) Age= 64.0±7.6 yrs Group 2: Low OA n=7 (4f) Age=59.3±5.9yrs	n=7 (4f) Age=24.2 ±2.2 yrs	Stance unclear EO/F Stance unclear EO/EC/F	20/20 (20 trials for each condition -"no vision" -period of "vision after a no vision period")	AP/ML Amplitude (mm) AP/ML Velocity (mm/s) AP/ML Displacement (mm)	NP higher AP amplitude, velocity and displacement in period of "no vision" condition and during period of "vision after a no vision period" ($p<0.05$)
Field et al. (2008)	n=30 (23f) Age=27.9yrs (SE=1.3)	n=30 (23f) Age=27yrs (SE=1.3)	Comfortable stance EO/EC/F/C Narrow stance EO/EC/F/C	30/1	AP/ML Sway energy (logged) AP/ML RMS amplitude (mm)	NP higher AP sway RMS in comfortable stance in EC/F, higher AP sway energy in narrow stance in EO/F, EC/F, EO/C, EC/C, and greater tandem failure rates. ($p<0.05$)
Palmgren et al. (2009)	n=15 (13f) Age=38.8±7.4 yrs	n=16(16f) Age=35.1±5.0 yrs	Comfortable stance EO/EC/F Tandem stance EO/EC/F	60/1	Sway area (mm^2) Displacement (mm)	NP had greater area in tandem stance EC ($p<0.05$)
Yahia et al. (2009)	n=30 (23f) Age=47.1 (no SD stated)	n=30 (25f) Age=47.1 (no SD stated)	Comfortable stance EO/EC/F	25.6/1	AP/ML Displacement (mm)	No significant differences between NP without vertigo and controls $p>0.05$
Jorgensen et al. (2011)	n=16 (exact age not available, range=24-58 yrs)	n=44 (exact age not available, range=23-69 yrs)	Comfortable stance EO/EC/F Single leg EO/F	30/1 (3 trials for single leg)	AP/ML Sway Area (mm^2)	NP higher sway area in comfortable stance EC ($p<0.05$) and higher failure rates for single leg ($p<0.01$)
Older Adults						
Poole et al. (2008)	n=20 (20f) Age=70.3 (SE= 1.1)	n=20 (20f) Age 71.4 (SE=0.88)	Comfortable stance EC/EO/F/C Narrow stance EO/EC/F/C	30/1	AP/ML Sway energy (logged) AP RMS amplitude (mm)	NP higher AP sway RMS in comfortable stance in EC/F, EO/C, ML sway RMS in narrow stance EO/F, AP sway energy comfortable stance in EC/F, ML sway energy narrow stance in EO/F and greater tandem failure rates $p<0.05$
Uthaikhup et al. (2012)	n=20 (12f) Age=73.2±6.2 yrs	n=20 (14f) Age=69.6±4.2 yrs	Comfortable stance EO/EC/F/C	30/1	AP/ML Sway energy (logged) AP/ML RMS amplitude (mm)	NP less ML RMS amplitude in EO/F $p<0.05$ NP trend higher AP amplitude EO/EC/F $p=0.07$

AP= Anteroposterior, C=Compliant, EO=Eyes Open, EC= Eyes Closed, f=female, F=firm, , ML= Mediolateral, OA= Osteoarthritis, RMS= Root Mean Square, SE=Standard Error

1.4.1.1.1 Complexities of analysis of centre-of-pressure and postural control measures

Previous studies investigating the effects of NP on static postural control have mostly employed traditional measures such as center-of-pressure (CoP) displacement, velocity and area (Ruhe et al., 2011). From the researcher's perspective, one issue that limits a clear understanding of these underlying balance mechanisms in NP may be the grossness of the information obtained from these methods of quantifying CoP. These variables assume that CoP displacement is a good proxy for postural performance and that conventionally, lower CoP sway parameters indicate greater postural control (Ruhe et al., 2011). However, this assumption can be challenged, with the argument that a decrease in sway parameters may also result from an increased-body stiffness associated with a fear of falling (Carpenter et al., 2001). As such, traditional balance measures have been criticized for their limitations in detecting context-dependent postural performance changes (Melzer et al., 2010) because they fail to capture the richness of postural data (Chagdes et al., 2009). Based on these reasons, in addition to standard balance measures there is a need to explore other approaches in measuring postural control to better describe postural performance (Lacour et al., 2008). In this regard, studies have employed analytical approaches such as wavelet analysis and sample entropy in order to better depict changes in postural control in people with NP (Liang et al., 2014; Madeleine et al., 2011; Quek et al., 2013).

1.4.1.1.1.1 Wavelet Analysis

Previous research has used wavelet analysis to reveal the total energy in the sway trace to try to capture the effort involved in maintaining postural control in NP (Treleaven et al., 2005b). However, further consideration of this technique is warranted. Multi-resolution wavelet transform appears to show greater potential as an analytical technique than standard postural control measures as it decomposes the postural sway data into multiple independent frequency bands (Chagdes et al., 2009) (see Appendix 10 for technical details of wavelet transforms). Recent research has postulated that each frequency band may represent involvement of a specific physiological domain. Specifically, Liang et al. (2013) identified four distinct bandwidths of the CoP signal ranging from moderate to ultralow frequency (Liang et al., 2014). Each frequency band was based on the hypothetical physiological significance of postural movements associated with muscular proprioception (Lacour et al., 2008; Paillard et al., 2002), the cerebellar (Paillard et al., 2002), vestibular

(Oppenheim et al., 1999) and visual systems (Chagdes et al., 2009) (see table 1-2). For instance, a high proportion of activity in the ultralow (<0.10Hz) and moderate (1.56-6.25Hz) frequency bandwidths have been associated with increased use of vision (Chagdes et al., 2009) and increased muscular activity in response to increased proprioceptive input (Paillard et al., 2002) respectively. In reviewing the literature, only one study (of which the thesis author was co-author) can be identified in patients with NP. This study compared standing postural control between people with NP, with and without cervical spine range-of-motion (ROM) asymmetry with the asymmetry group demonstrating higher proportion of ultralow frequencies (<0.10Hz) present in the CoP data (Quek et al., 2013). In the context of this study, the difference in postural strategy adopted by the asymmetrical group may be due to altered proprioceptive input and processing arising from cervical spine dysfunction. Consequently, based on the association between ultralow frequency and visual input, and given that both groups had similar levels of function, we speculated that the postural strategy adopted by the asymmetrical group was adaptive and that this group may be relying on the visual system to achieve these compensations. Despite these novel findings, and because this study lacked a concurrent control group, clear conclusions could not be drawn concerning these postural control mechanisms. Therefore it is clear that more research needs to be done using this type of wavelet analysis in the NP population.

Table 1-2 Physiological correlates of wavelet analysis frequency bands

Frequency bandwidth	**Physiological significance**
Moderate frequency (1.56-6.25 Hz)	Muscular proprioception
Low frequency (0.39-1.56 Hz)	Cerebellar
Very low frequency (0.10-0.39 Hz)	Vestibular
Ultralow frequency (<0.10 Hz)	Visual

1.4.1.1.2 Sample Entropy

In a similar vein, sample entropy, which uses a non-linear time-dependent analysis technique, has been suggested to quantify the complexity or regularity of the CoP signal (Borg & Laxaback, 2010). Higher entropy is suggested to reflect increased complexity and greater efficiency in postural control (Borg & Laxaback, 2010). Sample entropy has been investigated in a small number (n=11) of people with whiplash (Madeleine et al., 2011), with a trend towards decreased complexity of CoP motion during eyes closed standing balance when compared to control participants; however there remains a paucity of evidence in populations with NP and again, this may provide additional information to assist understanding of the mechanisms underpinning postural control in NP.

1.4.1.2 Dynamic measures

Previous research investigating the effect of NP on balance impairments has mainly used centre-of-pressure measurements as outcome measures (Ruhe et al., 2011; Silva & Cruz, 2012). Very few studies have included dynamic and functional measures despite the advantages and important domains dynamic postural control measures examine. It may be argued that dynamic measures of balance may be more relevant and sensitive than static measures because these tests incorporate context-specific tasks that may be similar to activities of daily living (Herman et al., 2009; Podsiadlo & Richardson, 1991b). To my knowledge, only three studies have reported dynamic balance performance in older adults with NP, specifically various spatiotemporal parameters of gait such as stride length and cadence (Poole et al., 2008; Uthaikhup et al., 2014), step length and step width, with and without head turns (Poole et al., 2008; Uthaikhup et al., 2012; Uthaikhup et al., 2014) and the step test (Poole et al., 2008). Two out of these three studies (Poole et al., 2008; Uthaikhup et al., 2012) measured gait with and without head turns and the third study

(Uthaikhup et al., 2014) measured gait without head turns, all at a self-selected speed over 10 metres. These studies reported conflicting results when comparing these gait parameters in older adults with NP to healthy controls: Poole et al. (2008) reported slower gait speed and reduced cadence with head turns, while Uthaikup et al. (2012; 2014) showed no differences in these measures but significant differences in the number of steps recorded within 15 seconds during the step test (Uthaikhup et al., 2012). Even though these studies have used dynamic measures of postural control, little is known about the fall risk of the population of interest of older adults with NP. Dynamic balance measures that are able to provide clinically meaningful outcomes, specifically those that are able to assess fall risk are needed. Given the aforementioned background on dynamic balance, we propose to include two clinically useful tools: the timed-up-and-go (TUG) test and dynamic gait index (DGI), which have established validity and reliability to assess function, dynamic balance and fall risk for older adults above the age of 60 years (Herman et al., 2009; Viccaro et al., 2011). Specifically, the TUG evaluates the ability to stand from sitting, walk, turn and sit down (Podsiadlo & Richardson, 1991a) whereas the DGI involves walking with a variety of postural challenges over 20 feet including walking with horizontal and vertical head turns (Shumway-Cook, Anne et al., 1997).

1.4.2 Global impairments related to postural instability: possible deficits that could underlie changes in postural control in older adults with NP

Given the multi-sensory complex nature of postural control, it is important to explore whether factors that might negatively impact on postural stability in any population such as physical activity levels, lower limb sensory and motor function, and vestibular and visual function are different in older adults with and without NP. Conceivably, NP by and of itself may not have direct effects on postural control, but rather through secondary effects such as impaired physical performance (Kendall et al., 2016) as a result of suffering from pain. It is biologically plausible that reduced physical activity (quantity and quality) may be associated with poorer lower limb function, such as reduced strength and flexibility (DiPietro, 2001). Consequently, this may contribute to reduced postural control in older adults with NP. Therefore, it is important to determine if lower limb function is any different between individuals with and without NP. In particular, deficits in big toe flexor strength (Mickle, K. J. et al., 2009), range-of-motion (Mecagni et al., 2000), light touch sensation (Lord & Ward, 1994) and vibration sense at the ankle (Bergin et al., 1995) have been closely associated with postural instability in older adults. Further, a disruption in the dynamics between the intricately blended systems

involved in sensorimotor control could be expected in elders with NP (Treleaven, 2008). The reason being, there is potential for not only cervical proprioception to be diminished but also a progressive decline in vestibular, visual and central nervous system function with ageing. In addition, vestibular dysfunction and specific to vision, deficits in visual contrast sensitivity, have been associated with increased falls risk in older adults (Herdman et al., 2000; Lord et al., 1991a). Given the complex connections the cervical spine has with the vestibular and oculo-motor reflex centers, NP may have the potential to cause sensorimotor disturbances in these systems (Treleaven, 2008). This may manifest as dizziness, and may cause subtle changes in eye control movements (Hood & Hood, 2016) thereby having an indirect effect on postural control. Therefore, this supports the need to explore vestibular and visual function in older adults with NP. Finally, chronic NP may potentially affect postural control via motor cortex reorganization as seen in patients with chronic low back pain (Tsao et al., 2008). Extensive research is required to investigate this issue which is beyond the scope of this thesis.

1.4.3 Other impairments related to NP: possible deficits that could underlie postural control changes in NP

This section describes the proposed impairments of NP that may influence balance and is classified into three categories: Biomechanical constraints, motor and sensorimotor impairments.

1.4.3.1 Biomechanical constraints

In our previous study of older adults with NP, patients with upper cervical spine ROM asymmetry demonstrated increased postural sway compared to those without ROM asymmetry (Quek et al., 2013). We postulated that patients with upper cervical spine rotation ROM asymmetry may have greater upper cervical spine dysfunction particularly at the level of C1-2 compared to the symmetry group, resulting in altered proprioceptive input and processing. This study supports previous notions that the upper cervical spine plays a crucial role in proprioception due to the high density of proprioceptors in the upper cervical spine (Boyd-Clark et al., 2002; Kulkarni et al., 2001). Furthermore, based on wavelet frequency band results, those with cervical spine rotation ROM asymmetry (specifically in the upper cervical spine) appeared to compensate for their impaired balance by using their visual system such that overall function was not compromised. However, the lack of a control group limited our ability to conclude whether the postural control strategies were adaptive or maladaptive. Also, the findings were not confirmed by including a condition of visual

deprivation. Therefore, cervical spine ROM asymmetry may be a factor that could influence postural control in patients with NP and this will be specifically considered in this thesis.

A recent cross-sectional study demonstrated a negative relationship between forward head posture and balance in a group of healthy office workers (Kang et al., 2012). However no study has been done to investigate the influence of head posture in older adults with NP. Given the close relationship between the thoracic spine and the cervical spine in older adults with NP (Quek et al., 2012), it is important to understand how the curvature of the entire spine (in addition to head posture) impacts postural control in this population. Noteworthy, individuals with NP had significantly greater thoracic kyphosis compared to healthy controls (Lau et al., 2010). It is therefore anatomically sound and biomechanically plausible that spinal posture affects both static and dynamic balance of an individual (Alin et al., 2016). Specifically, patients with NP may have poorer postural stability via a forward curvature of the spine which displaces the trunk centre of mass towards the limits of stability (Horak et al., 1989; Lynn et al., 1997).

1.4.3.2 Motor impairments— neck muscle function

Neck muscle fatigue has been shown to affect standing balance in healthy young adults (Gosselin et al., 2004; Liang et al., 2014; Schieppati et al., 2003) and patients with chronic whiplash (Stapley et al., 2006). In these studies, the targeted muscles included the neck extensor muscles (Schieppati et al., 2003; Stapley et al., 2006) and scapular elevators specifically the upper trapezius and levator scapulae muscles (Liang et al., 2014). Given the considerable experimental evidence that demonstrates neck muscle fatigue affects postural control, it may be important to measure neck muscle endurance/fatigue as an impairment that may underpin poor postural control in older adults with NP. Relatedly, even though neck muscle strength is known to be reduced in people with NP (Ylinen et al., 2004), neck muscle strength deficits have not yet been associated with standing postural control. Maximal strength testing of neck muscles can be limited by and exacerbate pain (Braith et al., 1993), therefore will not be included in this thesis. Whereas, individuals with chronic NP have shown altered timing of neck muscle activation in response to anticipated postural perturbation (using rapid unilateral shoulder flexion and extension movements) (Falla et al., 2011) and unanticipated full body perturbations in standing (using a computerized movable platform) (Boudreau & Falla, 2014). However, EMG measures and postural perturbations using a movable platform are clinically not viable and beyond the scope of this thesis, therefore will not be included.

1.4.3.3 Sensorimotor impairments

Previous studies have demonstrated inconsistent cervical spine joint position error (JPE) findings in patients with NP, with some studies indicating increased joint position error in idiopathic NP compared to healthy controls (Chen & Treleaven, 2013; Cheng et al., 2010; Rix & Bagust, 2001) while others found no differences between groups (Sjolander et al., 2008; Teng et al., 2007; Uthaikhup et al., 2012). Further, the degree of cervical spine JPE demonstrated a weak association with static standing balance (Treleaven et al., 2006) and this may be due to the tests of cervical proprioception used in previous studies that lacked specificity in isolating the cervical afferents in measuring joint position sense (Chen & Treleaven, 2013). Noteworthy, the conventional method of measuring cervical spine joint position error involves moving the head relative to the trunk that may stimulate both neck and vestibular afferents (Treleaven et al., 2006; Treleaven et al., 2008). Amongst the different methods that are available to measure joint position sense, the neck torsion test is suggested to be the most suitable test, because this test is able to bias afferent input towards the cervical spine by moving the body on a stationary head (Chen & Treleaven, 2013). Accordingly, the effect of neck torsion on postural control has been demonstrated in patients with whiplash injury (Yu et al., 2011) and in idiopathic NP (Williams et al., 2017). Given the above reasons, the JPE neck torsion appears to be a more suitable method for measuring joint position sense in the NP population.

Although studies have demonstrated associations between the presence of NP and increased postural sway (Treleaven, 2011), there is little evidence available about the relationship between the intensity of NP and postural control (Ruhe et al., 2011). It has been postulated that pain may influence postural control via several mechanisms such as central modulation as well as subcortical and cortical reorganization of the somatosensory system (Tinazzi et al., 2000). Given that the presence of NP may be a potential contributor to postural control, assessing its severity may provide important insight into postural control disturbances.

1.4.3.4 Whiplash or trauma induced NP

Patients with a whiplash injury may have direct or indirect involvement of the vestibular system, resulting in symptoms of dizziness, and reduced postural control (Rowlands et al., 2009; Toglia et al., 1969). Consequently, NP resulting from trauma may complicate the interpretations of mechanisms underlying impairments of postural control in

NP. For this reason, we will exclude patients with whiplash injury as well as those complaining of dizziness or vertigo suspected to be vestibular in origin.

1.5 Importance of translation of research into clinical practice

Another important aspect of this research concerns the ease of translation of research into clinical practice, specifically providing clinicians the practical means to access valid and reliable equipment to measure postural control deficits and impairments in people with NP. From the clinician's perspective, NP-related impairments are often measured using equipment that is laboratory based, and therefore difficult to implement clinically. Recent advances in technology such as the smart phone (Tousignant-Laflamme et al., 2013), the Nintendo Wii Balance Board (NWBB) (Clark et al., 2010) and the Microsoft Kinect (Clark, R. A. et al., 2012) may have the potential for new measurement tools that are portable, accurate and inexpensive yet practical for clinical use. By developing practical, affordable and easily accessible tools, clinicians will be empowered with the needed technology to identify potential impairments related to postural control deficits. One good example of such existing tools is the use of the NWBB to measure postural control, which has demonstrated good to excellent results in test-retest reliability and when validated against the gold-standard force plates (Clark et al., 2010), and hence will be used in this project. To this end, this research will exploit these technological advances for the evaluation of postural control and impairments relating to NP using methods that are not only cost-effective, but also clinically useful and widely commercially available. What follows is an account of the limitations of current available tools to measure NP-related and postural control impairments and the rationale for the new proposed methods. In particular, this thesis will explore the use of the smart phone technology to measure cervical range-of-motion, the Wii Balance Board to measure hallux flexor strength and the Microsoft Kinect to measure thoracic kyphosis for clinical and research purposes.

The first technology that will be explored is the validity of the Android smart phone to measure cervical ROM. Cervical spine ROM evaluation forms a vital part of the management of cervical spine disorders. Currently available tools for the assessment of cervical ROM include the cervical range of motion device (CROM) (Fletcher & Bandy, 2008) and the inclinometer (Bush et al., 2000). However, the CROM is cumbersome and relatively costly (US$395) whilst the inclinometer has been reported to have inconsistent and inferior validity for cervical rotation and lateral flexion measurements (Bush et al., 2000; Hole et al., 1995). On the other hand, given the widespread use of technology, the smart phone has shown

great potential as a measurement tool because it uses embedded sensors and may serve as a useful device for both clinicians and researchers to measure cervical ROM. Although the validity and reliability of the smart phone has been previously investigated by Tousignant-Laflamme et al. (2013), the authors of this study compared the phone to the CROM as the criterion reference, which may lack the sensitivity and precision of the multi-camera three-dimensional motion analysis (3DMA) system. Moreover, no effort was made to ensure that the head movements were well-controlled, specifically along the intended axis of head movement and the examiners were not blinded to the results of the phone and the CROM device. Therefore, this thesis will extend previous research by examining the validity and reliability of the Android smart phone application to measure cervical ROM using the 3DMA system as the criterion reference, adding a spirit-level type indicator to the phone application for accurate monitoring of the axis of movement and blinding the examiner to the results.

Next, the NWBB technology will be explored to measure the strength of the hallux flexor muscle. Hallux flexor strength has been shown to be a significant determinant of postural control (Spink et al., 2011) and an independent predictor of falls in older adults (Mickle, K. J. et al., 2009). Therefore hallux flexor strength is an important measure in the evaluation of postural control. However, strength assessment of the hallux flexor muscle comes with some challenges, one of which is the ability to selectively measure the strength of the intrinsic muscles and separating extrinsic and intrinsic foot muscle activity during the strength testing (Soysa et al., 2012). As a result, the validity of the methods used to specifically measure hallux flexor strength in previous studies such as the paper grip test (Menz et al., 2006a), plantar pressure sensors (Menz et al., 2006b) and dynamometry (Kwon et al., 2009; Senda et al., 1999; Spink et al., 2010; Unger & Wooden, 2000) were questionable. As such, given that the NWBB contains four strain-gauge type load cells and has shown to be reliable in weightbearing parameters such as asymmetry (Clark et al., 2011), the NWBB may have the potential to be used to measure hallux flexor strength in both clinical and research settings. Therefore, this thesis will explore the reliability of the NWBB when combined with a purpose built platform to measure hallux flexor strength.

The third technology that will be investigated is the validity and reliability of the Microsoft Kinect to measure thoracic kyphosis. Increased kyphosis has been associated with diminished physical performance (Kado et al., 2005), poor postural control (Sinaki, M. et al., 2005) and low quality of life (Takahashi et al., 2005). Furthermore, there is growing empirical evidence that thoracic kyphosis is associated with cervical spine impairments in individuals with NP (Cleland et al., 2007; Lau et al., 2010; Quek et al., 2012). In particular,

positive clinical outcomes were reported following thoracic spine manipulation and mobilization in patients with cervical spine dysfunction (Cleland et al., 2007; Lau et al., 2011). However, current available devices to evaluate thoracic kyphosis are limited and are often time-consuming to use, costly, cumbersome and unable to give instant feedback. For example, although the flexicurve has good evidence for validity and reliability (Barrett et al., 2014; Tran et al., 2016) and is affordable and easy to use, it has significant limitations such as inability to provide instant feedback and data processing is time consuming and tedious. Consequently, these barriers mentioned may account for the low frequency of assessment undertaken objectively by therapists in the clinical settings (Perriman et al., 2012). Therefore, this thesis hopes to overcome the aforementioned barriers to measure thoracic kyphosis by investigating the reliability and concurrent validity of the Microsoft Kinect against the flexicurve.

1.6 Summary

To summarize, although there exists sufficient evidence to substantiate the role of the cervical spine in influencing postural control, little is known about the mechanisms underlying this phenomenon. It is generally well accepted that the high density of mechanoreceptors in the upper cervical spine may play a crucial role in influencing postural control, however little is known about the associations between NP-related impairments and postural control. Having a greater understanding of the mechanisms underpinning postural control deficits is important to improve management of postural instability especially in the older population given their high risk of falls. The two main gaps identified in the literature that limit a clear understanding of the mechanisms underlying NP-related balance impairments are (i) from the researcher's perspective, the complexities of balance measures and (ii) from the clinician's perspective, the lack of clinically relevant tools. In order to address these gaps, (i) new balance measures such as wavelet analysis and sample entropy will be employed. Furthermore, dynamic balance measures that are context-specific and relevant to activities of daily living in older adults will also be included. (ii) This project will also evaluate the validity and reliability of new technology such as the Microsoft Kinect and smart phone for accurate measurement of NP-related impairments and the NWBB for measurement of impairment related to global balance for clinical purposes. Finally, as a first step in unravelling the mechanisms underlying NP-related balance impairments, this thesis includes studies comparing postural control and potential contributing impairments between people with and without NP, and will examine the associations between NP-related impairments and postural control during standing.

1.7 Aims of thesis

The overall objectives of this thesis were to i) explore new measurement tools and technique related to cervical spine impairments and postural control that may be potentially useful in research and in the clinical setting and ii) to better understand the mechanisms underpinning NP-related postural control deficits in older adults. Six studies were undertaken. Studies 1-3 investigated psychometric properties of clinically relevant measurement tools/techniques based on new technology to assist in the evaluation of factors contributing to NP in older adults. Studies 4-6 investigated postural control and factors contributing in older adults with and without NP. The specific aims of the individual studies were to:

1. Study 1: Determine the concurrent validity and test-retest reliability of the Android Smart Phone application to measure cervical range-of-motion.
2. Study 2: Determine the concurrent validity and intra-rater reliability of the Microsoft Kinect to measure thoracic kyphosis.
3. Study 3: Determine the intra-rater reliability of the Nintendo Wii Balance Board to measure hallux flexor strength.
4. Study 4: Explore the use of new measures of signal frequency (wavelet analysis) and complexity (sample entropy) and dynamic tests to obtain insights into the mechanisms of NP-related postural control dysfunction in older adults with and without NP.
5. Study 5: Compare several characteristics that are associated with impaired postural control in a group of older adults with and without NP.
6. Study 6: Determine if impairments related to NP are associated with static and dynamic postural control in older adults.

Chapter 2: Justification of Methods

This chapter is an overview of the methodology employed throughout the thesis. In summary, studies 1-3 explored new measurement tools and techniques that could be used to measure impairments associated with postural control deficits in people with NP. Studies 4-6 investigated new measures of postural control (study 4) or factors associated with postural control deficits in older adults with and without NP. The new measurement tool using the Wii Balance Board from study 3 and wavelet analysis approach from study 4 were employed in studies 5 & 6 because they showed potential for clinical or research use.

2.1 Overview of studies included in this thesis

The first three studies explored the use of technology, specifically the Android phone application, the Microsoft Kinect and the Nintendo Wii Board to measure cervical ROM, thoracic kyphosis and big toe strength respectively. At the point of conception of each study, no previous studies were published using any of these technologies. Therefore, as preliminary exploratory studies, healthy adult participants were chosen. The samples of all three studies were independent from each other. Please see table 2.1 for the details of the participants in each of the studies of the thesis. The subsequent three studies (4, 5 and 6) were clinical studies exploring the mechanisms underpinning NP related postural control impairments in older adults with idiopathic NP.

2.2 Research designs and sample population employed in the thesis

2.2.1 Research designs

A mix of study designs was used in this thesis. The first three studies were observational studies investigating the reliability and validity of measures compared to previously validated measures. Specifically, study 1 (chapter 3) investigated the concurrent validity of the Android phone application against the Vicon and examined the phone's test-retest reliability to measure cervical spine range of motion. Study 2 (chapter 4) examined the concurrent validity of the Microsoft Kinect to measure thoracic kyphosis against the flexicurve and examined the intra-rater reliability of the Kinect measurement. Study 3 (chapter 5) assessed the test-retest reliability of the Wii Balance Board to measure big toe strength. Studies 4, 5 and 6 (chapters 6, 7 and 8 respectively) were cross-sectional studies involving older adults with and without idiopathic NP. Study 4 was a retrospective study using data from a previous

study (Poole et al., 2008). The study sample from studies 5 & 6 was prospective and comprised of the same participants in both studies.

2.2.2 Participants

To assist and orient the reader to the participants in the six studies, information regarding their recruitment, and inclusion and exclusion criteria are detailed below. Convenience sampling was employed for all studies in this thesis. Further details on participants are found in each chapter. Studies 1-3 aimed to recruit healthy young adults; studies 4-6 aimed to recruit older adults with or without NP.

2.2.2.1 Studies 1, 2 and 3

In study 1, the participants were recruited from advertisements, word of mouth, introductions in lectures/tutorials and email to the staff and students of the Australian Catholic University in Melbourne, Australia. Inclusion criteria included healthy volunteers aged 18 years and above. Exclusion criteria included active NP; an inability to perform exercise; and an inability to understand spoken or written English.

Participants in study 2 and study 3 were recruited from advertisements, word of mouth and email to the staff and students from the University of Queensland in Brisbane, Australia. Inclusion criteria for both studies were healthy individuals aged 18 years and above. Exclusion criteria for study 2 were any active neck or back pain or known spinal deformities such as scoliosis. The exclusion criteria for study 3 also included any foot deformities or acute foot or ankle injuries over the past 3 months, as we examined big toe maximal strength.

Table 2-1 Sample details across studies

Study	Neck Pain (n, age ± SD)	Age Range	NDI (%)	NDI range	Females n (%)	Healthy (n, age ± SD)	Age Range	NDI (%)	NDI range	Females n (%)
1	NA	NA	NA	NA	NA	21, 31.0 ± 9.1	19-59	NA	NA	10 (48)
2	NA	NA	NA	NA	NA	33, 31.0 ± 11.0	21-64	NA	NA	16 (48)
3	NA	NA	NA	NA	NA	30, 34.9 ± 12.9	22-68	NA	NA	15 (50)
4	20, 70.3 ± 4.0	65-77	23.60 ± 10.2	10-48	20 (100)	20, 71.4 ± 5.1	65-82	3.00 ± 3.5	0-8	20 (100)
5	35, 69.6 ± 6.3	60-88	20.82 ± 7.14	12-38	22 (63)	49, 69.5 ± 4.9	61-82	1.18 ± 1.63	0-6	30 (61)
6	35, 69.6 ± 6.3	60-88	20.82 ± 7.14	12-38	22 (63)	49, 69.5 ± 4.9	61-82	1.18 ± 1.63	0-6	30 (61)

n= sample size, NA= Not Applicable, NDI = Neck Disability Index, SD= Standard Deviation

2.2.2.2 Studies 4, 5 and 6

In study 4, participants were recruited from the Brisbane metropolitan area using convenience sampling. Older adults >65 years were included in the NP group if they reported chronic NP for ≥3 months, and with a neck disability index (NDI) of ≥10%. Chronicity of NP of ≥3 months was chosen and only females were recruited. A NDI of ≥10% was chosen because according to Vernon and Mior (1991a), NDI<10% is interpreted as having no disability from NP and previous studies that used this cut off of NDI ≥10% were able to demonstrate sensorimotor disturbances in subjects with chronic NP (Field et al., 2008; Treleaven et al., 2011; Uthaikhup et al., 2012). Adults were recruited for this study if they were aged >65years. This cut off of 65 years was chosen because it is a common definition of an older adult in many western countries (Kowal & Dowd, 2001) and older adults >65 years old have demonstrated postural deficits in previous research (Choy et al., 2003).

Participants were included in the control group if they did not report current NP that required management by a medical professional at the time of recruitment and testing, and had a NDI score of <10% (NDI<10% is interpreted as having no disability from NP). This was to limit the contamination of this group with people with any acute NP and NP that resulted in sufficient pain and disability to affect daily life. The exclusion criteria were chosen to limit the likelihood of the presence of postural control deficits that were the result of known factors, not related to NP. These included: a history of repeated falls of unknown origin (no specific cause that could explain their falls – to reduce the influence of postural control deficits unrelated to NP); recent orthopaedic surgery; diabetes; neurological or vestibular pathology; visual impairments not corrected by prescriptive lenses; arthritis or musculoskeletal problems not including the neck that required active management or where the level of pain exceeded that of the neck; acute musculoskeletal injuries; or were taking more than four medications. Previous research has demonstrated a significant association between injurious falls and consumption of more than four medications (Koski et al., 1996). Hence, to avoid the confounding factor of the number of medications on postural control, all volunteers taking more than 4 medications were excluded. In order to obtain a sample that was representative of the older adult population, common medical conditions such as hypertension, hyperlipidemia, irritable bowel syndrome and osteoarthritis were included in the sample. With regards to pain arising from musculoskeletal conditions such as knee pain or low back pain, participants were admitted into the NP group as long as their pain score in the other regions of the body did not exceed that of the neck and would be excluded if their

predominant pain was not in the neck region. For those in the control group, participants were excluded if they had musculoskeletal pain that they were actively seeking treatment for.

Information regarding co-morbidities was obtained from the questionnaires and subjective interview and coded into four categories: (i) musculoskeletal conditions of the lower limb and non-specific low back pain, (ii) common medical conditions including hypertension, heart conditions, osteoporosis and depression, (iii) dizziness and (iv) previous traumatic neck injury. The maximum number of co-morbidities possible was four. For example, if a participant reported having knee pain and back pain, this will be coded as 1 under (i). If this same participant also had hypertension, the total number of co-morbidities was listed as two. All participants provided informed consent as outlined by the Medical Ethics Committee of the University of Queensland and all procedures were conducted according to the Declaration of Helsinki.

The inclusion and exclusion criteria for studies 5 & 6 were similar to that of study 4 with the following exceptions. First, because studies 5 & 6 focused on understanding the mechanisms underlying postural control impairments in NP, very strict guidelines were imposed such that all who reported a history of traumatic NP were excluded. By performing a detailed subjective evaluation, we also excluded those who reported dizziness that we suspected was associated with vestibular involvement. This included if they reported any known vestibular pathology (e.g. Menieres) or vestibular symptoms that required medical investigation or treatment. As such, we encountered difficulties with recruitment and as a result decided to lower the age limit by 5 years to 60 years old in order to increase the sample size. Postural control deficits in quiet standing with eyes open and closed are present in adults aged in the 60s, and are significantly more marked than those in their 50s, but not different from those in their 70s (Choy et al., 2003), thus we did not perceive that lowering the cut off by 5 years would significantly alter our findings. It is known that NP related studies in younger adults often restrict their age range to less than 45 years old so as to avoid having to account for age related changes (Field et al., 2008; Treleaven et al., 2005a). The mean ages were similar across studies 4 (70-71 years) and 5 & 6 (69 years). Next, the inclusion criteria into the NP group was two-fold: participants had to fulfil a minimum pain score of 2/10 on the NRS and NDI score of ≥10%. This is in contrast to study 4 where only a NDI score of ≥10% was required for admission to the NP group. The minimum pain score was added to the later studies to ensure that our sample accurately represented

the idiopathic NP population and demonstrated sufficient pain and disability to distinguish this group from the control group. Third, both females and males were recruited into studies 5 & 6 compared to only females in study 4. This was to maximise generalisability. Lastly, the number of co-morbidities were counted and entered as the total number, in contrast to study 4 where the co-morbidities were grouped into categories. For example, if the participant in the later studies had low back pain, knee pain and hypertension, the number of co-morbidities reported was 3 instead of a 2 as it would have been in study 4. The method of coding was modified because study 4 demonstrated no differences in comorbidities between NP and control groups and it could have been due to the way the coding of comorbidities was performed. As such, we decided to identify each comorbidity as one instead of coding it in categories. This was done to ensure that it would be more straightforward to identify the potential confounding effect of comorbidities (if any) on postural control in older adults with NP.

A total of 166 individuals responded to advertisements from posters, flyers, community health talks and by word of mouth. Seventy out of 166 people did not fit the inclusion and exclusion criteria, leaving 96 who were included in the study. Out of these 96 individuals, 12 were removed from the data analysis because they had NDI and pain scores that we considered to be ambiguous. Specifically, these 12 individuals did not fulfil the criteria of having both NDI score ≥10% and NRS ≥2/10. Instead they may have a NDI score of ≥10% but scored <2/10 on the NRS or they scored ≥2/10 on NRS but failed to score ≥10% on the NDI (Figure 2-1).

Figure 2-1 Flowchart of participant recruitment for studies 5 and 6

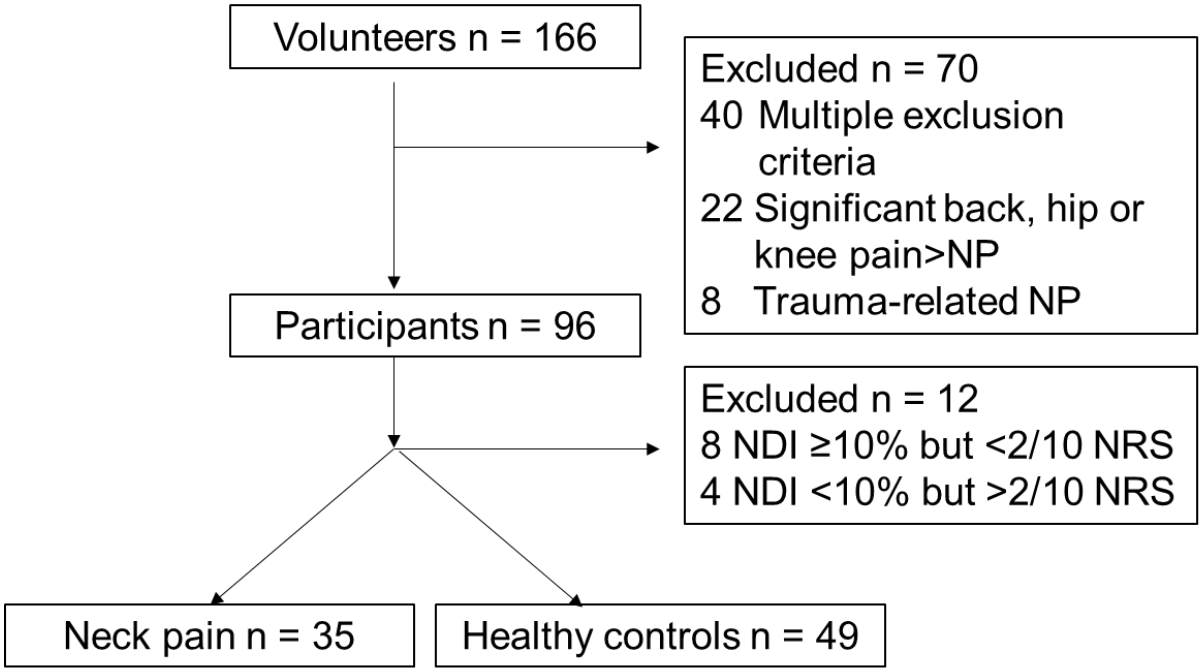
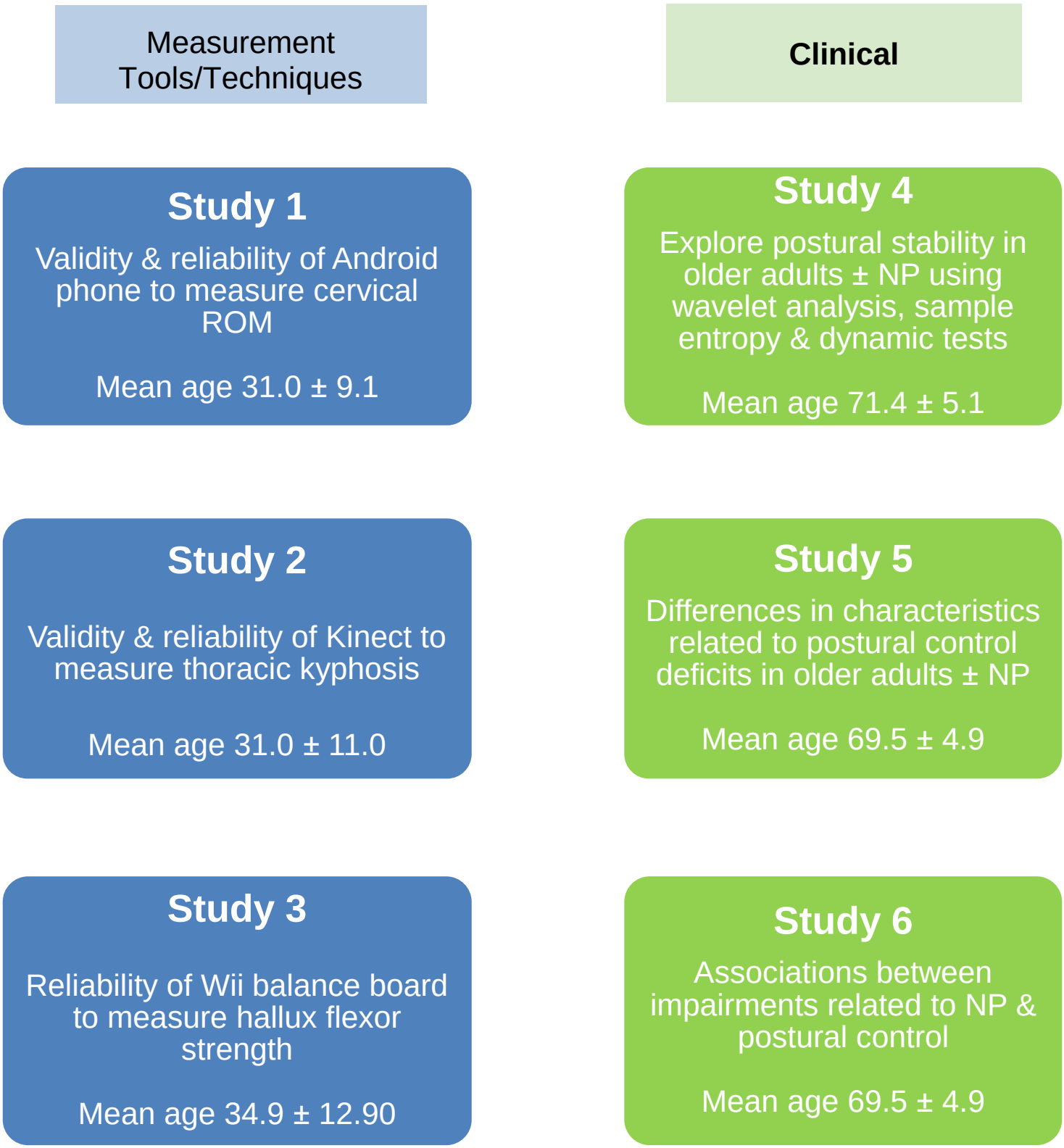


Figure 2-2 Thesis Overview



2.3 Experimental procedures

Justification of the experimental procedures and measures in studies 1, 2 and 3 are contained in each chapter. More detailed justification of procedures and measures for studies 4, 5 and 6 are provided below, with further details provided in each chapter.

For all studies 4-6, a phone interview was conducted to determine if potential participants met the eligibility criteria for study inclusion. Questions pertaining to their vestibular function were specifically asked to ascertain (as best as possible) that participants did not have any existing vestibular or neurological dysfunction that may affect their performance during postural control tests.

For studies 5 and 6, eligible participants were given a choice whether to perform the testing in the laboratory at the University of Queensland or at their residence and an appointment was made if they fulfilled all the inclusion and exclusion criteria. Potential participants were informed that the duration of the testing would take 1-1.5 hours longer if the research was performed at their residence because of the added time required to set up and pack up the equipment. If testing was performed outside the laboratory, all equipment was transported in the car of the investigator (JQ). For accountability and safety purposes, at least one supervisor was informed when testing was performed outside of the laboratory. Testing was performed mainly by one investigator (JQ) and only sometimes assisted by a physiotherapy student (when available).

Prior to the testing, in order to reduce time spent on the day of the testing, questionnaires (Appendix 9) were posted out to the participants one week before the testing date and participants were asked to fill up the questionnaires close to the testing date. Clarification was made (if necessary) on the day of testing regarding the participant's understanding of the questionnaires and their responses.

The order of testing was determined in order to limit the effects of fatigue, pain and or dizziness on the previous testing and was performed as follows:

- Subjective interview
- Standing posture- digital photograph and measurement of spinal curves
- Standing balance- eyes open followed by eyes closed
- Ankle ROM testing
- Sensory testing – filament followed by vibration
- Melbourne Edge test
- Joint position error test

- Big toe strength testing
- Dynamic Gait Index
- DVA
- HIT
- Neck muscle endurance tests
- Dix Hallpike test
- Cervical ROM

2.4 Sample size calculation

Studies 1 and 4 were exploratory studies and therefore we were unsure of the potential size of the effect, therefore a sample size of 20 per group was chosen. A sample size of 20 is common in laboratory studies of validity and reliability (Clark, Ross A et al., 2012; Koumantakis et al., 2002; Mariani et al., 2010). In study 4, a sample size of 20 per group was chosen as it has previously been sufficient to demonstrate differences in postural control between people with and without neck pain (Poole et al 2008). For studies 2 & 3, The sample size of 30 was selected because it provided an estimated power greater than 90%, based on the aim to detect a desired reliability of ICC=0.9 and a minimally acceptable reliability of 0.7 with an alpha level of 0.05 (1-tailed).

In study 5, the a priori sample size calculation based on two-tailed hypothesis using Cohen's d 0.5, alpha 0.05 was 64 per group (ie 128 in total). Nevertheless, our sample of 35 in the NP and 49 in the control groups (84 in total) were unfortunately below the targeted sample size. This was because it was very challenging recruiting older adults that fulfilled all of the inclusion and exclusion criteria ie with sufficient levels of neck pain and disability associated with their idiopathic NP but also minimal other co-morbidities. This explains why we were close to being able to meet the target for healthy controls but not the NP group. We had to exclude many who had NP of traumatic origin and those with significant co-morbidities because of their potential influence on postural control. We also had to exclude several participants (12) that did not quite meet the criteria of both NDI of ≥10% and a VAS of at least 2/10.In study 6, an a priori sample size estimate of 70 subjects was calculated based on conservative estimates using Cohen's f^2 method of effect size determination (f^2=0.2) and a maximum of 5 predictor variables to achieve 80% power. Noteworthy, multiple regression models with a minimum of 10-15 observations per predictor variable has been shown to reveal stable estimates (Babyak, 2004). In light of this evidence, multivariate regression models in Tables 8-4 and 8-5 consisted of mostly 3 variables (one model had 4

variables) for sample size of 35 (NP group) and 49 (control group) respectively. In the moderation analysis in Table 8-6, there was a maximum of 8 predictor variables for a sample size of 84. As it turns out, our a priori sample size calculation was conservative and therefore we think that the sample size obtained for the purpose of this study was mostly sufficient.

2.5 Statistics

All statistical procedures were performed using IBM SPSS Statistics for Windows, version 21.0 & 22.0 and Stata version 11 and 13. $P<0.05$ significance level was assumed across all studies. The details of the statistical analysis are described in each study.

2.6 Ethical Considerations

The studies conducted in this thesis were all approved by the Medical Research Ethics Committee of the University of Queensland (Appendix 6). Prior to the study, participants were given an information sheet that outlined the details of the study. The investigator verbally explained the purpose of the study, their right of withdrawal and possible risks and benefits associated with the study. Participants provided written informed consent to participate in any study.

In studies 1-3 there were minimal risks associated with these studies as they were performed on healthy young adults. Disrobing and exposing the back was required in study 2. In the process, female participants were required to unhook their bra. In order to respect the participant's privacy, female participants were given a choice to wear a gown if they felt uncomfortable having their back exposed. In study 3 and study 6 participants were informed that there was a potential risk of muscle soreness of the hallux flexor and the intrinsic muscles of the foot post maximal voluntary contraction as well as neck extensor and flexor muscles following the endurance test. Participants were monitored for any discomfort felt during and after the testing procedure, and testing would cease if participants demonstrated any signs of discomfort. No participants reported any muscle soreness in this study. In studies 5 and 6, there was a potential that participants could lose their balance. A physiotherapist with postgraduate qualifications (the candidate) stood beside every participant at all times. Further, there was a risk that participants could feel temporary dizziness after the sensorimotor measures. The order of testing was manipulated to perform these tests last and adequate rests were given if required. In studies 4-6, in people with NP there was a risk of aggravating the symptoms associated with their NP. To overcome this sufficient rest was given in between tests, the examiner closely monitored their symptoms during testing and test procedures were ceased if participants expressed discomfort that was beyond their usual pain scores during an active episode. In all studies, to ensure

confidentiality, information obtained were stored with multiple measures, de-identification performed during data management and secure storage was enforced.

Chapter 3 is adapted from the following publication
(Appendix 1 URL Link to Published Paper)

Quek J, Brauer SG, Treleaven J, Pua YH, Mentiplay B, Clark RA
"Validity and intra-rater reliability of an Android phone application to measure cervical range-of-motion"
Journal of Neuroengineering and Rehabilitation 2014; 11(1), 65

Chapter 3: Study 1 Validity and intra-rater reliability of an Android phone application to measure cervical range-of-motion

Cervical spine ROM assessment is important in the management of cervical spine disorders. ROM asymmetry of the cervical spine has been shown to be associated with reduced postural sway. However, the objective evaluation of cervical range-of-motion is often limited by the affordability, accessibility and ease of use of available equipment. Given the widespread use and advances in technology, the smart phone has great potential for use in research and clinical purposes. This study examines the validity and intra-rater reliability of a newly developed Android phone application to measure cervical range-of-motion.

3.1 Introduction

Cervical range-of-motion (ROM) assessment forms an integral part of physiotherapy evaluation in people with NP by quantifying an important physical impairment (Dall'Alba et al., 2001) and providing potentially useful diagnostic data (O'Leary, 2008). In this regard, the cervical range-of-motion device (CROM) (Fletcher & Bandy, 2008; Rheault et al., 1992) and single inclinometer are considered the most appropriate clinical measurement instruments. However, the CROM is relatively expensive (US$395) and cumbersome, and the inclinometer although more affordable, has been reported to have inconsistent and inferior validity for cervical lateral-flexion and rotation measurements (Bush et al., 2000; Hole et al., 1995). Advances in smart phone sensor technology have resulted in inexpensive ROM measurement tools with clinical and research potential. Specifically, the smart phone uses an embedded-accelerometer and a magnetometer to detect motion using gravity and the earth's magnetic field respectively. To our knowledge, only one published study (Tousignant-Laflamme et al., 2013) has examined the validity and reliability of the smartphone to measure cervical ROM. Although that study reported some promising findings, it did possess limitations including: a) the criterion reference used (i.e. CROM) did not allow for concurrent testing of the phone, and lacked the sensitivity and precision of a multi-camera three-dimensional motion analysis (3DMA) system, which may have negatively influenced the mostly moderate validity findings; b) no reported effort was made to ensure that movement was well-controlled and along the intended axis of head movement; and c) the examiner was not blinded to the results obtained from the phone and the CROM device, hence error due to reporting bias cannot be ruled out. This may potentially overestimate the validity results. Therefore the purpose of this study was to investigate the

concurrent validity and test-retest reliability of an Android smart phone to assess cervical ROM. Our study extends prior research by (i) verifying the validity of the smart phone by concurrently assessing with a 3DMA system, the gold-standard for capturing motion analysis (Goodvin et al., 2006), (ii) adding a spirit-level type indicator to the phone application to ensure a pure axis of movement (Quek et al., 2012) and (iii) examiner blinding to the results. We hypothesize that the phone will be valid and reliable.

3.2 Methods

3.2.1 Subjects

Twenty-one healthy individuals between 19 to 59 years (mean age: 31 ± 9.1 years, height: 172.7 ± 8.9 cm, weight: 68.5 ± 11.2 kg, male: 11) with no reported NP participated. Sixteen participants returned 1-7 days later to assess intra-rater reliability. All participants provided informed consent as outlined by the institution's Human Research Ethics Committee and all procedures were conducted according to the Declaration of Helsinki.

3.2.2 Procedures

Three reflective markers were located on the following anatomical landmarks: anterior to the tragus bilaterally and on the glabella (Figure 3-1) for 3DMA analysis. Markers were tracked using VICON Nexus V1.7.1 and a 9-camera VICON MX motion analysis system (VICON, UK). The angle of the head in the three planes was referenced to the laboratory axis, and normalized to the starting neutral position, and was deemed our benchmark reference kinematic data.

All measures were performed with the subject seated in the same high-back padded chair. To ensure minimal contribution from the thoracic spine, the participant was securely strapped across the shoulders to the chair using an inelastic belt (Figure 3-1:Mulligan Mobilization Belt). An Android 4.0 phone (Samsung Galaxy S3, GT-I9300T) was fitted to a phone cover that was mounted to a piece of hard cardboard affixed to a helmet (Figure 3-1). The helmet was then fastened securely on the patient's head using an internal adjustable head strap fixed within the helmet. This phone contains a LSM330DLC inertial monitoring unit combining tri-axial accelerometer and gyroscope sensors, and an AKM8975 tri-axial magnetometer.

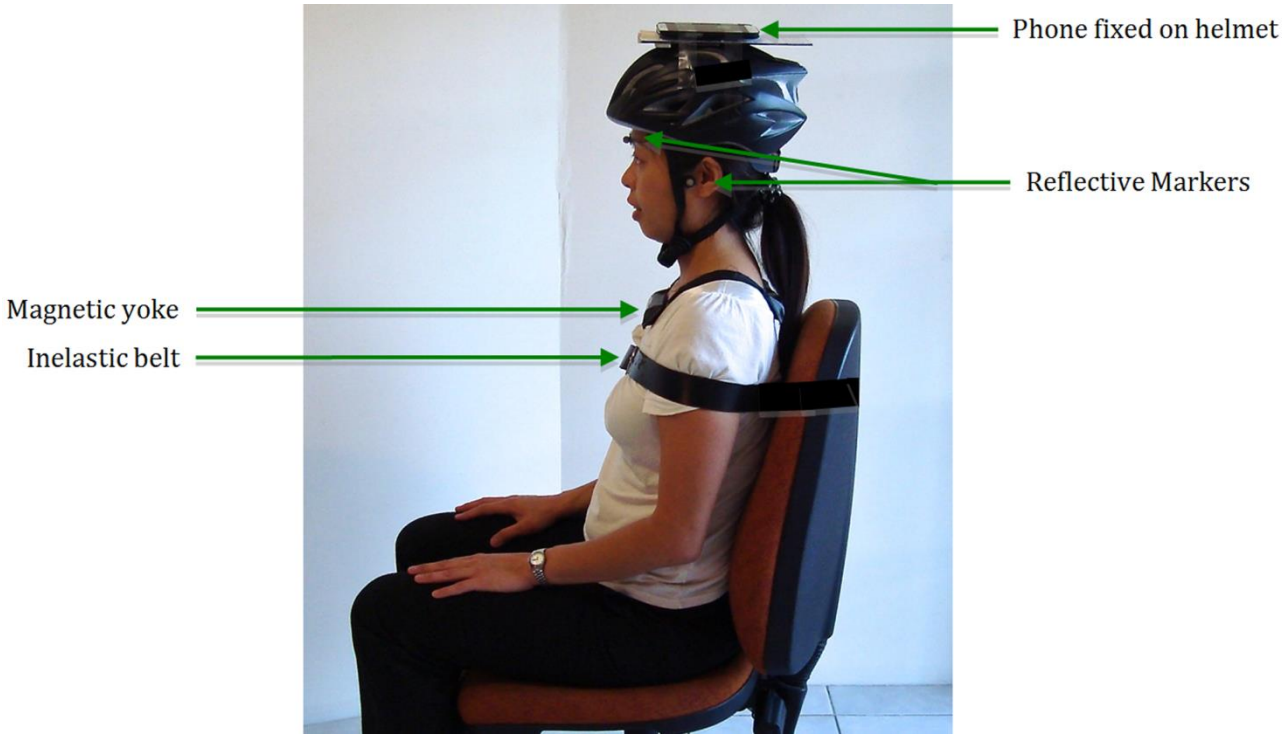


Figure 3-1. Experimental setup

This picture shows the starting position of the participant and the equipment set up.

The following cervical-spine ROM limit measurements were obtained in the same order in all subjects: (i) flexion, (ii) extension, (iii) right-lateral-flexion, (iv) left-lateral-flexion, (v) right-rotation and (vi) left-rotation. The flexion/extension, lateral flexion/extension and rotation axes were measured using the pitch, roll and azimuth angles respectively. Given that cervical rotation values are based on the magnetometer within the phone and the outcome may be influenced by the surrounding magnetic fields, a magnetic yoke was placed around the subject's neck in an attempt to address this problem. This replicates the use of the CROM, which also uses magnetic fields to determine angles and requires the use of a magnetic yoke.

The participant was instructed to perform each test actively, with manual guidance provided by the examiner to ensure that the movement was along the pure axis of alignment if necessary. Specifically, the examiner determined the end of ROM when a firm resistance was felt. No pain was reported by any subject during the procedure. Three consecutive trials using concurrent measurements from the VICON and the phone were obtained for each movement. The mean value of the three measurements for the first testing day was used to calculate validity, and an inter-day comparison of these mean values was performed to determine intra-rater reliability.

All subjects were assessed by the same examiner (the thesis author) who has 12 years of clinical musculoskeletal physiotherapy experience. Noteworthy, because it is difficult for the examiner to visually detect when the subject deviates away from the pure movement plane, one of the advantages of this phone application over previous applications (Tousignant-Laflamme et al., 2013) was that it included a visual representation of a circular spirit device (Figures 3-2A and 3-2B). This enabled the examiner to guide subjects along the desired plane of movement using the real-time visual feedback. This program sampled data at 100Hz using a custom program designed by co-author RC using MIT App Inventor. The standard angle data parsed from the angle calculation performed within the Smartphones operating system was used, indicating that our results are likely to be applicable regardless of the software program used. Two separate examiners were assigned to each device (phone and 3DMA), hence they were blinded to the results of the other device.

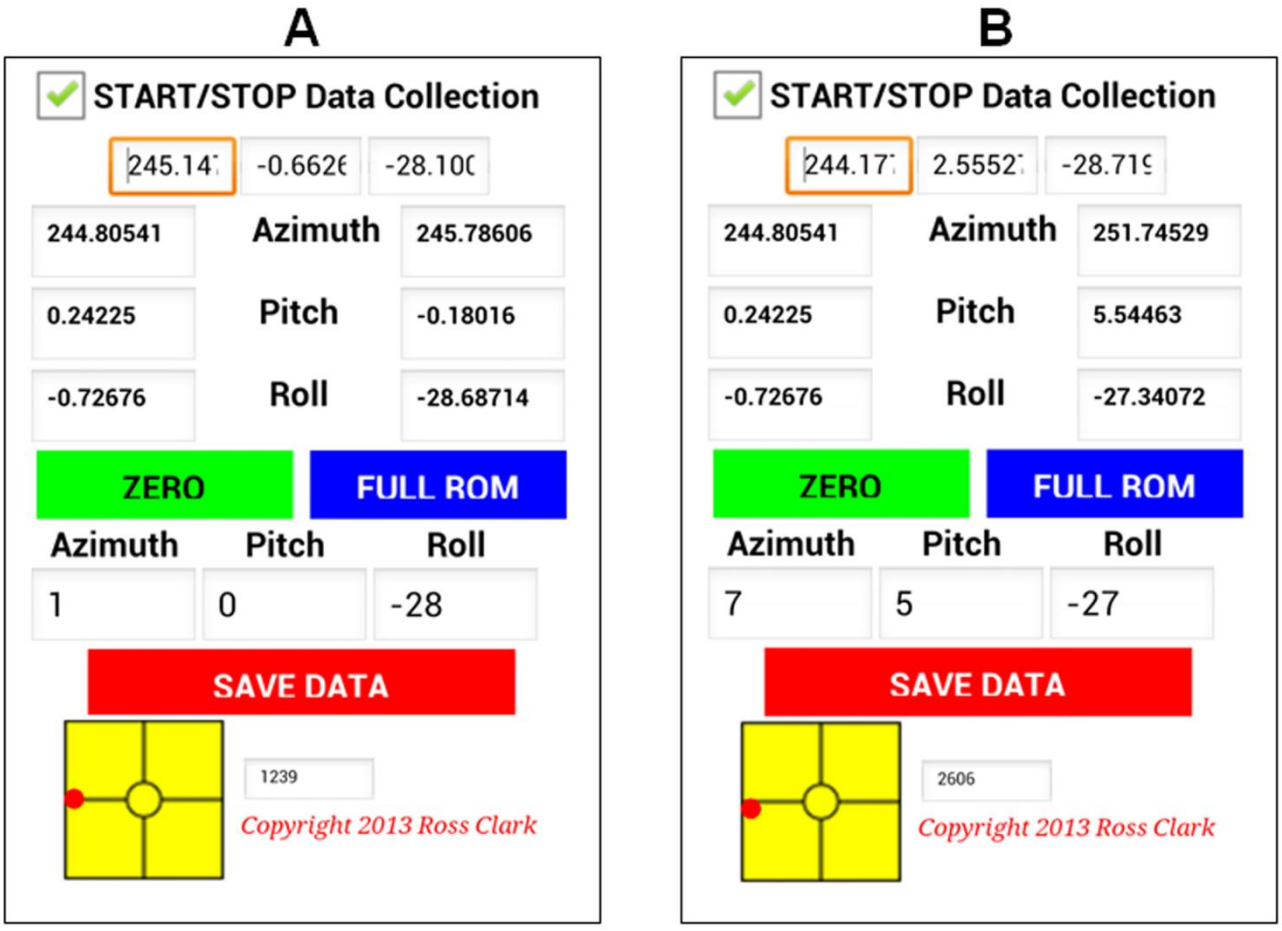


Figure 3-2 Comparison of lateral flexion assessment techniques.

(A) Right lateral flexion in a single axis. Note that the red dot is aligned with the horizontal line. (B) Right lateral flexion with some cervical flexion. Note that the red dot is not aligned with the horizontal line.

3.3 Statistical Analysis

3.3.1 Validity

Validity was determined from Spearman's correlation and intra-class correlation coefficient (ICC) in combination with assessment of systematic bias. Bland and Altman plots were constructed to determine the 95% limits of agreement (LoA) between the 3DMA and phone measures (Bland & Altman, 1986; Bland & Altman, 1999). Ordinary least products (OLP) regression, which accounts for error in both devices, was used to determine fixed and proportional biases (Ludbrook, 2002). All calculations were performed as described previously (Ludbrook, 1997).

3.3.2 Reliability

Intra-rater reliability was determined using intra-class coefficients (ICC [3,3]), and OLP regression to quantify the relationship between sequential measurements for both instruments. ICC was calculated in a 2-way analysis of variance based on absolute agreement. Point estimates of the ICC values >0.75 were considered excellent, 0.4-0.75 modest or <0.4 poor (Fleiss, 1986). To estimate measurement error, standard error of measurement (SEM), LOA, and minimal detectable change (MDC) were calculated. Statistical analyses were completed using PASW software V21.

3.4 Results

3.4.1 Validity

The phone demonstrated excellent concurrent validity for flexion, extension, and lateral flexion ROM based on Spearman's ρ-values >0.84 and ICC values >0.90, but only modest validity results for left-rotation (ICC =0.53, Spearman's ρ =0.52) and right-rotation (ICC =0.53) (Table 3-1). Furthermore, for right- and left-rotation, both proportional and fixed biases were observed (see Table 3.1 and Figures 3-3 for the OLP and LOA plots).

3.4.2 Intra-rater reliability

Intra-rater reliability is presented in Tables 3-2 & 3-3. Excellent intra-rater reliability results were observed for both phone and 3DMA measurements in cervical flexion, extension and right- and left-lateral flexion (ICC=0.82-0.90), but results were poor for the phone in right- and left-rotation (ICC=0.05-0.33), whilst the 3DMA showed modest intra-rater reliability (ICC=0.64-0.77). Percentage error values for the phone ranged from 7-40% and 6-9% for 3DMA (Tables 3-2 & 3-3). LOA plots are presented in the Figures 3-4 & 3-5.

Table 3-1 Validity of the phone compared to 3DMA using 3 repetitions of each cervical movement

	Phone (Mean ± SD)	3DMA (Mean ± SD)	ICC (3,3)	Spearman's ρ*	95% CI	Average Systematic Bias (CI)	Width of 95% LoA	% Error†	Prop Bias€	Fixed Bias€
Flexion	52.0 ± 8.7	49.9 ± 8.8	0.98	0.991	0.30 to 0.996	None	2.3	2	N	N
Extension	79.3 ± 8.0	80.4 ± 9.9	0.92	0.83	0.80 to 0.97	None	9.6	6	N	N
Right Lateral Flexion¥	45.0 ± 7.3	43.0 ± 7.0	0.96	0.93	0.71 to 0.99	None	4.6	5	N	N
Left Lateral Flexion	48.8 ± 8.8	47.8 ± 8.0	0.95	0.92	0.89 to 0.98	None	7.1	7	N	N
Right Rotation	57.1 ± 9.7	70.9 ± 7.2	0.53	0.81	-0.13 to 0.85	-33.7 + 0.31	9.6	8	Y	Y
Left Rotation	65.3 ± 15.1	71.4 ± 5.8	0.53	0.52	-0.60 to 0.80	-71.2 + 0.95	18.6	14	Y	Y

SD = standard deviation; 3DMA = three dimensional motion analysis; ICC = intra-class coefficients; CI = confidence interval; LoA = limits of agreement; Prop Bias = proportional bias; N = no; Y = yes

*All correlations were $p<0.001$ except Left Rotation ($p= 0.02$).

¥ Based on n = 20 as markers on one subject were missing.

† % Error = 0.5*Width of 95% LOA/[($Mean_{Phone}$+$Mean_{Vicon}$)/2].

€ Proportional and fixed bias were determined from ordinary least products analysis.

Table 3-2 Intra-rater reliability of the phone

	Phone D1 (Mean ± SD)	Phone D2 (Mean ± SD)	ICC (3,3)	95% CI	Sys Bias	Width of 95% LoA	% Error†	Prop Bias€	Fixed Bias€	SEM	MDC	LOA 2SD (mean diff ±2.1*SDdiff)
Flexion	51.3 ± 7.9	54.9 ± 7.5	0.864	0.38-0.96	N	9.1	9	N	N	3.1	9.2	-12.84 to 5.48
Extension¥	79.0 ± 7.6	80.8 ± 7.03	0.821	0.49-0.94	N	11.8	7	N	N	5.0	11.9	-13.67 to 10.3
Right Lateral Flexion	43.5 ± 6.7	44.9 ± 7.0	0.903	0.73-0.97	N	8.3	9	N	N	2.8	8.3	-9.73 to 6.95
Left Lateral Flexion	49.1 ± 8.8	51.2 ± 7.4	0.846	0.57-0.95	N	11.8	12	N	N	4.1	12.2	-14.20 to 10.16
Right Rotation	50.0 ± 17.1	70.5 ± 22.7	0.331	-0.34-0.73	N	48.2	40	N	N	16.4	48.7	-70.79 to 29.81
Left Rotation	64.3 ± 16.3	69.8 ± 15.6	0.046	-1.7-0.67	N	46.8	35	N	N	15.8	46.9	-52.38 to 41.36

SD = standard deviation; ICC = intra-class coefficients; CI = confidence interval; Sys Bias = systematic bias; LoA = limits of agreement; Prop Bias = proportional bias; N = no; Y = yes; SEM = standard error of measurement; MDC = minimal detectable change; diff = difference

¥Based on n=15 as one subject's thoracic spine was not well stabilized.

†% Error= 0.5*Width of 95% LOA/[($Mean_{Phone}$+$Mean_{Vicon}$)/2]

€ Proportional and fixed bias were determined from ordinary least products analysis.

SEM= √WMS

MDC=SEM X 2.1 X √2

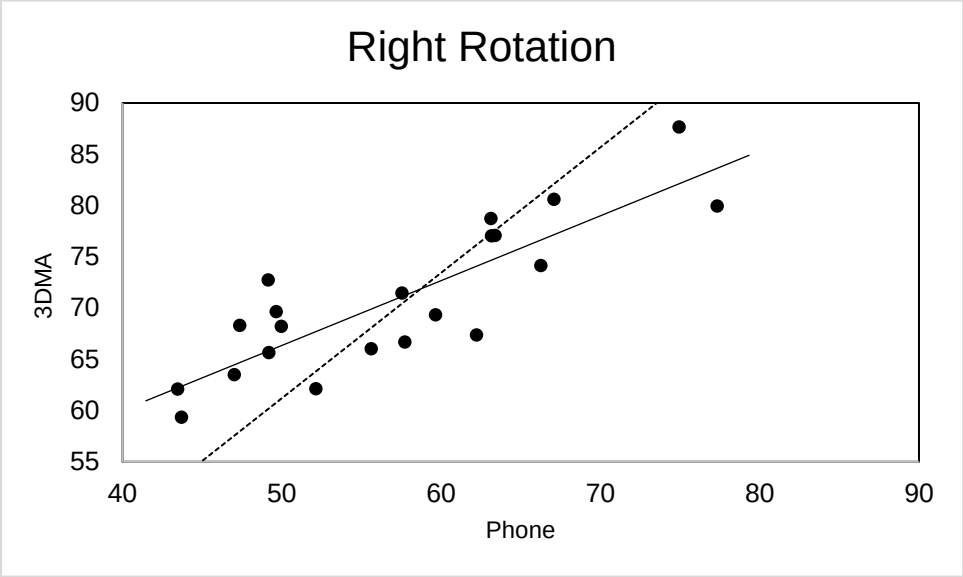
WMS= Mean Square Error term from ANOVA

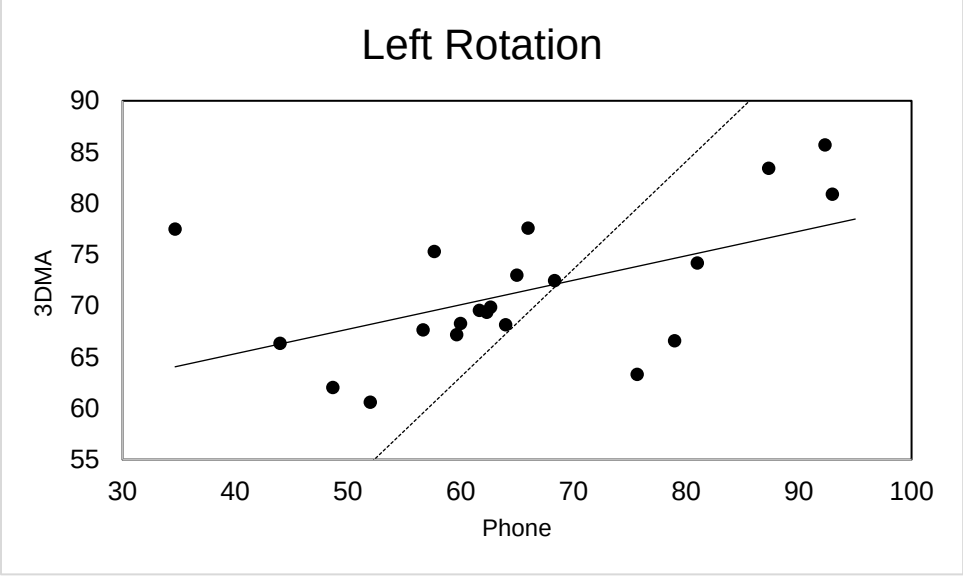
Table 3-3 Reliability of the 3DMA (n = 16)

	Phone D1 (Mean ± SD)	Phone D2 (Mean ± SD)	ICC (3,3)	95 % CI	Sys Bias	Width of 95 % LoA	% Error†	Prop Bias€	Fixed Bias€	SEM	MDC	LOA 2SD (mean diff ±2.1*SDdiff)
Flexion	48.9 ± 7.7	51.9 ± 6.9	0.88	0.54-0.96	N	8.7	9	N	N	3.0	8.91	−14.77 to 8.90
Extension¥	79.1 ± 9.9	81.6 ± 9.2	0.88	0.67-0.96	N	10.0	6	N	N	3.4	10.1	−12.69 to 7.56
Right Lateral Flexion	41.7 ± 6.7	42.9 ± 6.9	0.94	0.82-0.98	N	6.8	8	N	N	2.3	6.83	−8.01 to 5.51
Left Lateral Flexion	46.7 ± 7.6	47.1 ± 6.6	0.92	0.78-0.97	N	8.0	9	N	N	2.8	8.32	−8.57 to 7.89
Right Rotation	68.8 ± 5.1	72.7 ± 5.9	0.64	−0.010-0.88	N	10.4	7	N	N	3.6	10.69	−14.45 to 6.81
Left Rotation	70.2 ± 6.7	73.4 ± 6.7	0.77	0.32-0.92	N	11.2	8	N	N	3.8	11.29	−14.35 to 8.03

SD = standard deviation; ICC = intra-class coefficients; CI = confidence interval; Sys Bias = systematic bias; LoA = limits of agreement; Prop Bias = proportional bias; N = no; Y = yes; SEM = standard error of measurement; MDC = minimal detectable change; diff = difference.
¥Based on n = 15 as one subject's thoracic spine could not be effectively stabilized using the experimental technique utilized.
†% Error = 0.5*Width of 95 % LOA/[(MeanPhone + MeanVicon)/2].
€ Proportional and fixed bias were determined from ordinary least products analysis.
SEM= √WMS
MDC=SEM X 2.1 X √2
WMS= Mean Square Error term from ANOVA

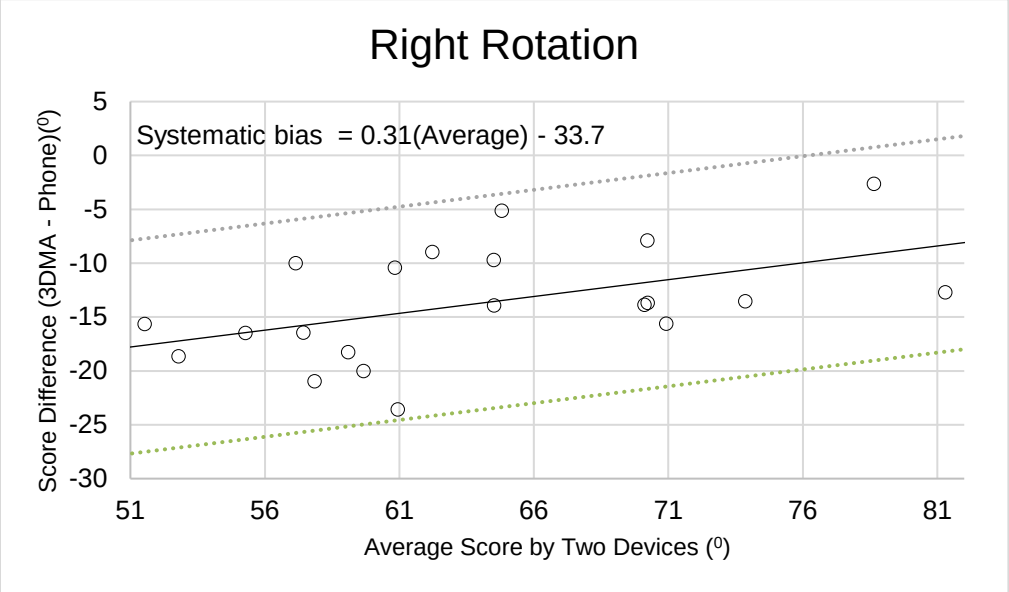
Figures 3-3 Validity assessment using OLP plots for measurements with proportional bias

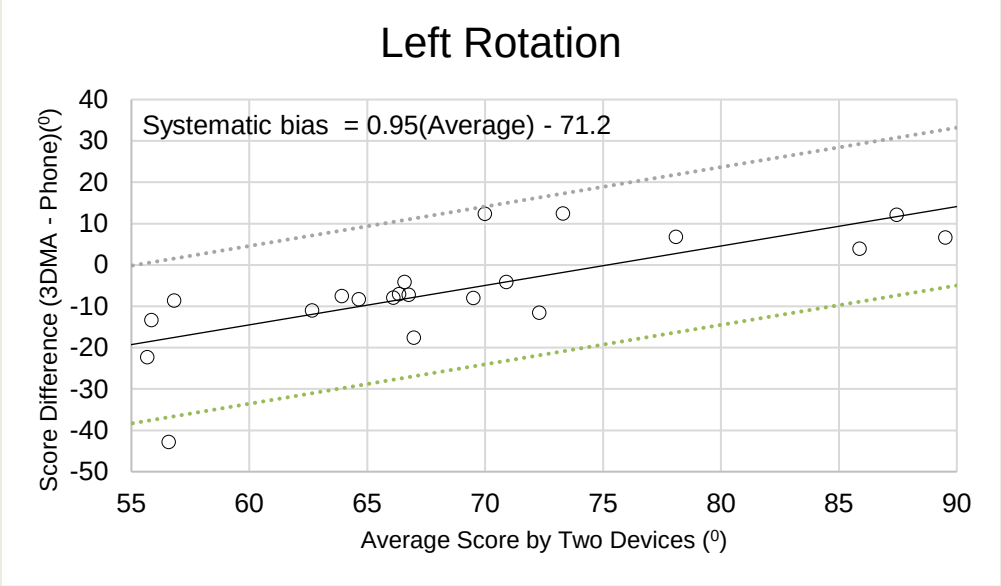




OLP= Ordinary Least Products
3DMA=Three-Dimensional Motion Analysis
Dotted lines indicate perfect agreement between two devices
Solid lines indicate line of best fit through data points

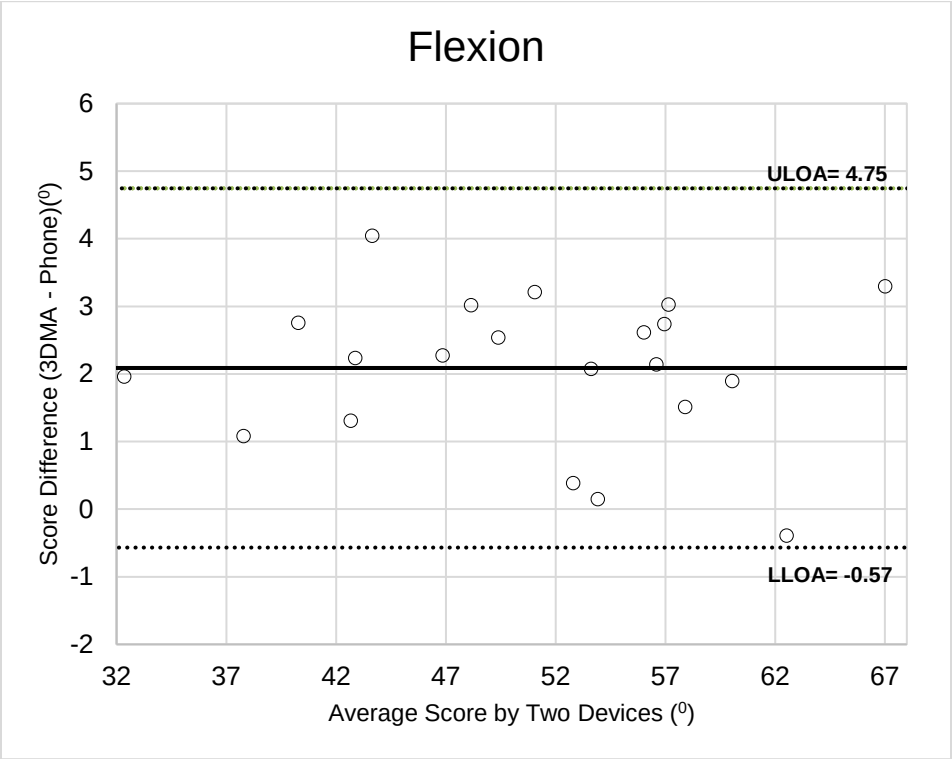
Figures 3-4 Regression-based Bland Altman Plots with proportional bias (Validity)

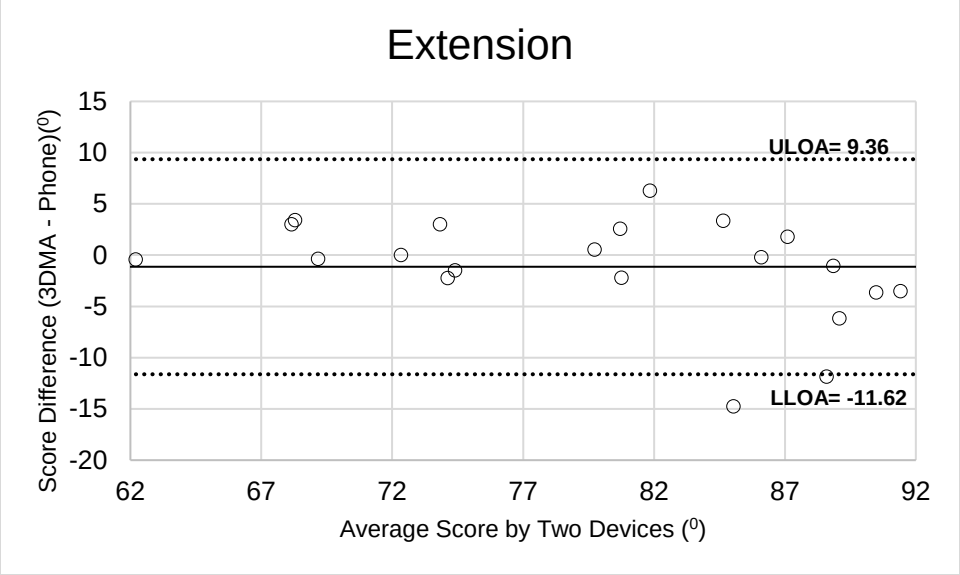




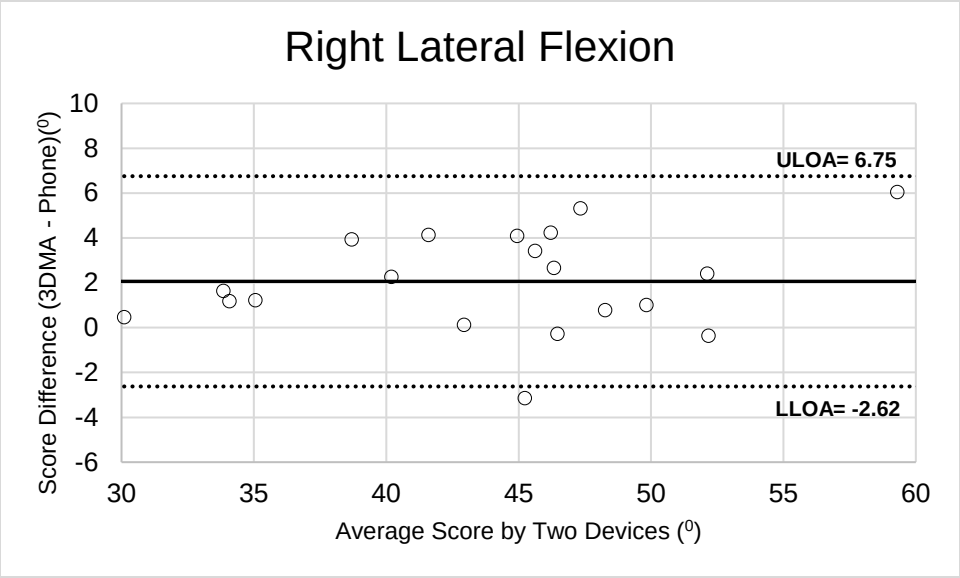
3DMA=Three-Dimensional Motion Analysis
Dotted lines indicate Limits of Agreement

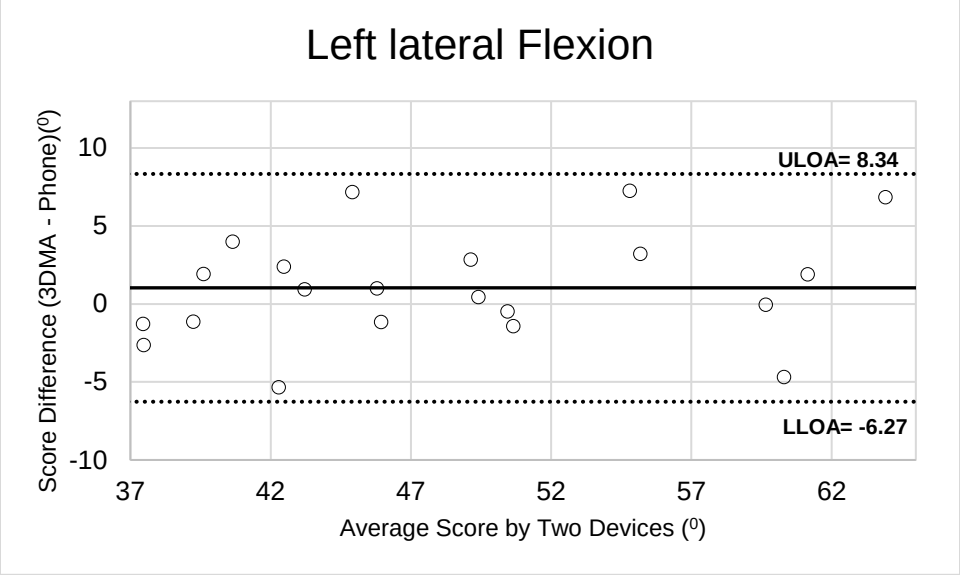
Figures 3-5 Standard Bland Altman Plots (Validity)





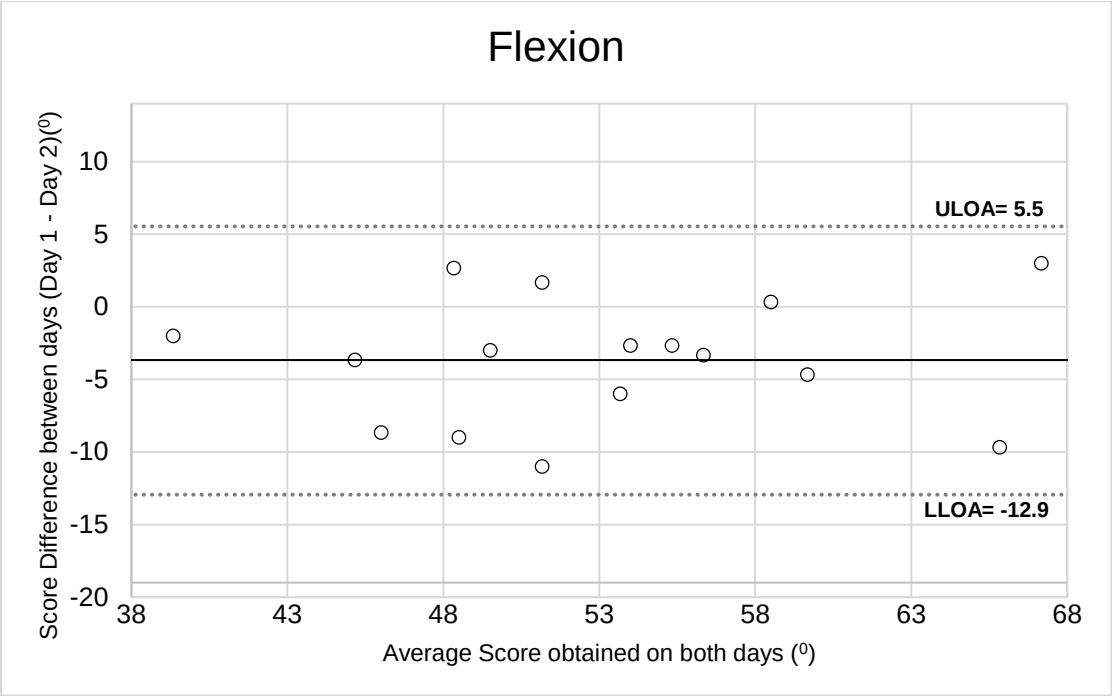
3DMA=Three-Dimensional Motion Analysis
ULOA= Upper Limits of Agreement
LLOA= Lower Limits of Agreement

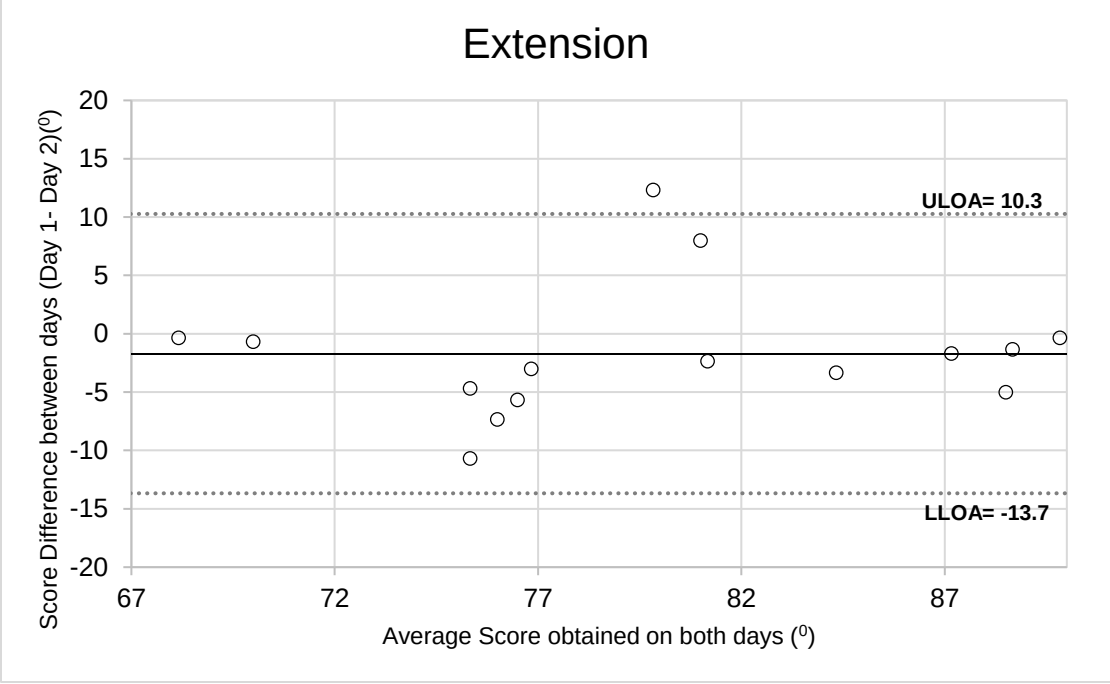




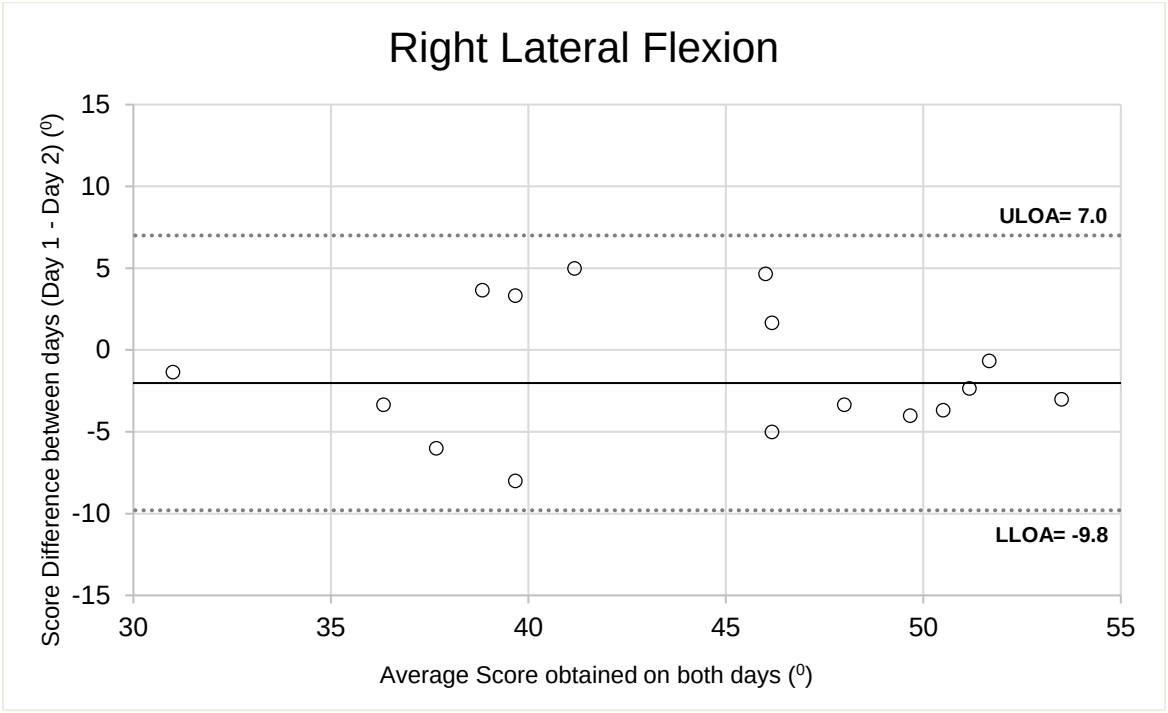
3DMA=Three-Dimensional Motion Analysis
ULOA= Upper Limits of Agreement
LLOA= Lower Limits of Agreement

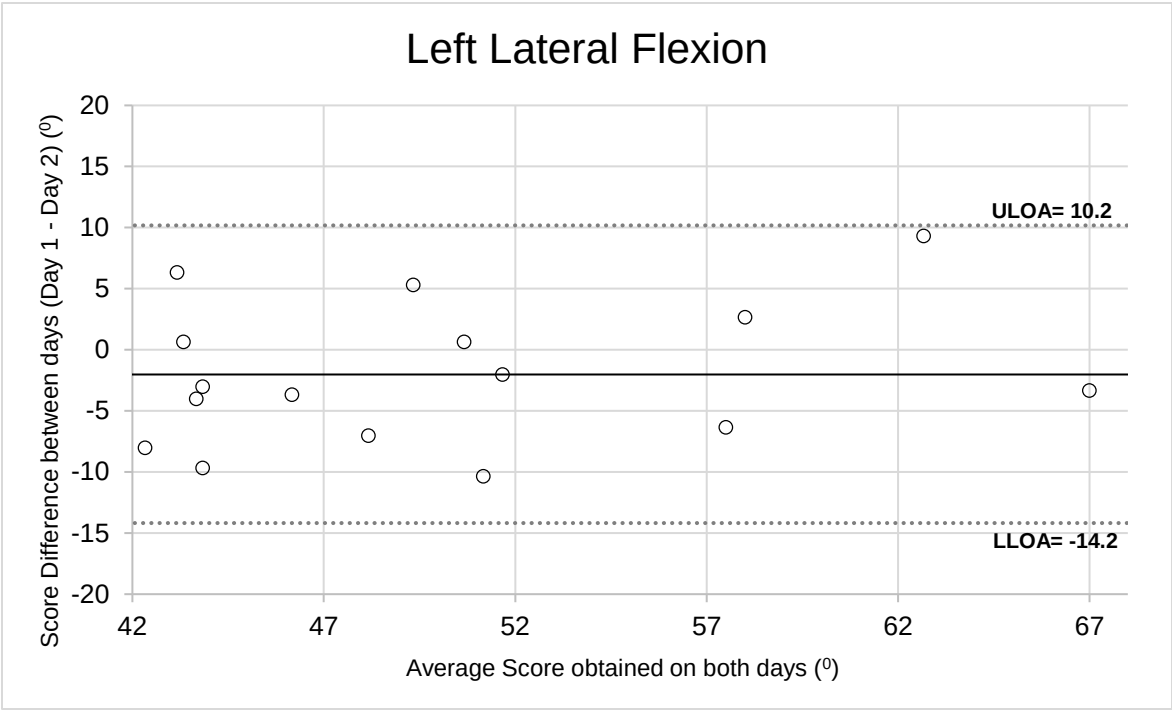
Figures 3-6 Standard Bland Altman Plots (Reliability of Phone)



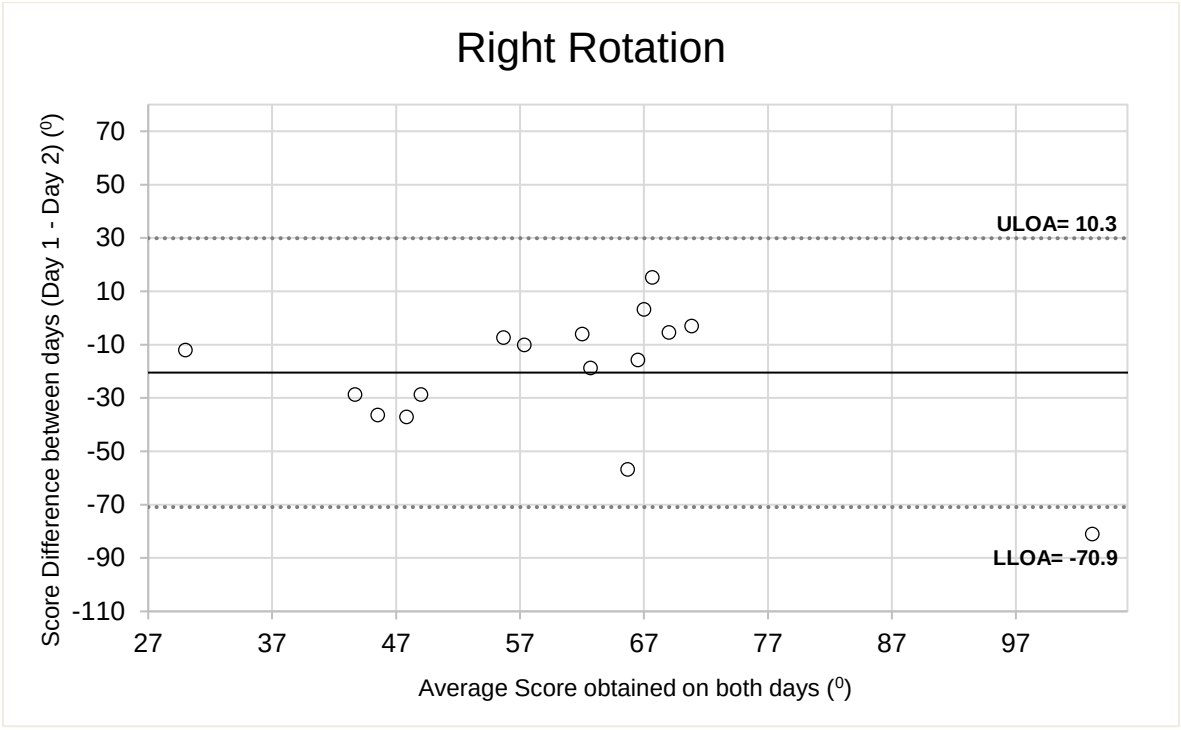


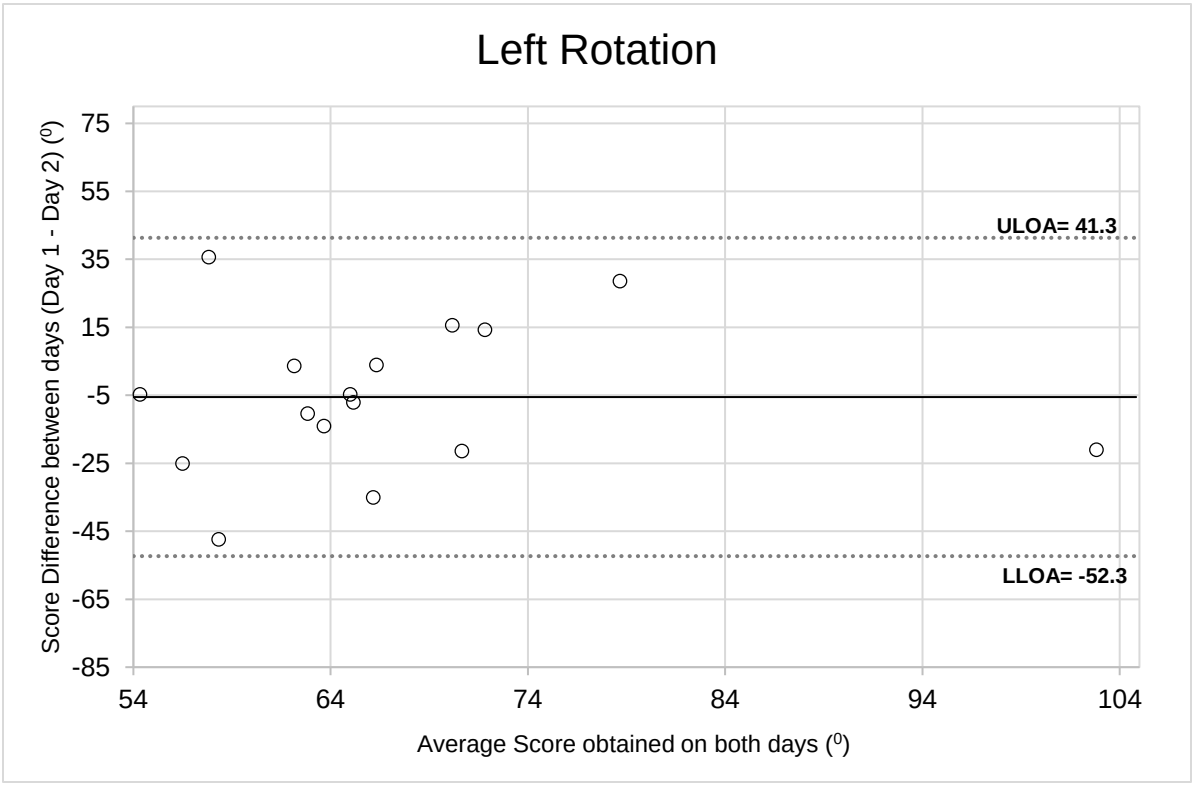
ULOA= Upper Limits of Agreement
LLOA= Lower Limits of Agreement





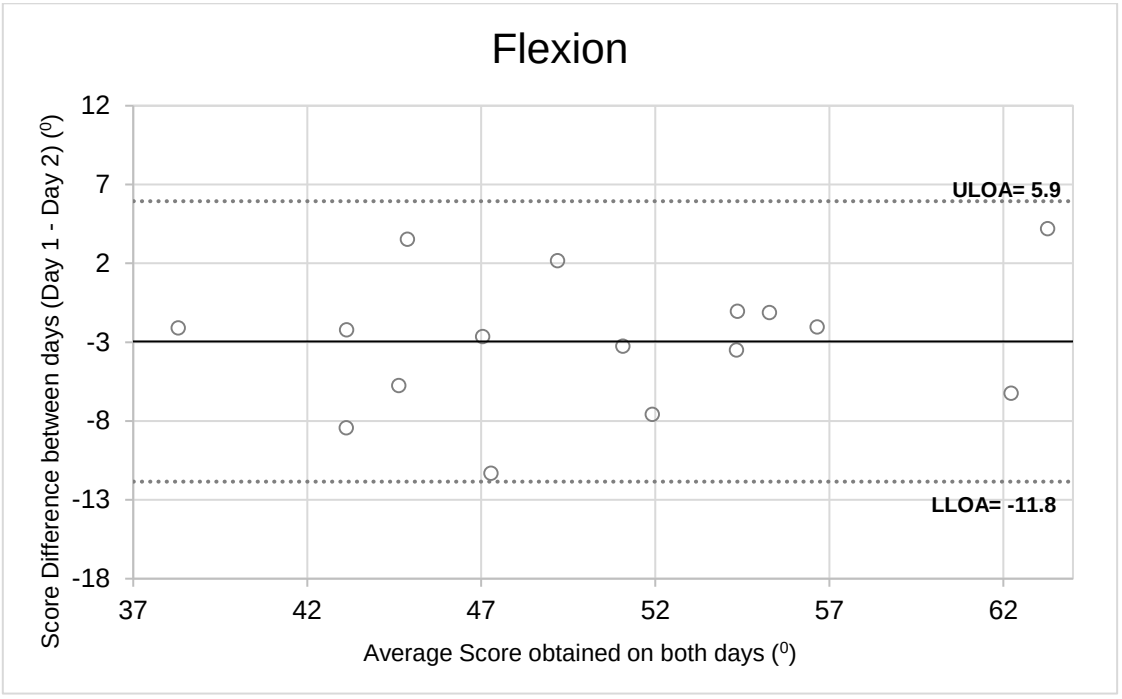
ULOA= Upper Limits of Agreement
LLOA= Lower Limits of Agreement

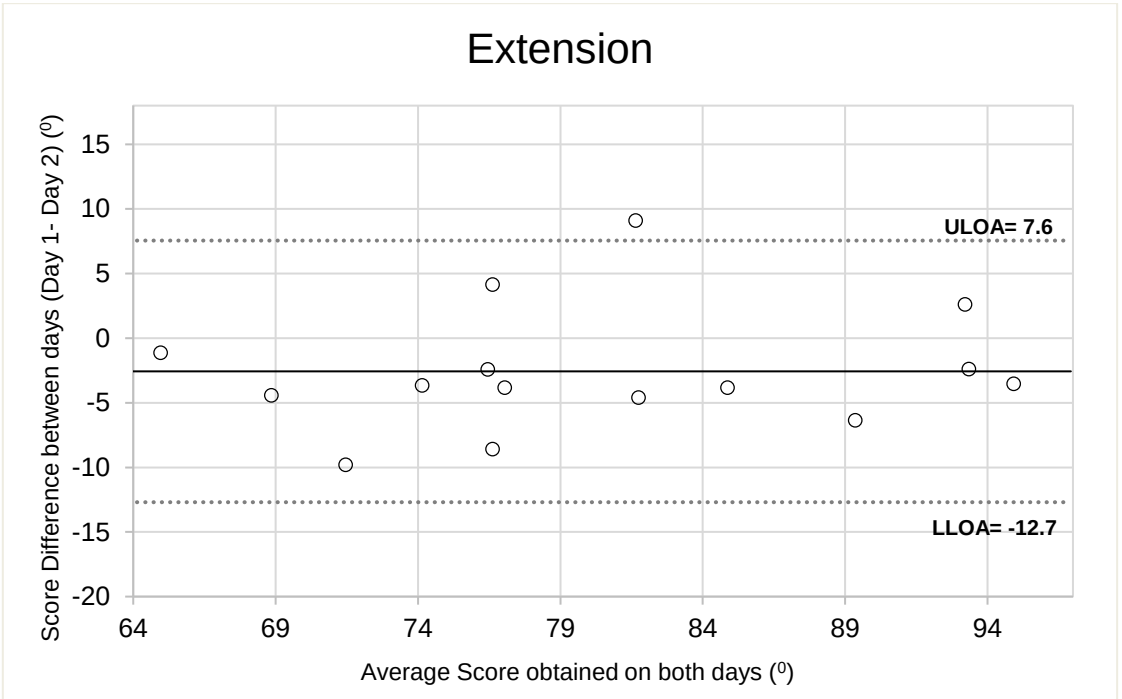




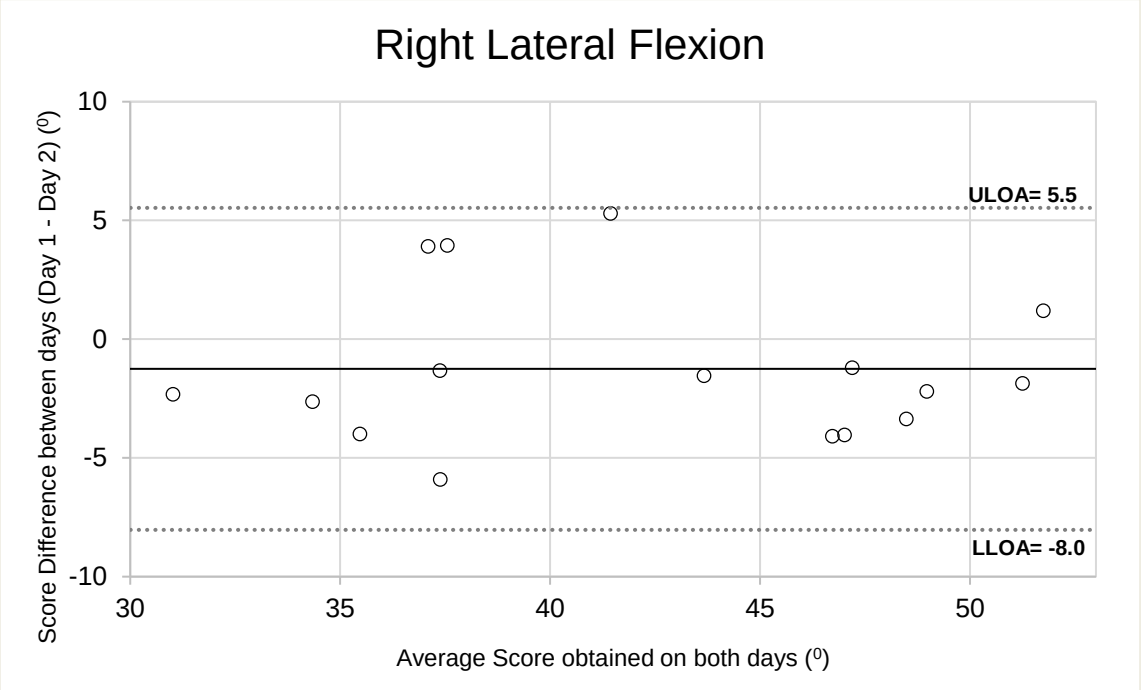
ULOA= Upper Limits of Agreement
LLOA= Lower Limits of Agreement

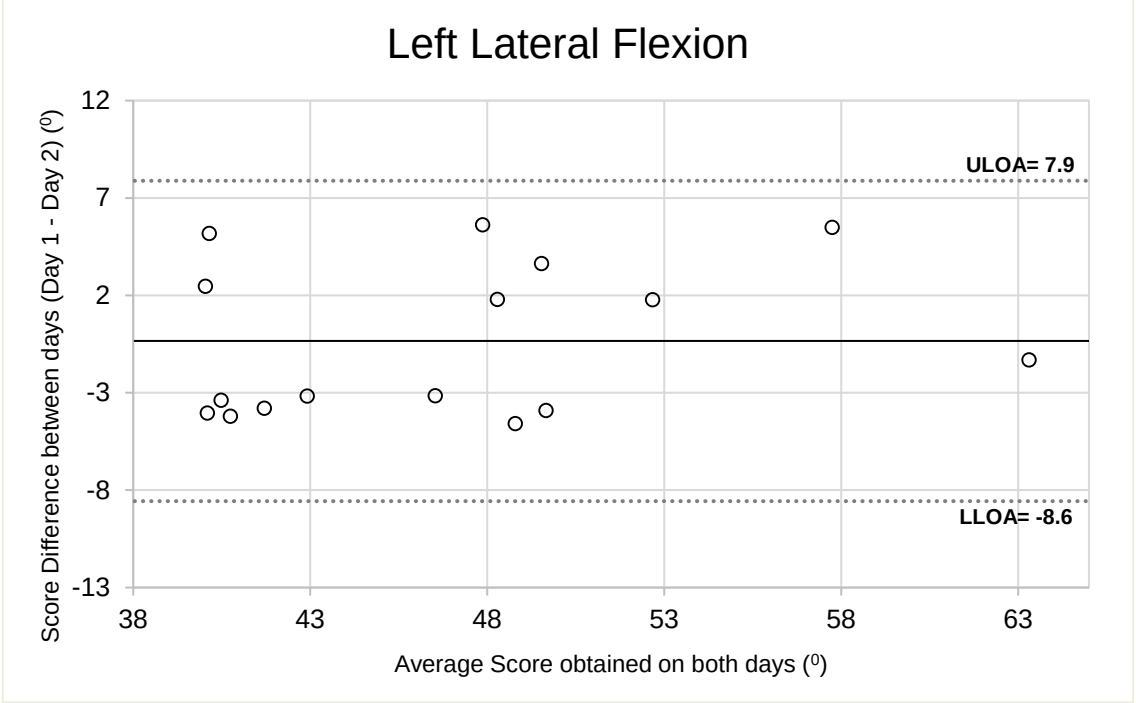
Figures 3-7 Standard Bland Altman Plots (Reliability of 3DMA)



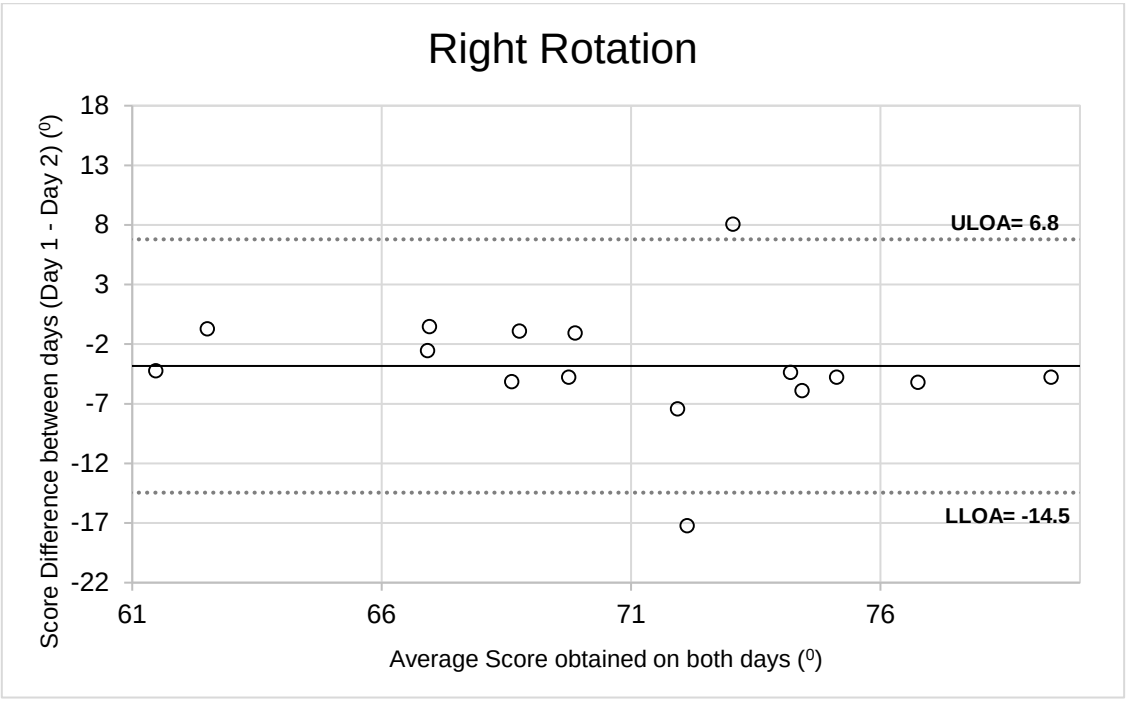


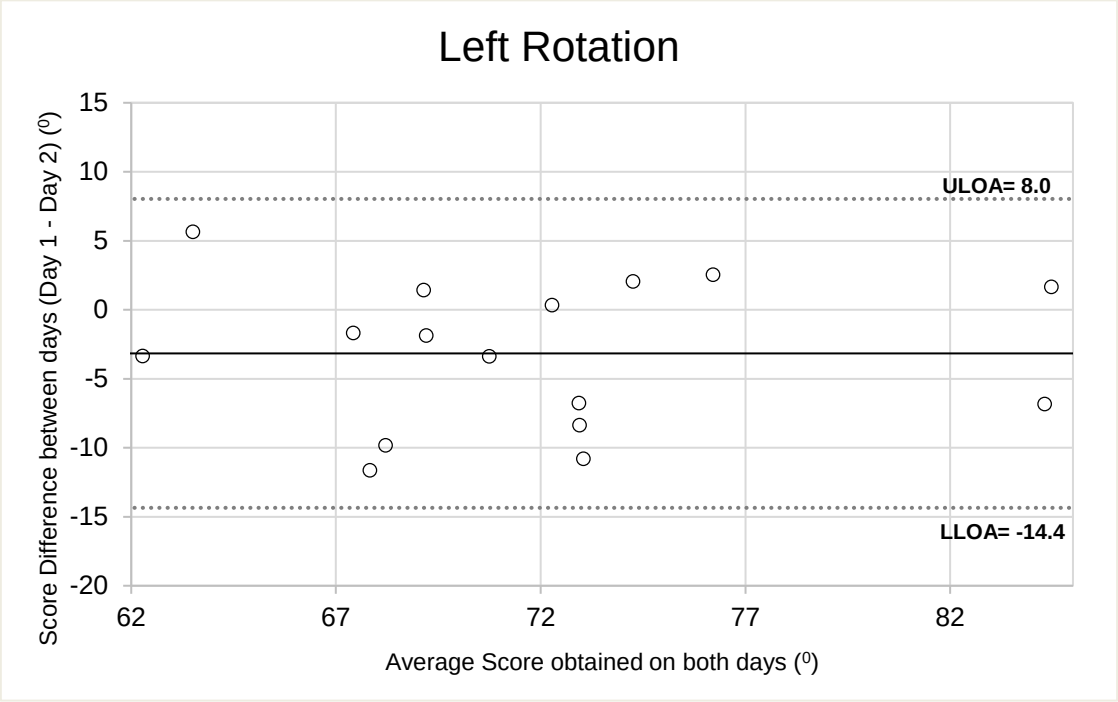
3DMA=Three-Dimensional Motion Analysis
ULOA= Upper Limits of Agreement
LLOA= Lower Limits of Agreement





ULOA= Upper Limits of Agreement
LLOA= Lower Limits of Agreement





ULOA= Upper Limits of Agreement
LLOA= Lower Limits of Agreement

3.5 Discussion

This study demonstrates that an Android phone can be a valid and reliable tool to measure ROM of cervical flexion, extension and lateral-flexion but not cervical rotation, consistent with previous results (Tousignant-Laflamme et al., 2013). Cervical rotation results cannot be seen as valid and reliable as, although the rotation measurements from the phone showed moderate validity values (ICC=0.53), the reliability results were poor. Possible reasons for these results are that, in the position tested, both sagittal and frontal measurements rely on the gravity-dependent accelerometers within the phone but the movements in the transverse plane are detected by the magnetometer, which can be adversely affected by any surrounding magnetic fields. This includes equipment such as computers, speakers and some automatic doors, which were all present in the laboratory and may have caused the error observed in this axis. We attempted to overcome this issue using the magnet supplied with the CROM, however our results were still invalid in this axis. This is clinically relevant because strong magnetic fields are likely to be present in many clinical settings and thus rotation ROM assessment using devices that rely on data from the magnetometer cannot be recommended (i.e. rotation in sitting).

Potential reasons for the greater ICC values in the present study compared to previous work (Tousignant-Laflamme et al., 2013) are the concurrent measurements and the addition of the spirit level indicator to improve the accuracy of measurement. The latter is especially important because the cervical-spine is a multi-joint structure and susceptible to coupled movements. Furthermore, we minimized measurement errors by standard fixation of the phone on a helmet, compared to the phone being held by hand on the participant's head in the previous study (Tousignant-Laflamme et al., 2013). This also implies that the phone ought to be mounted on a helmet when it is being used in the clinical setting, and may be considered a limitation of this study. Furthermore, we found that when measuring cervical extension, the combined weight of the helmet and the phone tended to cause the helmet to slip. The examiner overcame this problem by providing adequate support to ensure that the helmet was firmly fixed on the head during the movement.

This study has several other limitations. (i) We did not assess inter-rater reliability and this may potentially limit the applicability of our findings in clinical settings between observers. (ii) We did not include a rigorous warm-up regime to ensure consistent inter-day readiness to perform the movements. While this is unlikely to affect the concurrent validity data (i.e. an increase in range of motion intra-session would be detected by both devices if they are comparable), it may have negatively affected our reliability results. (iii) As a preliminary step to assess the validity and reliability of the Android phone application, all

participants were healthy, therefore the results need to be replicated in populations of interest, such as those with NP. (iv) The reliability data of the 3DMA system for the rotation axis was not particularly good, and it is not possible to determine whether this is due to intra-day subject variation (which would provide justification for the poor phone reliability results) or equipment-related measurement error (which would not have affected the phone reliability values). It could be possible that there were differences in what was being measured between devices, as the phone was placed on the centre of the top of the head and the reflective markers were on the tragus and glabella. Given the large differences between results between rotation and the other planes, and the fact that it is measured using a magnometer, we expect that this is the primary reason, but investigation using the phone without environmental magnetic influences would be a potential future study.

In summary, this study aimed to establish the validity and intra-rater reliability of an Android phone application to measure cervical-spine ROM and found that cervical flexion, extension and lateral-flexion measurements are both valid and reliable in sitting and may be used in the clinical setting. In contrast, cervical rotation measurements in sitting are neither valid nor reliable likely due to magnetic field interference. We suggest further study to determine whether the phone is valid to measure cervical-rotation in supine, which would use the accelerometer derived angles and is therefore likely to provide more consistent results. This limitation is likely to impact any movement that involves rotation (such as the flexion-rotation test for the upper cervical spine in supine) so evaluation of any combined movement involving rotation is not likely to be accurate.

Chapter 4 is adapted from the following publication
(Appendix 2 URL Link to Published Paper)

Quek J, Brauer SG, Treleaven J, Clark RA
"The concurrent validity and intra-rater reliability of the Microsoft Kinect™ to measure thoracic kyphosis"
Journal of Rehabilitation Research 2017; 40 (3), 279-284

Chapter 4: Study 2 The concurrent validity and intra-rater reliability of the Microsoft Kinect to measure thoracic kyphosis.

Thoracic kyphosis is often associated with poor postural control and cervical spine impairments. However, it is not routinely evaluated in the clinical setting possibly due to barriers to the accessibility and affordability of available valid and reliable equipment. This study examined the validity and reliability of the Microsoft Kinect to measure thoracic kyphosis, with the hope of overcoming these barriers.

4.1 Introduction

Increased kyphosis is associated with diminished physical performance, impaired respiratory function and increased mortality (Di Bari et al., 2004; Kado et al., 2009; Sinaki, Mehrsheed et al., 2005). Further, thoracic kyphosis is closely linked with cervical spine impairments in patients suffering from NP (Cleland et al., 2007; Lau et al., 2010; Quek et al., 2012). Interestingly, studies demonstrated positive clinical outcomes following thoracic spine manipulation and mobilization in patients with cervical spine dysfunction (Cleland et al., 2007; Lau et al., 2011). However, its objective measurement is rarely undertaken clinically (Perriman et al., 2012), potentially because the assessment devices are time-consuming, costly and cumbersome and are unable to provide instant feedback. Currently available tools are limited, and there is no present tool that fits the criteria of possessing high levels of both validity and reliability as well as being affordable and clinically useful by providing instant feedback and being easy to use. The Flexicurve demonstrated one of the strongest levels of evidence for validity and reliability (Barrett et al., 2014; Tran et al., 2016) and is affordable and easy to use, which is why it is a recommended clinical tool of choice (Barrett et al., 2014; Greendale et al., 2011). However, data processing using the Flexicurve method is time-consuming and tedious and does not provide instant feedback. Given the advances of the Microsoft Kinect^{TM} and its potential uses for research and clinical practice (Clark et al., 2013), this study investigated the concurrent validity and intr-rater reliability of the Kinect^{TM} to measure thoracic kyphosis and overcome these barriers to implementation.

4.3 Methods

Thirty-three healthy individuals between 21 and 64 years (mean age: 31 ± 11.0 years, Height: 170.2 ± 8.2cm, Weight: 64.2 ± 12.0kg, Male: 17) with no active neck or back pain participated. Twenty-nine returned within 1-7 days to be re-examined for intra-rater reliability

(12% dropout rate). The sample size was selected because it provided an estimated power greater than 90%, based on the aim to detect a desired reliability of ICC=0.9 and a minimally acceptable reliability of 0.7 with an alpha level of 0.05 (1-tailed). All participants provided informed consent as outlined by the institution's Human Research Ethics Committee and all procedures were conducted according to the Declaration of Helsinki.

4.3.1 Procedures

Participants were instructed to stand "as straight as possible", with their exposed spine facing a Microsoft Xbox 360 Kinect™ interfaced to a laptop computer using the Microsoft Software Development Kit (SDK), Redmond, Washington, United States of America. The Kinect™ was positioned approximately 82 cm above the ground, at 1.8cm away from the participant. Prior to testing, the Kinect™ was calibrated using a previously described technique (Mentiplay et al., 2013). Spinous processes of C7, T12 and S2 were manually palpated by the examiner using previously described techniques (Ernst et al., 2013; McGaugh et al., 2007). The position of T12 was further confirmed by palpating the spinous processes from C7 to T12 and palpating upwards from S2. C7, T12 and S2 were then marked with a 1cm diameter paper sticker. Subsequently, the mouldable Flexicurve was placed over the spinous processes to conform to the sagittal curve of the spine. Next, the Flexicurve was marked at C7, T12 and S2 (Figure 4-1a) and then carefully placed on a stable surface. A digital image of the Flexicurve was captured using a 16.1 megapixel digital camera (Sony DSC-W630) as previously described (Quek et al., 2012). Each Flexicurve measurement was followed immediately by a Kinect™ measurement (within 5 seconds). This consisted of recording 5 consecutive frames of depth and image data from the Kinect™ sensors using the technique outlined in Mentiplay et al. (2013). The protocol described in standing was then repeated in sitting. In both positions, 3 measurements were obtained from both the Flexicurve and the Kinect™ and the average was calculated.

Fig. 4-1a

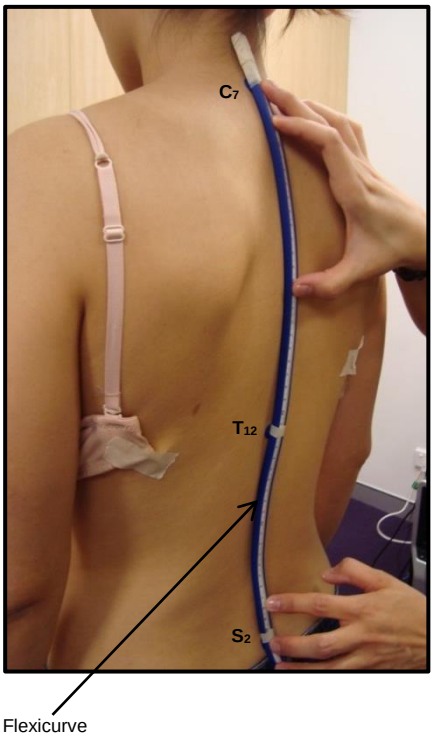


Fig. 4-1b

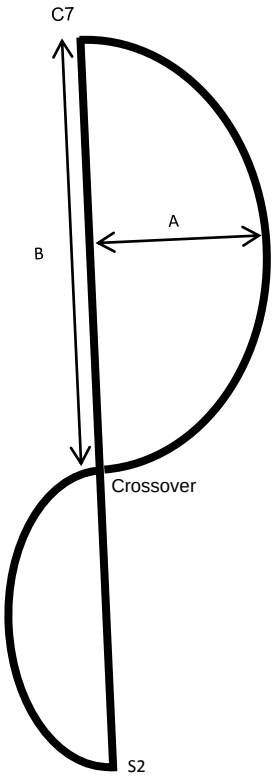


Fig. 4-1c

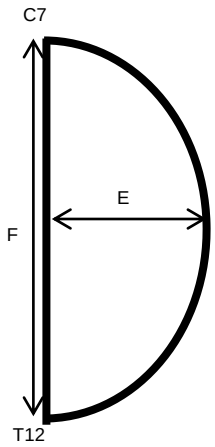


Figure 4-1. Implementation of the Flexicurve and calculation of the anatomical indexes.

The Flexicurve is a flexible ruler that conforms to the shape of the spine (A). The Flexicurve is marked accordingly at C7, T12 and S2. The Kyphosis Index is then calculated using the formula A/B * 100 (B), and the Kyphosis Angle is calculated using the formula E/F * 100 (C). Length of B = C7 to crossover. Length of F = C7 to T12.

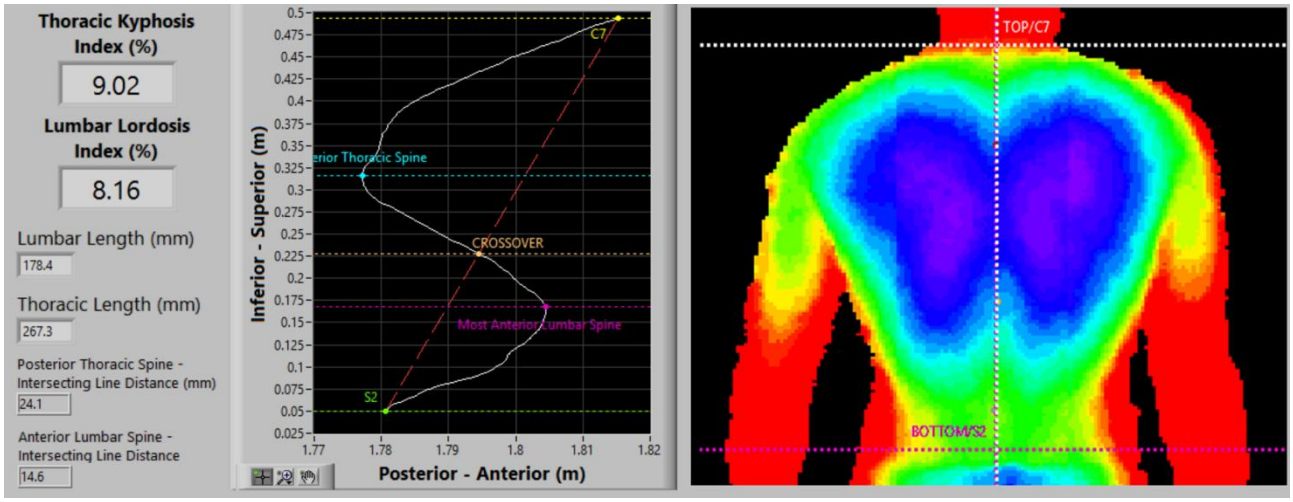


Figure 4-2 Example data from the Kinect system

The depth (right side of the image) and image (not shown) sensor data were recorded and averaged over consecutive frames to create a 3D anatomical representation of the person's back. By aligning two cursors with the S2 and C7 the system was able to automatically calculate the indexes described in Figure 4-1.

4.4 Data Analysis

4.4.1 Kinect™

Prior to analysis the Kinect™ depth data was filtered temporally and spatially by averaging the depth position at each individual pixel across the 5 consecutive frames, then implementing a 3x3 pixel median filter to these averaged depth data respectively. This technique has been used in previous research to reduce the noise inherent in the Kinect™ data (Mentiplay et al., 2013). This 2D representation of depth from the camera was then aligned with the image data, and combined with the camera's field of view specifications and the pixel position vertically and horizontally to identify the position of the pixel in 3D space using the protocols included in the SDK. Using this procedure we placed cursors on each of the visible stickers representing the anatomical landmarks, allowing us to obtain the position in 3D space of the C7, T12 and S2, which was needed to perform our analysis. This is presented in Figure 4-2.

4.4.2 Flexicurve

The kyphosis index and kyphosis angle were calculated as described previously, and shown in Figure 4-1b & 4-1c (Quek et al., 2012; Seidi et al., 2014). All participants were assessed by the same examiner (JQ) who has 13 years of clinical musculoskeletal physiotherapy experience.

4.5 Statistical Analysis

Intra-class correlation coefficient (ICC) in combination with assessment of systematic bias were used to determine validity. Bland and Altman plots were constructed to determine the 95% limits of agreement (LoA) between the Flexicurve and Kinect™ measures (Bland & Altman, 1986; Bland & Altman, 1999). Fixed and proportional biases were determined from ordinary least products (OLP) regression. All calculations were performed as previously described (Ludbrook, 1997). Intra-rater reliability was determined from ICC [3,3], and OLP regression quantified the relationship between sequential measurements for both devices. Two-way analysis of variance based on absolute agreement was used to calculate ICC. ICC values of >0.75 were considered excellent, 0.4-0.75 modest or <0.4 poor (Fleiss, 1986). Measurement error was estimated using standard error of measurement (SEM), LOA, and minimal detectable change (MDC). Statistical analyses were completed using IBM SPSS Statistics for Windows, Version 22.0. Armonk, NY: IBM Corp.

4.6 Results

4.6.1 Validity

The Kinect™ demonstrated excellent concurrent validity (ICC= 0.76-0.82) based on ICC values >0.75. (see Table 4-1 and 4-3 for LOA plots).

4.6.2 Reliability

Intra-rater reliability results are presented in Table 4-2. Excellent results were observed for both methods in standing and sitting (ICC= 0.81-0.98 see Table 4-2). LOA plots are presented in 4-4 and 4-5.

Table 4-1: Kinect vs Flexicurve Validity (n=33)

	Kinect	Flexicurve	ICC (3,3)	95% CI	Sys Bias	95% LoA Width	% Error†	Prop Biasđ	Fixed Biasđ
Standing Thoracic Kyphosis Index	9.77 ± 2.4	9.07 ± 2.2	0.77	0.53 to 0.89	None	1.9	10	N	N
Standing Thoracic Kyphosis Angle	9.86 ± 2.4	9.12 ± 2.1	0.76	0.51 to 0.88	None	1.9	10	N	N
Sitting Thoracic Kyphosis Index	8.55 ± 2.0	7.80 ± 2.1	0.82	0.59 to 0.92	None	1.5	9	N	N
Sitting Thoracic Kyphosis Angle	9.00 ± 1.9	8.10 ± 1.9	0.79	0.48 to 0.90	None	1.5	9	N	N

Results for the Kinect and Flexicurve are reported as Mean ± SD

†*% Error= 0.5*Width of 95% LOA/[(MeanKinect+MeanFlexicurve)/2]*

ICC=Intra-class correlation coefficient; Sys Bias= Systematic Bias; Prop Bias= Proportional Bias

đProp and fixed bias were determined from ordinary least products analysis.

N=No

SEM= √WMS

MDC=SEM X 1.96 X √2

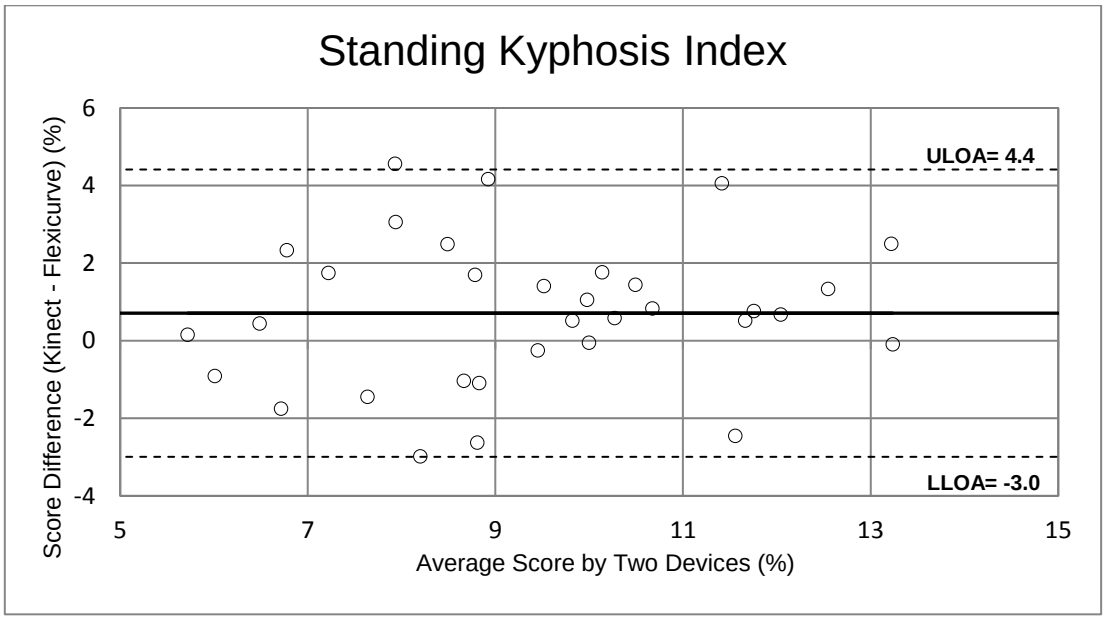
WMS= Mean Square Error term from ANOVA

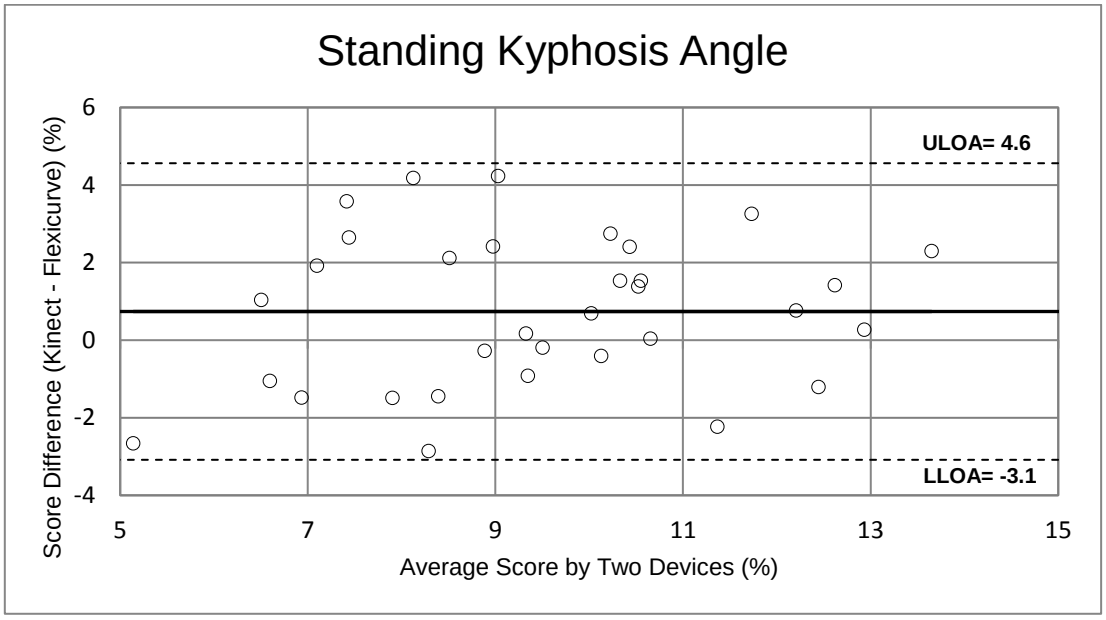
Table 4-2: Intra-rater reliability of the Kinect (n=29)

	Day 1	Day 2	ICC (3,3)	95% CI	SEM	MDC	Sys Bias	95% LoA Width	% Error†	Prop Bias‡	Fixed Bias‡
Kinect											
Standing Thoracic Kyphosis Index	9.78 ± 2.4	9.84 ± 2.5	0.98	0.95 to 0.99	0.53	1.5	None	1.4	7	N	N
Standing Thoracic Kyphosis Angle	9.86 ± 2.4	9.79 ± 2.5	0.96	0.92 to 0.98	0.69	1.9	None	1.9	10	N	N
Sitting Thoracic Kyphosis Index	8.55 ± 2.0	8.14 ± 1.7	0.81	0.60 to 0.91	1.01	2.8	None	2.8	17	N	N
Sitting Thoracic Kyphosis Angle	9.00 ± 2.1	8.67 ± 1.8	0.81	0.60 to 0.91	1.07	3.0	None	2.9	17	N	N
Flexicurve											
Standing Thoracic Kyphosis Index	9.12 ± 2.1	8.94 ± 1.9	0.83	0.63 to 0.92	1.11	3.1	None	3.0	17	N	N
Standing Thoracic Kyphosis Angle	7.80 ± 2.1	7.73 ± 1.8	0.83	0.63 to 0.92	0.99	2.7	None	2.7	18	N	N
Sitting Thoracic Kyphosis Index	8.10 ± 1.9	7.96 ± 2.0	0.86	0.73 to 0.94	0.92	2.6	None	2.5	16	N	N
Sitting Thoracic Kyphosis Angle	9.07 ± 2.2	8.68 ± 2.2	0.85	0.69 to 0.93	1.09	3.0	None	3.0	17	N	N

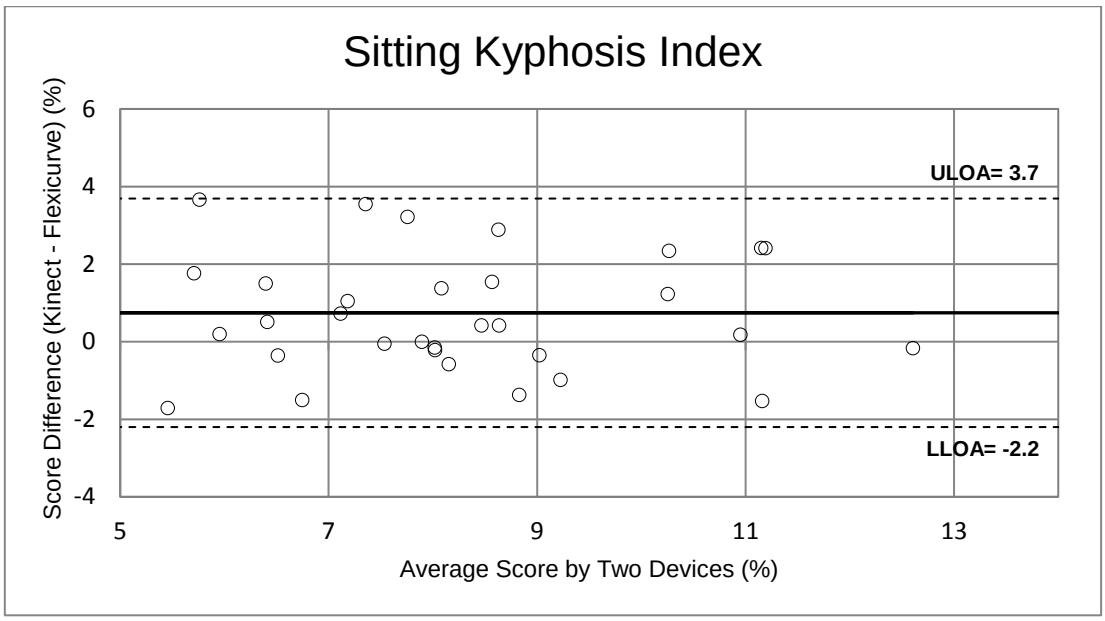
†*% Error= 0.5*Width of 95% LOA/[(MeanKinect+MeanFlexicurve)/2]*
ICC=Intra-class correlation coefficient; SEM= Standard error of measurement; MDC= Minimum detectable change;
Sys Bias= Systematic Bias; Prop Bias= Proportional Bias
‡Prop and fixed bias were determined from ordinary least products analysis.
N=No
SEM= √WMS
MDC=SEM X 1.96 X √2
WMS= Mean Square Error term from ANOVA

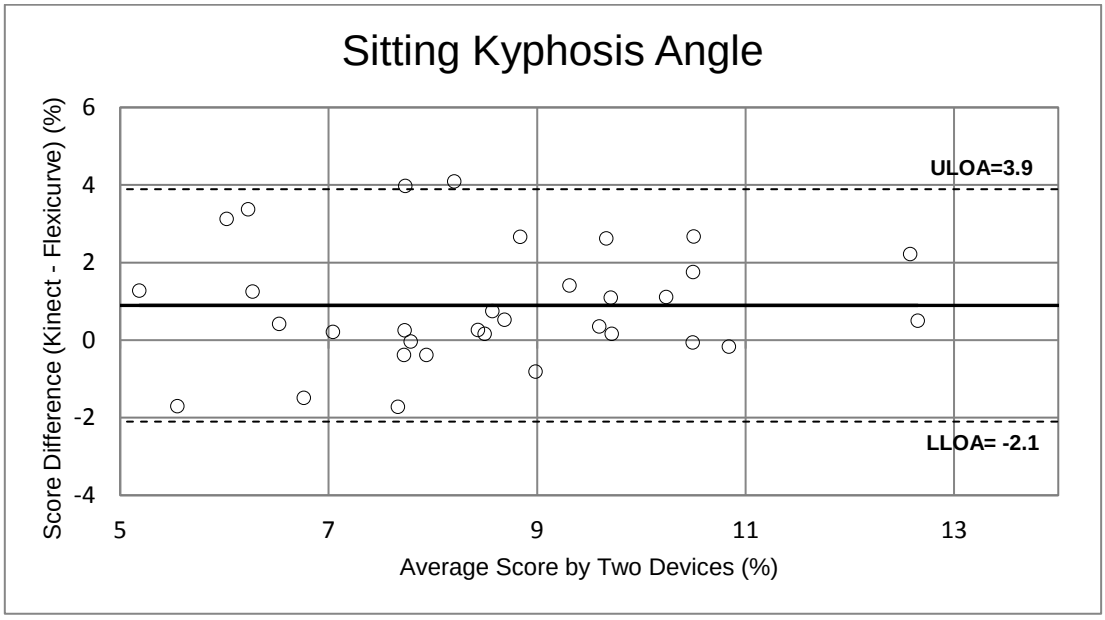
Figures 4-3 Standard Bland Altman LOA Plots (Validity)





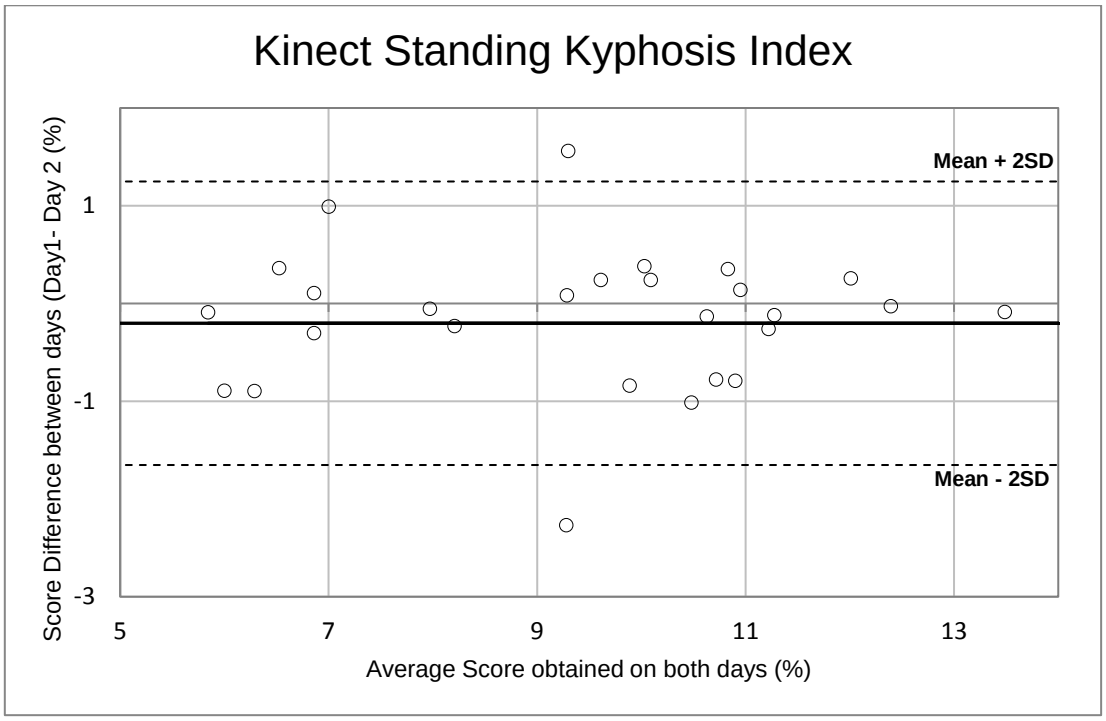
ULOA= Upper Limits of Agreement
LLOA= Lower Limits of Agreement

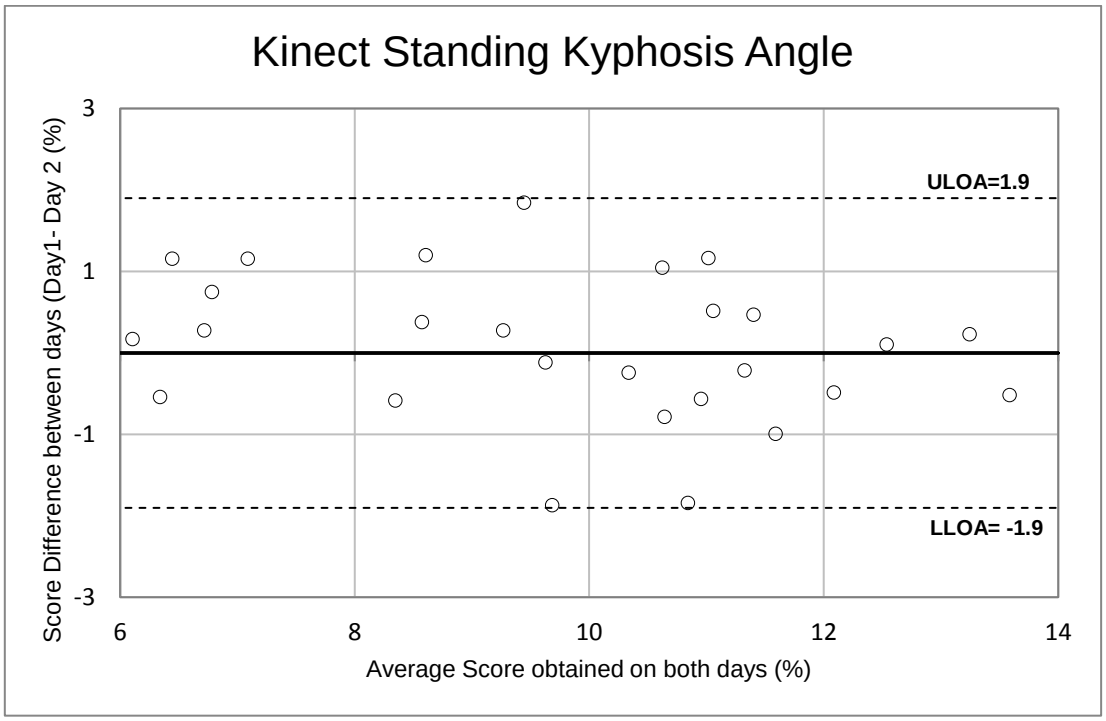




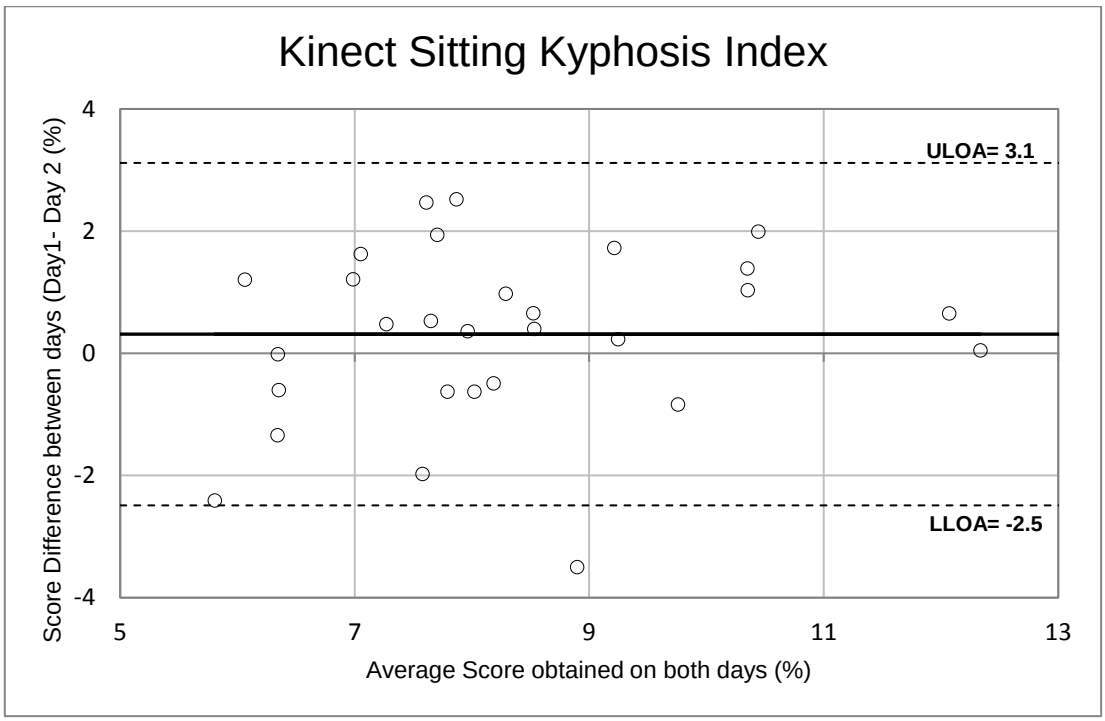
ULOA= Upper Limits of Agreement
LLOA= Lower Limits of Agreement

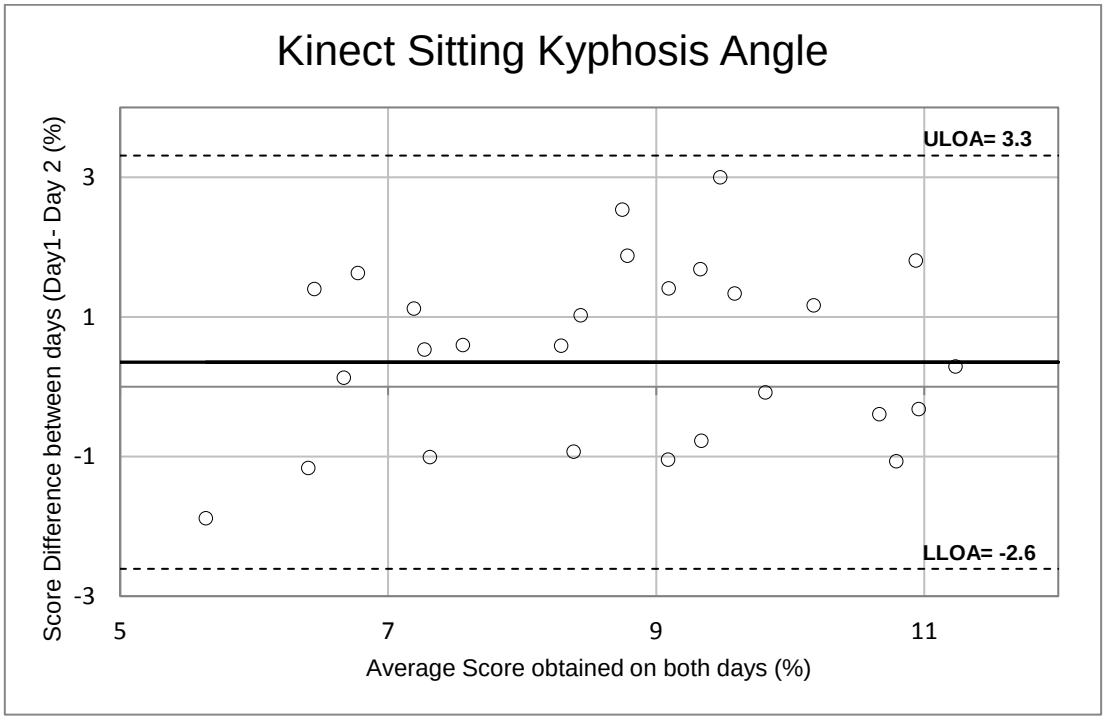
Figures 4-4 Standard Bland Altman LOA Plots (Reliability of the Kinect)





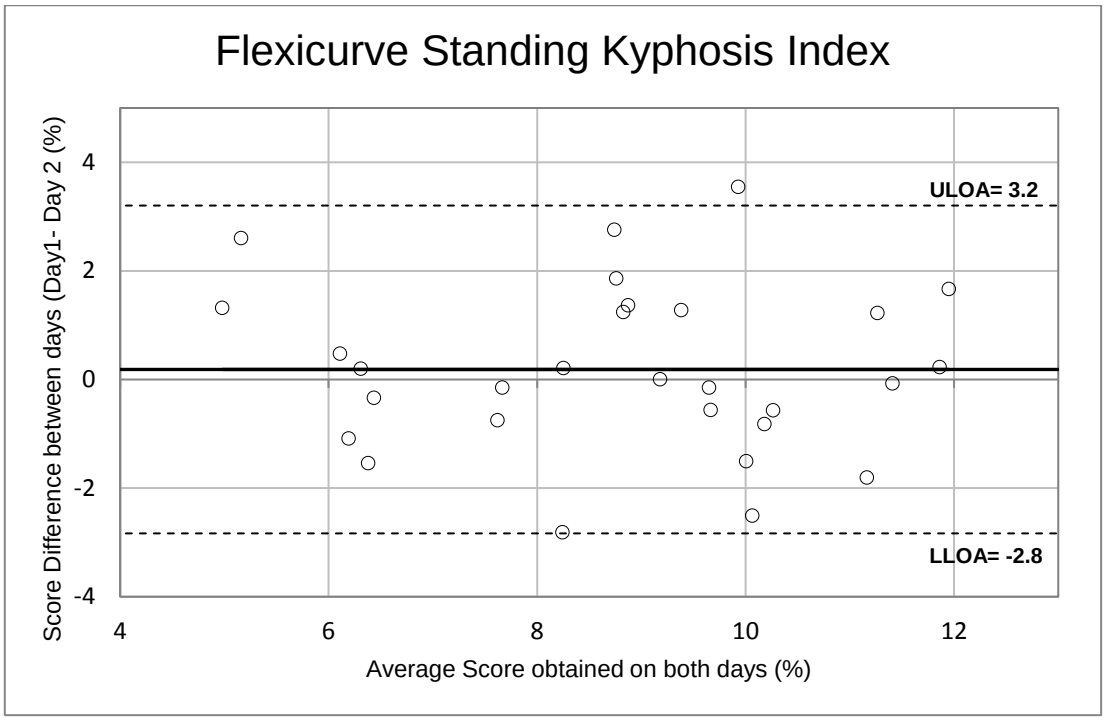
ULOA= Upper Limits of Agreement
LLOA= Lower Limits of Agreement

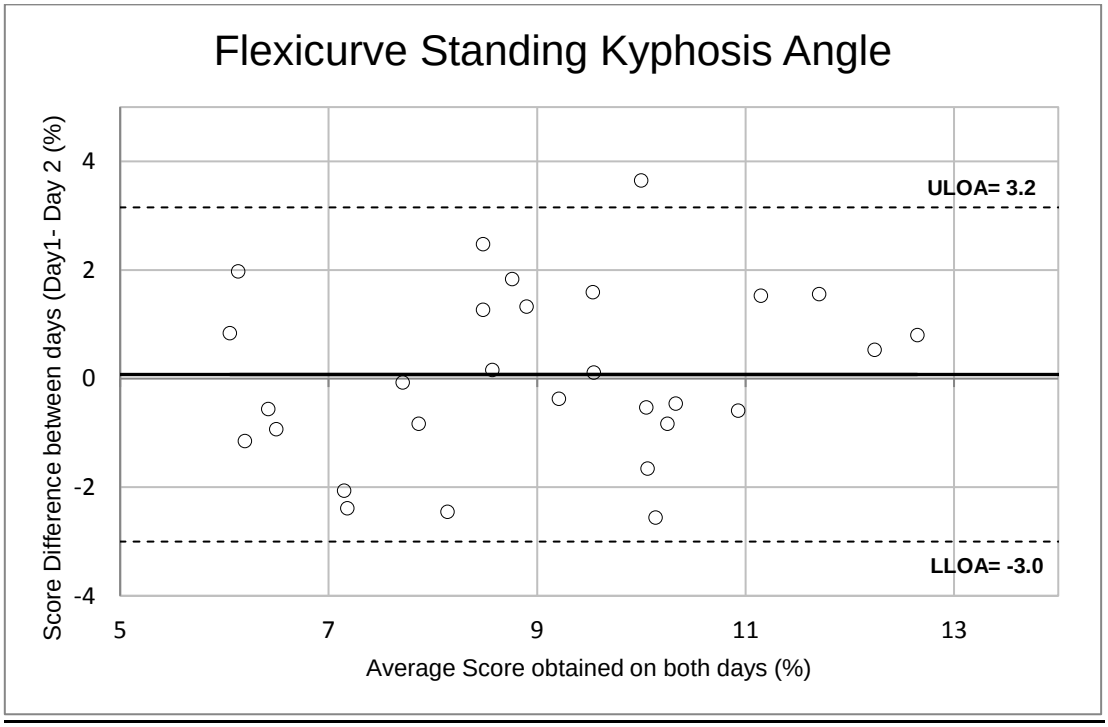




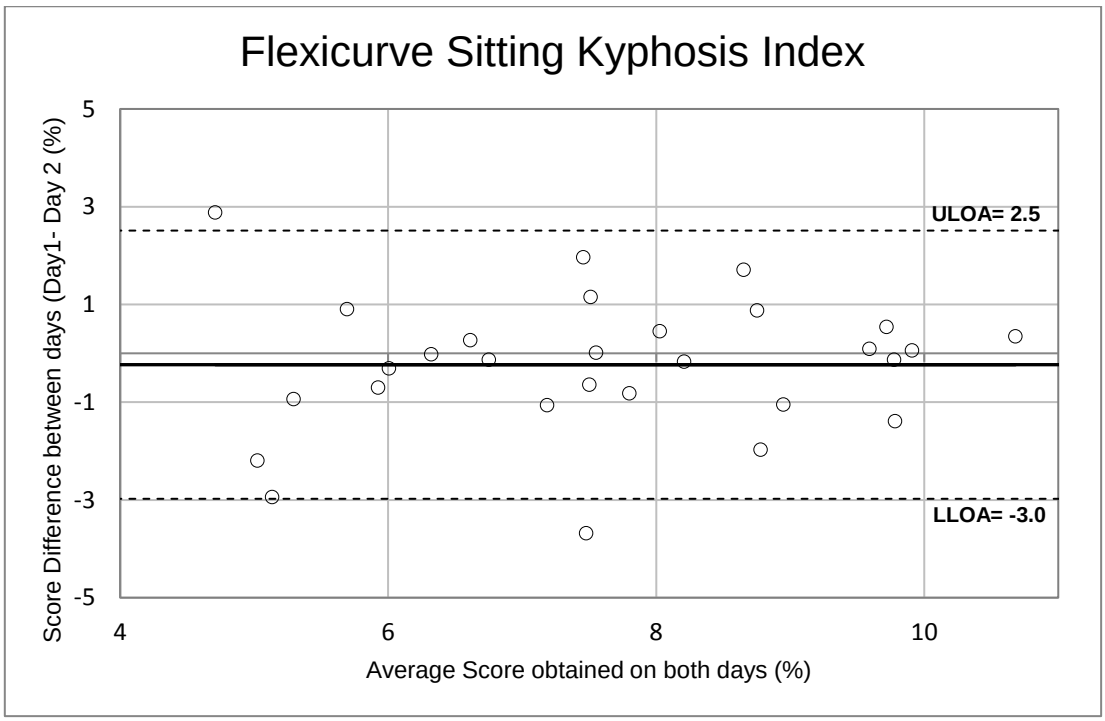
ULOA= Upper Limits of Agreement
LLOA= Lower Limits of Agreement

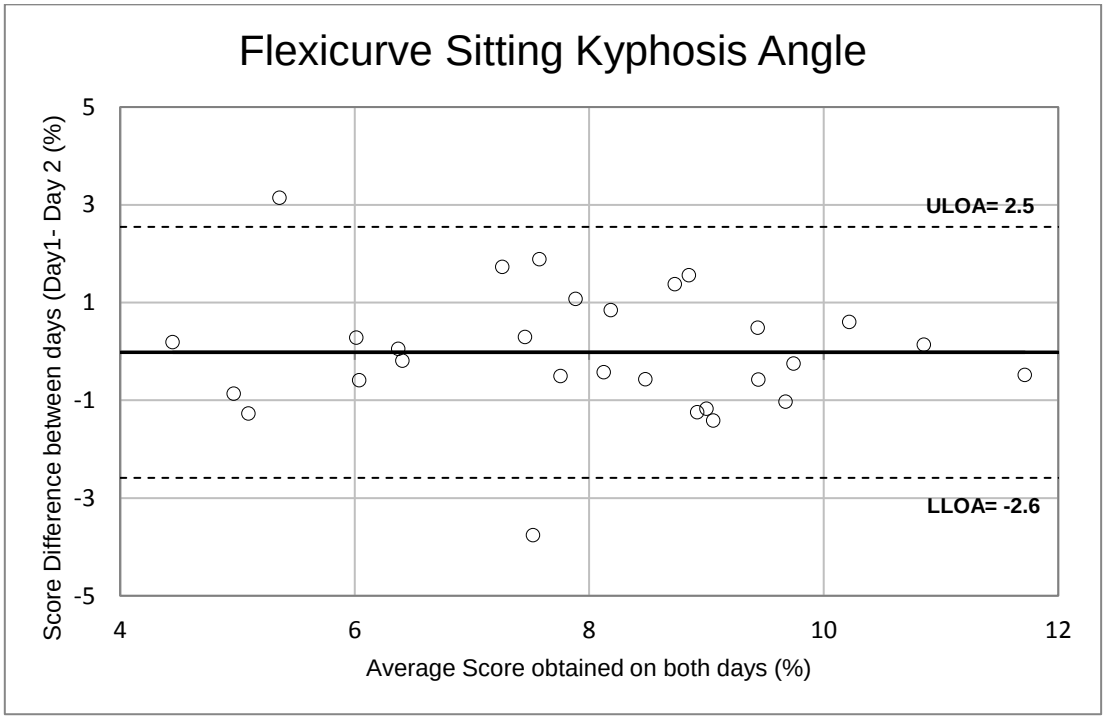
Figures 4-5 Standard Bland Altman LOA Plots (Reliability of the Flexicurve)





ULOA= Upper Limits of Agreement
LLOA= Lower Limits of Agreement





ULOA= Upper Limits of Agreement
LLOA= Lower Limits of Agreement

4.7 Discussion

The results of this study demonstrate that the Kinect™ is both valid (ICC= 0.76-0.82) and reliable for measuring thoracic kyphosis in standing and sitting positions in healthy adults. These promising results provide new avenues and opportunities for both researchers and clinicians to measure thoracic kyphosis accurately and efficiently. We propose that the Kinect™ has advantages over the use of the Flexicurve and may potentially overcome some barriers of previous measuring tools to facilitate the routine measurement of thoracic kyphosis.

The most significant advantage of the Kinect™ over the Flexicurve is that the image obtained by the Kinect™ can be processed within seconds with almost instant results. This is in contrast to the Flexicurve, which requires the user to download the image file to the computer where a program (eg. Image J) (Schneider et al., 2012) is used to process the image to obtain the relevant data. Therefore, given the overall ease-of-use and excellent accuracy, we anticipate that the Kinect™ has the potential to boost the frequency and confidence of use in the clinical setting. Noteworthy, customised software is needed for data collection and plans are now being considered to make the software publicly available.

However the Kinect is not without disadvantages. A minor disadvantage of the Kinect™ over the Flexicurve is that it is more costly, however, it remains affordable and readily accessible (US $150) for many potential users. Although the Kinect™ is portable and assessment may be performed anywhere, the Kinect™ requires calibration, which takes about 5-10 minutes to complete. Moreover the Kinect needs a power supply and this may be a problem in some homes depending on the home set up. Therefore, it may not be suitable for clinicians who are required to travel (e.g. home therapy) but would be ideal for an outpatient clinic setting. In order to reduce the time needed for repeated calibration, we recommend a designated area for assessment.

4.8 Limitations

The major limitations of our study are that we did not compare the Kinect™ to the gold standard of radiological images, and that we used a healthy population. Although the flexicurve has been used in large epidemiological studies to measure kyphosis in older adults (Kado et al., 2009), we acknowledge that compared to radiological images and 3D-motion analysis, the flexicurve is inferior. Future research should consider validating the Kinect™ against radiological images in older adults or patients who have spinal pain or deformities.

4.9 Conclusion

In conclusion, the Kinect™ is comparable to the Flexicurve and is valid and reliable to measure thoracic kyphosis. Given that the Kinect™ is widely accessible and has advantages of ease-of-use over the Flexicurve, the Kinect™ has the potential to facilitate the routine evaluation of thoracic kyphosis, thereby enhancing evidence-based clinical practice.

Chapter 5 is adapted from the following publication
(Appendix 3 URL Link to Published Paper)

Quek J, Treleaven J, Brauer SG, O'Leary S, Clark RA
"Intra-rater reliability of hallux flexor strength measures using the Nintendo Wii Balance Board".
Journal of foot and ankle research. 2015; 81:48.

Chapter 5: Study 3 Intra-rater reliability of hallux flexor strength measures using the Nintendo Wii Balance Board

Hallux flexor strength has been shown to be an independent predictor of postural control in older adults but there are limited tools available that accurately measures this group of muscles. This study assessed the intra-rater reliability of a newly developed Nintendo Wii Balance Board application to measure hallux flexor strength.

5.1 Introduction/Background

Hallux flexor muscle strength is a significant determinant of balance and functional ability in older adults (Spink et al., 2011) and an independent predictor of falls in this population (Mickle, K. J. et al., 2009). Whilst hallux flexor strength is mainly contributed by flexor hallucis longus and flexor hallucis brevis (FHB) muscles, attention is drawn towards FHB because it is one of the intrinsic foot muscles that is thought to be essential for the stability of the longitudinal foot arch (Soysa et al., 2012). As such training hallux flexor strength has been shown to improve balance (Kobayashi et al., 2001) and potentially reduce falls in the elderly. However, assessment of intrinsic muscles of the foot with respect to the prevention of falls is largely neglected in clinical and research settings (McKeon et al., 2014). This is unfortunate as falls in older adults are prevalent (Hausdorff et al., 2001) and present a substantial health problem for society (Lajoie & Gallagher, 2004).

One of the challenges encountered by researchers and clinicians is the difficulty in selectively measuring the strength of intrinsic foot muscles. Previous methods to measure the strength of the intrinsic foot muscles such as the paper grip test (Menz et al., 2006a), plantar pressure sensors (Menz et al., 2006b), and various dynamometry methods (Kwon et al., 2009; Senda et al., 1999; Spink et al., 2010; Unger & Wooden, 2000) are of questionable validity due to the difficulty in separating intrinsic and extrinsic foot muscle activity during testing (Soysa et al., 2012). It has been suggested that these methods may promote flexion of the interphalangeal joint during strength tests, a movement that is thought to result from extrinsic foot muscle activity (Garth JR & Miller, 1989). In a review article, Soysa and colleagues (2012) have recommended the use of hand-held dynamometry (HHD) to measure toe flexor strength as it permits concurrent metatarsophalangeal (MTP) joint flexion and interphalangeal joint extension and thus minimises the contribution of the extrinsic muscles. However, previous study using the HHD did not report any efforts in

stabilising the foot or toe to minimise the extrinsic foot muscles contribution (Spink et al., 2009), thereby questioning the validity of their methodology.

A potentially useful tool which could replicate a HHD assessment of hallux flexor muscle strength is the Nintendo Wii Balance Board (NWBB). The NWBB contains four individual strain-gauge type load cells and is a reliable measurement tool to assess balance (Clark et al., 2010) and other weightbearing parameters such as asymmetry (Clark et al., 2010; Clark et al., 2011). Using the NWBB to assess hallux flexor muscle strength is therefore particularly appealing, because if it is shown to be valid it could be used as a centrepiece tool for assessment of multiple components of balance and falls risk. The purpose of this study is to evaluate the use of the NWBB when combined with a purpose built platform for the measurement of hallux flexion strength. Specifically, we assessed the intra-rater reliability of hallux flexor strength measurements using this new method. We hypothesised that this method will provide reproducible measurements of hallux flexion strength as the NWBB/platform configuration minimises extraneous foot movement, thereby improving selectivity of the intrinsic foot muscles (Garth JR & Miller, 1989).

5.2 Methods

5.2.1 Participants

Thirty healthy individuals between 22 to 68 years (mean age: 34.9 ± 12.9 years, height: 170.4 ± 10.5 cm, weight: 69.3 ± 15.3 kg, female= 15) were recruited by convenience sampling. The examiner visually inspected the foot and ankle to ensure that the participants did not have any foot deformities. Participants reported that they did not have any acute foot or ankle injuries over the past three months that may affect the consistency of their maximal performance. All participants gave informed consent as outlined by the institution's Human Research Committee and all procedures were conducted according to the Declaration of Helsinki.

5.2.2 Equipment

For the purpose of this study a NWBB was turned upside down and one of its four load cells was utilised for all measurement procedures (Figure 5-1). The NWBB was interfaced via Bluetooth with a customized software program on a Windows computer, and the force data (in kg) was derived using the internally stored calibration information unique to each NWBB. To improve the accuracy of these data, the value derived from the load cell used in the measurement of force was re-calibrated in the testing position. This consisted of applying a range of known loads (0.1-20 kg) to the load cell. A regression equation

evaluating the relationship between expected force and that obtained from the NWBB load cell exceeded $R^2 = 0.999$, demonstrating the accuracy of the equipment consistent with a previous study (Clark et al., 2010).

To ensure accurate positioning of the hallux onto the load cell, and to minimise the influence of the extrinsic muscles of the foot (ankle plantarflexors and flexor hallucis longus) and the 2nd to 4th toes, a purpose-built wooden platform was constructed and positioned under the NWBB. As shown in Figure 5-2 this permitted the tested foot to be positioned such that the proximal metatarsophalangeal joint of the big toe was at the edge of the platform, and a Velcro strap was used to secure the anterior section of the foot onto the platform. To prevent the heel from lifting adhesive Velcro tape was applied under the participant's heel and fixed onto Velcro fastened to the platform, and the participants thigh was additionally strapped to the platform with a non-elastic belt (Figure 5-1). Excessive adduction moments from the big toe were minimized by a toe separator made of smooth plastic that was positioned between the first and second toes and fastened to the platform (Figure 5-2). Finally, a circular wooden block of 2.8 cm in diameter was placed over the NWBB load cell to ensure the application point of the load cell was level with the platform and therefore the hallux positioned in its anatomic neutral position for testing.

5.2.3 Procedure

To assess intra-rater reliability all participants attended two measurement sessions spaced 1-7 days apart. All procedures on both days were identical and supervised by the same physiotherapist (JQ) who has postgraduate qualifications and 13 years of clinical experience in the musculoskeletal field. Participants were seated on a firm chair positioned on the wooden platform (See Figure 5-1). The sitting position was standardised using high density foam mats if required, (0 to 4 mats, 1.2 cm in depth each) and positioned on the chair to ensure 90 degrees of hip and knee flexion (Soma et al., 2014). The dominant foot was then positioned accurately on the platform and the other foot also rested on the platform.

Participants were given one warm-up trial where they were instructed to apply 50% of their perceived maximal effort. Participants then performed a minimum of three trials at maximal effort with a 1-minute rest period between trials to minimize muscle fatigue. Participants were blinded to the results throughout the testing procedure. Standardised instructions were given throughout testing to; (i) keep the heel planted on the platform, (ii) avoid leaning backwards or forwards at the trunk (iii) avoid flexion at the interphalangeal joint of the big toe and (iv) apply a vertical downward force at the interphalangeal joint of the big toe. To minimize movement from the foot, a Velcro strap was firmly secured across the

foot and fixed onto the platform between the first metatarsophalangeal joint to the middle of the arch (see Figure 5-2).

To prevent the heel from lifting, besides giving standard instructions, the heel was fixed using a strap placed over the knee. This was also assisted by the fact that the Velcro under the heel would make a sound if the participant raised the heel (indicating use of the calf muscles) during testing. The examiner was alerted to this incorrect manoeuvre by the sound of the Velcro that held the heel to the platform separating. In the event of this occurring the trial would be discarded and repeated. Testing was ceased when three consistent measures were obtained (no greater than 20% difference in measures) or a maximum of 6 trials had been performed. The average of three consistent measures was calculated. Strength was measured in kilograms.

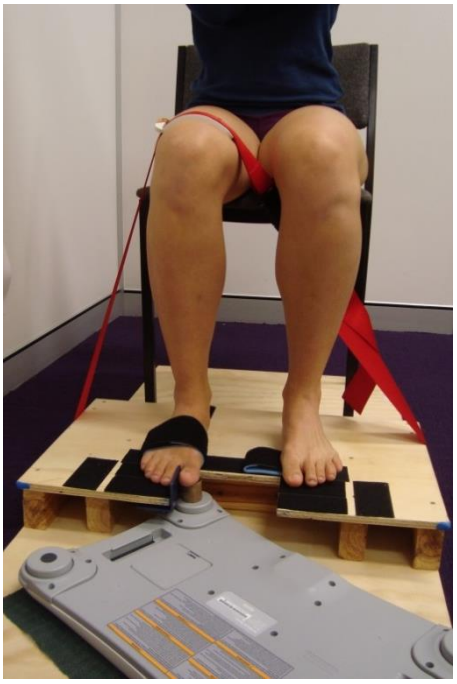


Figure 5-1 Experimental set up for strength testing of the flexor hallucis muscle of the right foot.

Figure 5-2 Close up image of the position of the foot on the platform

The foot is secured with Velcro and the position of the sensor placed under the interphalangeal joint of the big toe.

5.2.4 Sample Size

We determined the sample size of 30 participants using the method proposed by Walter et al s(1998). This was calculated based on a minimum acceptable reliability of 0.70 and an expected ICC value of 0.90 in a test-retest (k=2) design, with alpha level (1-tailed) of 0.05 and power of 95%.

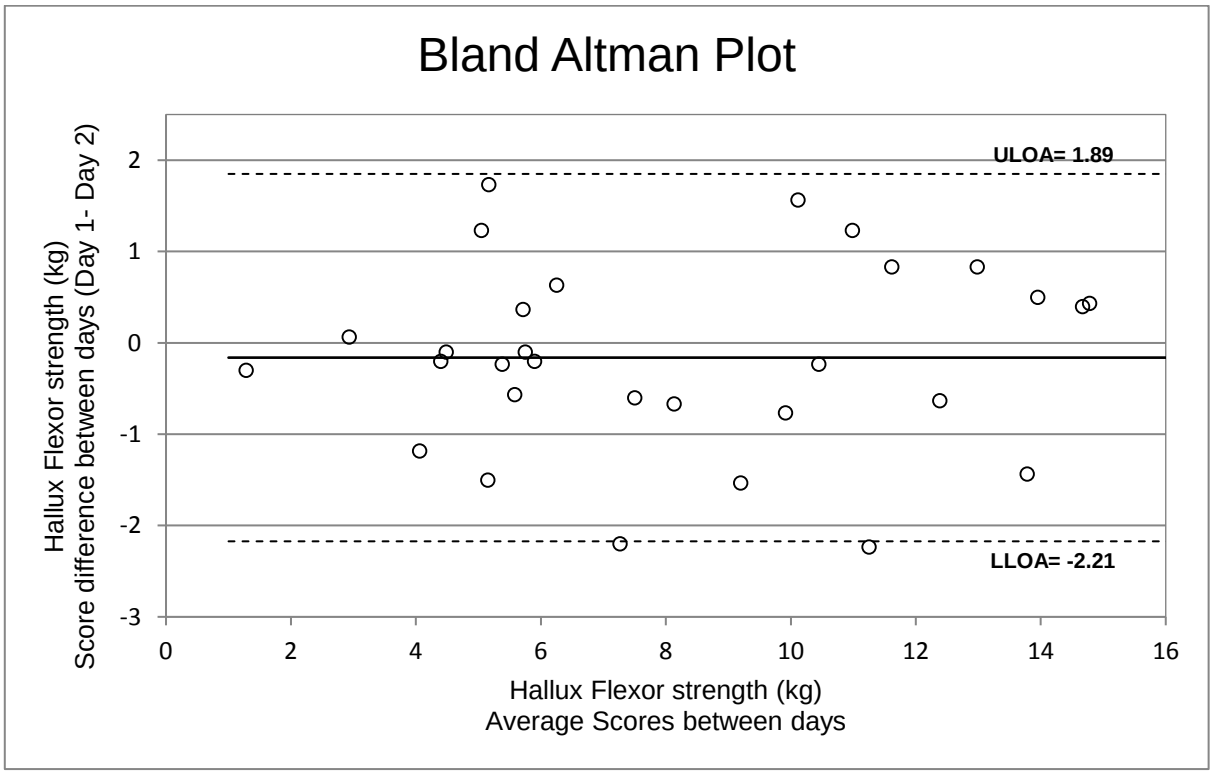
5.3 Statistical analyses

Visual inspection for bias and heteroscedasticity was performed by examining a generated Bland-Altman plot for the difference between the scores obtained on both days against their means. Intra-rater reliability was calculated using intra-class coefficients (ICC [3,3]) and Ordinary Least Product (OLP) regression analysis. To calculate ICC, two-way analysis of variance based on absolute agreement was performed. ICC values of >0.75 were considered excellent, 0.40 to 0.75 modest or <0.40 poor (Fleiss, 1986). Next, systematic biases (proportional and fixed biases) were determined using OLP regression analysis (Ludbrook, 2002). To estimate measurement error, standard error of measurement (SEM), 95% limits of agreement (LoA), and minimal detectable change (MDC) calculations were performed.

5.4 Results

The results are presented in Table 5-1. This new method of hallux flexor strength measurement demonstrated excellent intra-rater reliability (ICC=0.982, 95% CI= 0.96 to 0.99) with percentage error of 12% and no presence of systematic bias and no evidence of heteroscedasticity. The LOA plot is presented in Figure 5-3.

Figure 5-3 Agreement analysis of measurements between days by Bland Altman plot



ULOA= Upper Limits of Agreement
LLOA= Lower Limits of Agreement

Table 5-1. Mean strength recordings (± SD) and reliability coefficients for hallux flexor muscle strength measurement

	Wii Board Day 1 (Mean ± SD)	Wii Board Day 2 (Mean ± SD)	ICC (3,3)	Spearman's ρ*	95% CI	Systematic Bias (CI)	Width of 95% LoA	% Error†	SEM	MDC	Prop Bias€	Fixed Bias
Toe Strength (kg)	8.12 ± 3.86	8.28 ± 3.80	0.982	0.933	0.96 to 0.99	None	2.01	12	0.5	1.4	No	No

SD = standard deviation; ICC = intra-class coefficients; LoA = limits of agreement; SEM = standard error of measurement; MDC = minimal detectable change; €Prop Bias= Proportional Bias, CI= Confidence Interval

†% Error= 0.5*Width of 95% LOA/[(MeanDay1+MeanDay2)/2]*100

*All correlations were p<0.001

ᵈProp and fixed bias were determined from ordinary least products analysis.

SEM= SD√(1-ICC)

MDC=SEM X 1.96 X √2

WMS= Mean Square Error term from ANOVA

5.4 Discussion

In this study a new method of measuring hallux flexion strength with an emphasis to selectively measure flexor hallucis brevis (an intrinsic foot muscle) strength using the NWBB was described and intra-rater reliability of this method was investigated. The findings suggest this new method reliably measures hallux flexion strength (ICC=0.982). Moreover the method is inexpensive and straight-forward to set up and therefore has application for research and clinical settings. Furthermore, the NWBB has other useful applications such as for balance assessment (Clark et al., 2010) and rehabilitation (Gil-Gómez et al., 2011), and therefore has diverse clinical and research utility.

To address issues of previous studies (Soysa et al., 2012) the method described in this study attempted to minimise compensatory strategies from the trunk and ankle, as well as extrinsic muscles of the foot, from confounding accurate measurement of the intrinsic foot muscle strength. Specifically we attempted to minimise extrinsic foot muscle activity by localising toe flexion at the MTP joint and extension at the interphalangeal joint (Soysa et al., 2012). This resulted in force being applied to the load cell under the interphalangeal joint. Strength trials were subsequently ceased and discarded if toe curling was observed. Performing the test in this manner is proposed to optimise selective activity of the FHB, an intrinsic foot muscle, with minimal contribution from the extrinsic foot muscles (Garth JR & Miller, 1989), although future electromyographic studies are required to validate this proposition.

From a clinical perspective this new method permits an accurate and selective measure of flexor hallucis brevis muscle performance, and could have positive implications for clinical assessment and rehabilitation. This is particularly relevant in light of evidence suggesting that improved intrinsic foot muscle strength is associated with improved dynamic support of the medial longitudinal arch and balance (Mulligan & Cook, 2013). From a statistical perspective, it is useful to note that the percentage error of 12% would suggest that any differences observed in flexor hallux strength following an intervention must exceed 12% in order to indicate that a real change has occurred.

5.5 Limitations

This study has some limitations. Firstly we did not assess the inter-rater reliability of the method which potentially limits the applicability between observers. Secondly, although all effort was taken to ensure that participants did not use compensatory strategies by using appropriate physical restraints and standardised instructions, it was not possible to know if

the experimental set-up was able to separate the extrinsic and intrinsic foot muscle activity, which will need to be investigated in future studies. Similarly, while we attempted to minimise adduction of the big toe by using a smooth plastic separator between the first and second toes, it was not possible to separate the influence of toe adduction moments during measurements.

5.6 Future Considerations

Given that the purpose of this study was to test the reliability of within-subject measures across 2 time-points, we did not need to include variables such as foot arch height and length, the size of interphalangeal joint prominence, the length of the first MTP shaft and the range of motion of MTP joint. However these are important when comparing between subjects, and should be considered in future studies.

5.7 Conclusions

Despite the growing evidence of the importance of maintaining hallux flexion strength for optimal gait and balance in older adults (Misu et al., 2014; Spink et al., 2011), it remains poorly addressed in rehabilitation (McKeon et al., 2014). The results of this study demonstrate that hallux flexion strength can be reliably assessed using a NWBB application. Given that hallux flexion strength may be an indicator of intrinsic foot muscle performance, this method utilising the NWBB is of great potential for future research and clinical application. Potentially this method may also have application for other foot conditions requiring accurate measurement of hallux flexion strength.

Chapter 6 is adapted from the following publication

(Appendix 4 URL Link to Published Paper)

Quek J, Brauer SG, Clark R, Treleaven J

"New insights into neck pain-related postural control using measures of signal frequency and complexity in older adults"

Gait and Posture 2014; 39(4), 1069-1073.

Chapter 6: Study 4 New insights into neck pain-related postural control using measures of signal frequency and complexity in older adults

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The mechanisms underlying postural control impairments in NP are not yet well understood but are important especially in older adults who may have a high risk of falls. This study aimed to gain new insights to these mechanisms by exploring new analytical techniques of postural control measures in static standing in older adults with and without NP.

6.1 Introduction

There is growing evidence to implicate the role of the cervical spine in influencing postural control, with most studies demonstrating greater postural sway in people with NP when compared with healthy controls (Ruhe et al., 2011). Given that the neck has extensive connections with the vestibular, visual and central nervous systems, balance impairments associated with cervical spine dysfunction are thought to be due to aberrant cervical afferent input causing a mismatch between this abnormal input and normal information from the vestibular and visual systems (Treleaven, 2008). Despite these postulations, the mechanisms underlying NP-related balance impairments remain unclear. Considering that the prevalence of NP is high in the elderly population – approximately 33% and 40% in men and women respectively (March et al., 1998), and older adults are at high risk of falls (Tinetti & Williams, 1998), an in-depth understanding of the mechanisms underlying the effects of NP on postural stability is warranted.

One issue that limits clear understanding of these underlying balance mechanisms in NP may be the complexity in interpreting information obtained from standard balance measures. Previous studies investigating the effects of NP on postural control have mostly employed traditional measures such as centre-of-pressure (CoP) displacement, velocity and area (Ruhe et al., 2011). This assumes that CoP displacement is a good proxy for postural performance and that conventionally, lower CoP sway parameters indicate greater postural stability (Ruhe et al., 2011). However, this assumption can be challenged, with the argument that a decrease in sway parameters may also result from an increased-body stiffness that may be associated with a fear of falling (Carpenter et al., 2001). As such, traditional balance measures have been criticised for their limitations in detecting context-dependent postural performance changes because they fail to capture the richness of postural data (Chagdes et al., 2009). Consequently, this demonstrates a need for additional measures to better

describe postural performance (Lacour et al., 2008). Based on these reasons, studies have employed analytical approaches such as “rambling and trembling” decomposition of a stabilogram (Juul-Kristensen et al., 2013; Röijezon et al., 2011), wavelet analysis and sample entropy in order to better depict changes in postural stability in NP (Liang et al., 2014; Madeleine et al., 2011; Quek et al., 2013). “Rambling and trembling” represent dynamic components of CoP. An increase in the slow component in patients with chronic NP is argued to reflect increased sensory input and processing (Jorgensen et al., 2011). An increase in the fast component is thought to reflect normal centre-of-mass control in healthy individuals but the mechanisms underlying whiplash remains unknown(Juul-Kristensen et al., 2013).

Wavelet transform is an analytical technique which decomposes the postural sway data into multiple independent frequency bands (Chagdes et al., 2009), where each frequency band is postulated to represent involvement of a physiological domain. Specifically, CoP signals in four distinct bandwidths ranging from moderate to ultralow frequency have been identified (Liang et al., 2014) based on the hypothetical physiological significance of postural movements associated with muscular proprioception (Lacour et al., 2008; Paillard et al., 2002), the cerebellar (Paillard et al., 2002), vestibular (Oppenheim et al., 1999) and visual systems (Chagdes et al., 2009). For instance, a high proportion of activity in the ultralow (<0.10Hz) and moderate (1.56-6.25Hz) frequency bandwidths have been associated with increased use of vision (Chagdes et al., 2009) and increased muscular activity in response to proprioceptive input (Paillard et al., 2002) respectively.

We have performed two recent, neck-related experimental studies using wavelet analysis. One assessed the effects of neck muscle fatigue on postural control in healthy subjects, and demonstrated that fatigue significantly increases the energy in the ultralow and moderate frequency bandwidths of the signal (Liang et al., 2014). The second study compared postural control between people with NP, with and without asymmetry of cervical spine range of motion, with the asymmetry group demonstrating standing postural sway skewed towards ultralow frequencies (<0.10Hz) (Quek et al., 2013). In the context of this study, the difference in postural control strategy adopted by the asymmetrical group was potentially due to altered proprioceptive input and processing arising from cervical spine dysfunction. Consequently, based on the association between ultralow frequency and visual input, and given that both groups had similar levels of function, we speculated that the postural strategy adopted by the asymmetrical group was adaptive and that this group may be relying on the visual system to achieve these compensations. Despite these novel

findings, and because this study lacked a concurrent control group, clear conclusions could not be drawn concerning these postural control mechanisms. Our current study extends prior research by (i) using additional analytical techniques of wavelet analysis and sample entropy, and (ii) incorporating a control group, to further investigate postural mechanisms in this population.

Sample entropy uses non-linear time-dependent analysis that can quantify the complexity or regularity of the CoP signal (Borg & Laxaback, 2010), with higher entropy suggested to reflect increased complexity and greater efficiency in postural control (Borg & Laxaback, 2010). Sample entropy has been investigated in a small number (n=11) of whiplash patients (Madeleine et al., 2011), with a trend towards decreased complexity of CoP motion during eyes closed standing balance when compared to control participants, however there remains a paucity of evidence in populations with NP.

Against this background, we aimed to explore possible mechanisms underpinning impaired standing balance in older adults with NP using wavelet analysis and sample entropy. We hypothesized that older adults with NP will demonstrate reduced postural stability compared to healthy controls, wavelet analysis will reveal an increased proportion of ultralow frequency postural movement, indicating increased visual system dependence for postural stability, an increased proportion of moderate frequency postural movement, indicating changes to muscular proprioceptive input, and finally, sample entropy will demonstrate decreased signal complexity.

6.2 Methods

6.2.1 Participants

This cross-sectional study involved 40 older women with (n=20, age=70.3±4.0 years) and without (n=20, age=71.4±5.1 years) NP. Participants >65 years reporting chronic NP for ≥3 months, and with a neck disability index (NDI) of ≥10, were recruited from the Brisbane metropolitan area using convenience sampling. Subjects were excluded if they had a history of falls, recent orthopaedic surgery, diabetes, neurological or vestibular pathology, visual impairments not corrected by prescriptive lenses, arthritis that required active management, acute musculoskeletal injuries, or were taking more than four medications. All participants provided informed consent as outlined by the Medical Ethics Committee of the University of Queensland and all procedures were conducted according to the Declaration of Helsinki.

6.2.2 Questionnaires

Age, weight, number of medications, number of co-morbidities and other demographic details were obtained. The Neck Disability Index (NDI) (Vernon & Mior, 1991a) was used to assess the degree of self-reported NP and disability (Vernon, 2008; Vernon & Mior, 1991a). The NDI has been shown to be a valid and reliable tool consisting of 10 questions related to an individual's activities of daily living and recreational activities in those suffering from NP (Appendix 8).

6.2.3 Standing Balance

Standing balance was assessed using a force platform (400x600mm Kistler 9286A, Switzerland). Participants were instructed to stand as still as possible while looking straight ahead, in a standardized position 1.5m away from a wall with arms by their side. Foot position for comfortable stance was repositioned exactly using a paper trace as described by McIlroy and Maki (1997). One trial of 30-seconds was performed with eyes open then closed in standing. This test duration is sufficient to demonstrate differences between NP (idiopathic NP and whiplash) and controls (Field et al., 2008). Force platform signals were analog-to-digital converted at a sampling rate of 100Hz and recorded using a LabVIEW (National Instruments, U.S.A.) programme and a USB-6008 (National Instruments, U.S.A.) data acquisition system.

6.2.4 CoP Measures

The CoP measures consisted of:

a) Discrete wavelet transform, a signal processing method that separates the CoP data into multiple independent signals based on frequency content (see Appendix 9 for technical details). Specifically, the signal is spilt into four bands: 1) moderate (1.56-6.25Hz), 2) low (0.39-1.56Hz), 3) very-low (0.10-0.39Hz), and 4) ultralow (<0.10Hz) frequency. These frequency ranges are believed to capture postural movements associated with the muscular proprioception (moderate) (Paillard et al., 2002), cerebellar (low) (Paillard et al., 2002), vestibular (very-low) (Oppenheim et al., 1999), and visual systems (ultralow) (Chagdes et al., 2009) respectively. Signal bandwidths were separated using a 9-level Symlet-8 wavelet, with multiresolution analysis used to combine detail levels where necessary. In order to better represent the spectral content of the data, we took into account inter-individual variability by expressing the CoP velocity of each frequency band as a percentage of the overall CoP velocity.

b) Sample entropy, a measure of the complexity of the CoP signal. Specifically, higher sample entropy values are indicative of greater signal complexity (Borg & Laxaback, 2010). The increment (i.e. instantaneous velocity) data were analysed using the input parameters m=3 and R=0.30 to remove the long-term correlations in the signal and improve robustness to sampling rate and noise (Ramdani et al., 2009). Data were analysed using a custom program combining LabVIEW (National Instruments, U.S.A.) and Matlab (Mathworks, U.S.A.) code for sample entropy freely available at physionet.org.

This study focused on CoP signals in the anterior-posterior (AP) direction because previous studies have shown that postural sway in the AP direction was more sensitive than the medio-lateral direction in detecting NP-related balance deficits (Ruhe et al., 2011).

6.2.5 Secondary balance measures

Two performance-based clinical balance measures were also included: (i) the Timed Up and Go (TUG) (Viccaro et al., 2011) and (ii) the Dynamic Gait Index (DGI) (Herman et al., 2009). TUG test evaluates functional mobility skills has been shown to be a sensitive and specific measure for identifying older adults who are at risk of falls (Shumway-Cook et al., 2000). TUG time of ≥12.6 is associated with a higher risk of future falls (Kojima et al., 2015). The DGI test assesses one's ability to modify gait in response to changing task demands and has demonstrated excellent inter-rater and test-retest reliability (Shumway-Cook, Anne et al., 1997). A score of ≤19/24 indicates a higher risk of falls (Shumway-Cook, A. et al., 1997).

6.3 Statistical Analyses

Descriptive statistics characterized the study population and their clinical characteristics. Wilcoxon-Mann-Whitney or Welch-t test was used to compare the continuous data between groups as the data did not fulfil the assumptions of normality. In sensitivity analyses, potential confounding factors of age and number of medications were accounted for by comparing the 2 groups on the CoP measures using multiple regression analysis. All statistical analyses were completed using PASW software, version 21. Statistical significance was determined at the 2-sided 0.05 level.

6.4 Results

Table 6-1 compares the demographic and clinical variables for the two groups. Older adults with NP showed greater use of medications ($p = 0.015$), slower walking speed during the TUG test ($p < 0.001$) and poorer scores on the DGI ($p = 0.008$). By design, NDI levels were significantly higher in the NP group than healthy controls ($p < 0.001$)**.** As indicated in

Table 6-2, the wavelet-derived percentage velocity signal in CoP measures represented by the very-low frequency bandwidth (0.10-0.39Hz) was 27% and 54% greater in the eyes open and closed conditions respectively in the NP group when compared to the healthy controls (Figure 6-1). In contrast, the percentage velocity signal in CoP measures represented by the moderate frequency bandwidth (1.56-6.25Hz) in the NP group was 7% and 17% lower in eyes open and closed conditions respectively than that of the healthy controls (Figure 6-1). These observed between-group differences persisted after adjustment for age and number of medications taken (Table 6-2). There were no significant differences between groups in the ultralow and low frequency bandwidths. Noteworthy, when the wavelet results were compared between groups using absolute values, there were no differences across all frequencies. When sample entropy measures were compared, there was a trend towards decreased complexity in the NP group compared to the healthy controls in the eyes closed condition (p = 0.051), but no differences with eyes open (Table 6-2).

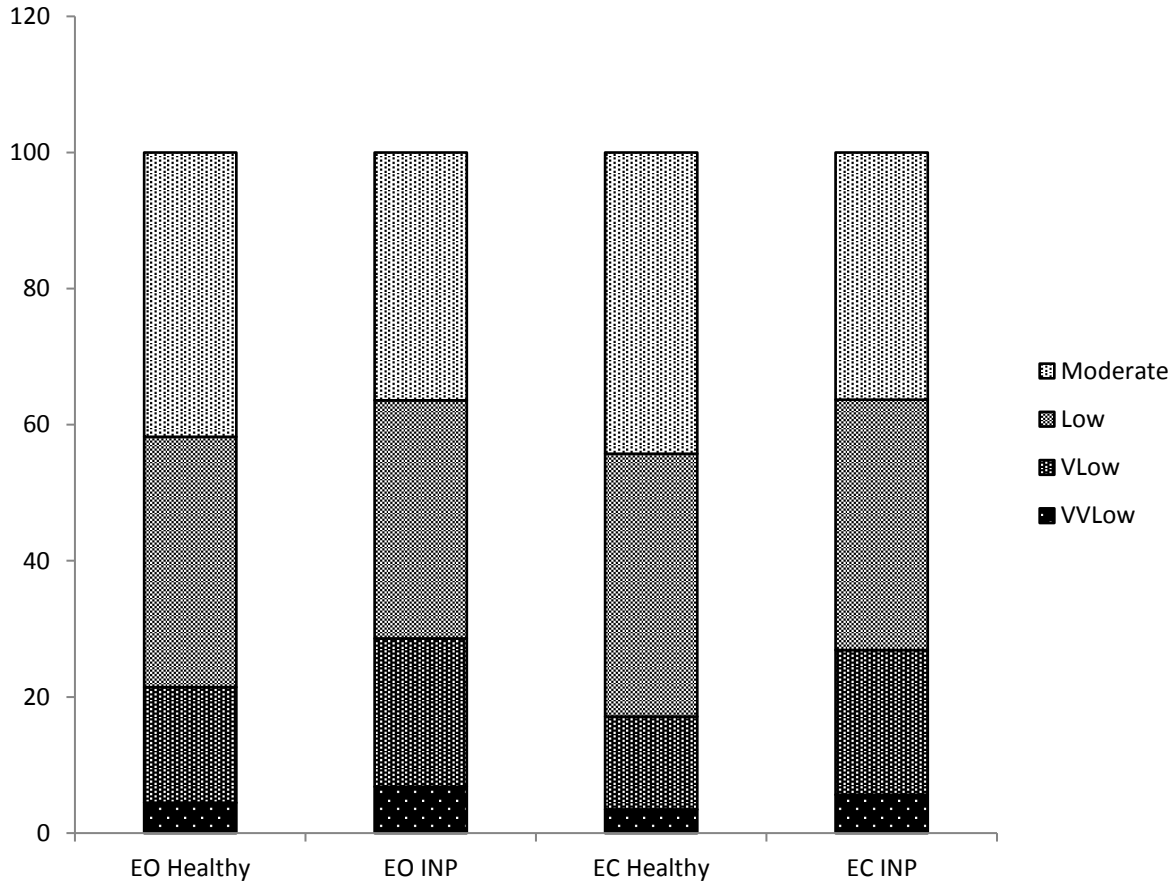


Figure 6-1. Each group within each condition is represented by a vertical (100%) stacked column showing the proportion of individual component of each frequency band. EO: Eyes open, EC: Eyes closed.

Table 6-1 Characteristics and comparison of Neck Pain and Healthy subjects

Clinical characteristics	NP (n = 20)	Healthy (n = 20)	*p*-Value
Age (mean, SD) years	70.80 ± 4.1	71.40 ± 5.1	0.429
Weight (mean, SD) kg	66.27 ± 11.9	67.70 ± 10.1	0.769
NDI (mean, SD), (%)	23.60 ± 10.2	3.00 ± 3.5	0.000
Number of co-morbidities, n (%)			
0	0 (0)	1 (5)	0.112
1	1 (5)	6 (30)	
≥2	19 (95)	13 (65)	
Medication, n (%)			
0	2 (10)	6 (30)	0.015
1-2	7 (35)	10 (50)	
≥3	11 (55)	4 (20)	
DGI (mean, SD)	18.70 ± 1.7	21.35 ± 2.0	<0.001 (<0.001*)
TUG (mean, SD)	8.74 ± 1.5	7.70 ± 1.1	0.008 (0.032*)

NDI: Neck Disability Index
DGI: Dynamic Gait Index
TUG: Timed Up & Go
**Adjusted P values for age and number of medications using multiple regression analysis*

Table 6-2 Comparison of CoP measures between Neck Pain Subjects and Healthy Controls

	Eyes Open		*p*-Value	Adjusted *p*-Value*	Eyes Closed		*p*-Value	Adjusted *p*-Value*
	Neck Pain	Healthy			Neck Pain	Healthy		
AP Axis								
Velocity (cm/s)	4.23 ± 1.2	4.67 ± 1.7	0.440	0.411	5.57 ± 2.0	6.36 ± 2.8	0.411	0.410
SD (cm)	2.55 ± 1.3	2.33 ± 0.9	0.536	0.759	3.30 ± 1.9	2.30 ± 1.1	0.049**	0.113
Wavelet (%)								
<0.10 Hz (%) †	6.46 ± 6.0¥	4.44 ± 1.8	0.164	0.583	5.63 ± 3.5	3.48 ± 1.7	0.021	0.059
0.10-0.39 Hz (%)†	21.48 ± 5.3	16.98 ± 4.5	0.006***	0.039**	20.95 ± 7.1	13.61 ± 3.4	0.000***	0.000***
0.39-1.56 Hz (%)†	35.28 ± 7.2	36.82 ± 4.2	0.413	0.303	36.91 ± 6.2	38.65 ± 6.1	0.376	0.675
1.56-6.25 Hz (%)†	38.79 ± 7.3	41.75 ± 5.8	0.023**	0.039**	36.51 ± 6.6	44.25 ± 8.2	0.002***	0.012**
Wavelet (absolute)								
<0.10 Hz (%)	0.33 ± 0.1	0.48 ± 0.4	0.138	0.729	0.34 ± 0.22	0.55 ± 0.40	0.052	0.138
0.10-0.39 Hz (%)	1.31 ± 0.5	1.62 ± 0.6	0.099	0.155	1.32 ± 0.46	2.08 ± 1.22	0.016	0.251
0.39-1.56 Hz (%	2.96 ± 1.2	2.75 ± 1.2	0.588	0.276	4.07 ± 1.95	3.76 ± 1.65	0.597	0.536
1.56-6.25 Hz (%)	3.31 ± 1.3	2.69 ± 0.7	0.066	0.217	4.66 ± 2.3	3.53 ± 1.4	0.069	0.271
Sample Entropy	1.72 ± 0.1	1.73 ± 0.1	0.485	0.347	1.66 ± 0.1	1.73 ± 0.1	0.051	0.117

Values are mean ± standard deviation
**Adjusted P values for age and number of medications using multiple regression analysis.*
†Frequency band measures are expressed as percentages.
CoP: Center of pressure, SD: standard deviation, AP: anteroposterior.
EO: Eyes open, EC: Eyes closed.
¥High standard deviation due to 2 outliers. Results remained insignificant between groups even if outliers were removed.
***p<0.05*
****p<0.01*

6.5 Discussion

In this exploratory cross-sectional study, wavelet analysis showed that the very-low frequency content was significantly higher and the moderate frequency lower in the NP group than in the healthy controls under both visual conditions. Furthermore, sample entropy results showed trends towards decreased complexity in the NP group compared to the healthy controls, but this did not reach statistical significance. Older adults with NP demonstrated worse scores on performance-based balance measures (TUG and DGI) than the healthy controls, confirming that balance deficits did exist in this population. Noteworthy, the mean DGI scores of ≤19 revealed an increased fall risk in older adults with NP as compared to healthy controls (Shumway-Cook, A. et al., 1997). This is a clinically important and relevant finding and highlights the importance of developing a clear understanding of NP-related balance deficits, a topic that has received scant attention to date.

The results of our study however, did not support our hypothesis. No differences were observed in the ultralow frequency between groups, indicating comparable visual system reliance for postural stability and the proportion of signals in the moderate frequency bandwidth did not increase. Instead, the NP group demonstrated a greater percentage of CoP signal in the very-low (0.10-0.39Hz) and lower percentage of CoP signal in the moderate (1.56-6.25Hz) frequency bandwidth compared to controls in standing with eyes open and closed. There is indirect evidence to indicate that the very-low and moderate frequency bands may be associated with the vestibular (Oppenheim et al., 1999) and muscular proprioceptive systems respectively (Golomer & Dupui, 2000), with a greater proportion of CoP signal in each frequency band suggesting greater reliance on the respective systems.

We infer two possible interpretations of these findings. First, because older adults with NP demonstrate a diminished ability to recruit the muscular proprioceptive system compared to healthy controls (Treleaven, 2008), they rely more on the vestibular system for postural stability. This finding is consistent with expectations that reweighting of sensory input occurs to maintain postural stability (Peterka & Loughlin, 2004). Specifically, in the context of this study, because older adults with NP were not successful in recruiting vision for compensation, the central nervous system re-weighs available sensory information to recruit the vestibular system for balance to a greater degree than healthy controls. Second, the increased sway signal in the very-low frequency band may reflect the characteristic of an exploratory behaviour of the postural control system. Specifically, NP individuals may be deliberately increasing sway in the very-low frequency, in order to “get the vestibular system

up and running" (Roerdink et al., 2011). This concept is not new, as previous authors have suggested that increased postural sway is an exploratory strategy used by the CNS to gain essential sensory information from the environment in both healthy subjects and older adults with NP (Carpenter et al., 2010; Quek et al., 2013).

The results of our study were not consistent with that of Liang et al (Liang et al., 2014). In that study, young asymptomatic adults with neck muscle fatigue increased in moderate and ultralow frequency signals when compared with that pre-fatigue, whereas our study demonstrated a reduced proportion of moderate frequency signal and no difference in ultralow frequency signal in older adults with NP when compared with controls. This discrepancy was not related to differences in numerical details as there were no differences between groups when our wavelet analysis results were expressed in absolute values. Given that our sample size was small, in order to account for inter-subject variability, we believe that expressing our data in percentages may be a better representation of relative contribution of systems to postural control. Noteworthy, our study involved older adults with NP whereas Liang et al. (2014) used young asymptomatic adults. Future research should include the two methods to permit comparison with past literature and to determine which method of analysis would enhance understanding of mechanisms in postural control.

When we reviewed the literature on sample entropy measures specifically in the NP population, we found only one study, and consistent with our results, this study also showed no differences in sample entropy between whiplash and healthy control participants (Madeleine et al., 2011). Despite the paucity of research, we speculate that sample entropy may not be a straightforward measure of postural control because of potential ambiguity in its' interpretation. Specifically, high entropy may indicate increased complexity and hence signs of a healthy vigilant system, or it may be interpreted as an ineffective attentive control of balance (Borg & Laxaback, 2010). Consequently, our study results bring into question the usefulness of sample entropy as a meaningful measure of postural control in the NP population.

Wavelet analysis in older adults with NP has been previously used in the study this data is based on (Poole et al., 2008), however it is important to note that a markedly different method of analysis was employed between studies. Because in the previous study (McIlroy & Maki, 1997) the authors analysed the energy in the signal as a whole (similar to the traditional COP analysis measure of root-mean-square), this method did not offer additional insights to postural mechanisms when compared with traditional balance measures. In

contrast, this current and our previous study (Quek et al., 2013) have investigated postural control mechanisms in people with idiopathic NP using a distinct frequency band breakdown method of wavelet analysis based on the hypothesised movement velocity associated with the independent sensory inputs which regulate postural control.

6.6 Implications

Our study has several implications. First, our study not only confirms the negative impact neck dysfunction has on postural stability, but also supports the theory that the CNS is highly plastic and adaptable and is able to compensate for the lack of one system by relying more strongly on information from the remaining intact subsystems (Walston et al., 2006). Second, the results suggests that older adults with NP may have a reduced ability to recruit the muscular proprioception system and an increased reliance on the vestibular system, thus therapists may need to be mindful of this especially in older adults with NP with known vestibular problems. Third, our study reveals that wavelet-based frequency analysis may provide new insights into postural mechanisms.

6.7 Limitations

Our study has limitations. First, as a preliminary step toward understanding the underlying postural control mechanisms in older adults with cervical spine dysfunction, we adopted a cross-sectional approach. As a result, a causal link between cervical spine dysfunction and postural impairments could not be definitively inferred. Second, even though we inferred from wavelet analysis that the use of muscular proprioceptive system was proportionally reduced compared to controls, we were not able to identify whether the proprioceptive deficits arose from the neck or lower limb musculature or both. Future studies are warranted to determine this. Thirdly, we used an advanced, non-stationary technique (discrete, multi-resolution wavelet transform based filter) to separate the signal. This provides many benefits, including reduced leakage between signal bands and improved stop-band attenuation which means the true signal can be reconstructed. This is very difficult to achieve using a Butterworth filter. However, this uses the cascading filter banks technique, which essentially halves the upper frequency threshold for each subsequent bank to produce its pass-band signals. Consequently, the upper and lower pass-band thresholds are defined by a combination of the sampling rate and the level of the filter bank, which explains why all of our upper and lower thresholds are a division of the sampling rate of 100Hz. While this may not allow the precision of setting the thresholds to a specific desired frequency, we believe that the combination of improved signal separation compared to other methods and the limited knowledge of the exact frequencies in which the distinct

mechanisms of balance occurs, makes this technique sound. However, this results in the limitation that we cannot directly compare our findings to other studies. Fourthly, the frequency widths chosen are unlikely to be strictly limited to a discrete system, and overlap between the signal frequencies and the system they represent may occur. This must be taken into account when interpreting the data. Next, although we took into account the number of impairments in this study, the severity of these impairments was difficult to quantify and analyze given the small sample size. Future studies with larger cohorts may consider including the severity of impairments and their influence on postural control in older adults with NP. Lastly, the type of medication was not specified in this study and may have the potential to influence postural control and ought to be considered in future studies.

6.8 Conclusion

In summary, this study confirmed that older adults with NP demonstrate balance deficits and may be at higher risk of falls. Our findings suggest that, because older adults with NP demonstrate a diminished ability to recruit the muscular proprioceptive system, the CNS reweighs sensory information to recruit the vestibular system to maintain postural stability. Finally, our results advocate the use of wavelet analysis to examine postural mechanisms in people with NP.

Chapter 7 is adapted from the following publication
(Appendix 5 URL Link to Published Paper)

Quek J, Treleaven J, Clark RA, Brauer SG
"Towards understanding factors underpinning postural instability in older adults with neck pain"

Chapter 7: Study 5 An exploratory study examining factors underpinning postural instability in older adults with neck pain

As a preliminary step towards elucidating the basic mechanisms of postural control deficits in NP, this study compared the level of physical activity, lower limb, vestibular and visual function between older adults with and without NP. Wavelet analysis was also employed as a consequence of initial exploratory research in study 1 (chapter 2), to further evaluate the usefulness of this method to give insights to postural control mechanisms.

7.1 Introduction

The cervical spine plays a critical role in sensorimotor function. Abundant mechanoreceptors found in the muscles of the cervical spine are important in integrating multisensory afferent input from the vestibular, visual, proprioceptive and central nervous systems (Treleaven, 2008). Individuals with NP have demonstrated sensorimotor disturbances, amongst which is the negative impact of NP on postural stability (Treleaven, 2008). Of greater relevance is that older adults with NP have demonstrated poor dynamic postural stability which places them at a higher risk of falls (Quek et al., 2014). Given the potential serious consequences of falls and the burden it imposes on public health (Hartholt et al., 2011), this highlights the need for a comprehensive assessment to inform intervention for this population. Unfortunately, there is limited understanding of the fundamental mechanisms underlying this phenomenon of NP-related postural control deficits.

Because of the multi-sensory complex nature of postural control, it is important to explore whether other factors that might negatively impact on postural stability such as physical activity levels, lower limb sensory and motor function, and vestibular and visual function are different in older adults with and without NP. First, level of physical-activity has been negatively associated with onset of NP (Sitthipornvorakul et al., 2015). This finding lends support to the biological plausibility that lower levels of physical activity may be associated with poorer lower limb function such as reduced strength and flexibility (DiPietro, 2001) and consequently contribute to a decrease in postural stability in older adults with NP. Hence, it is important to determine if lower limb function is any different between individuals with and without NP. In particular, big toe flexor strength (Mickle, K. J. et al., 2009), range-of-motion (Mecagni et al., 2000), light touch sensation (Lord & Ward, 1994) and vibration sense at the ankle (Bergin et al., 1995) have been closely associated with postural stability in older adults. Second, a disruption in the dynamics between the intimately blended systems involved in sensorimotor control could be expected in older adults with NP

(Treleaven, 2008). This is because there is potential for not only cervical proprioception to be diminished but also a progressive decline in vestibular, visual and central nervous system function with ageing. Moreover, vestibular dysfunction and specific to vision, deficits in visual contrast sensitivity, have been associated with increased falls risk

(Herdman et al., 2000; Lord et al., 1991a). Consequently, this supports the need to explore vestibular and visual function in older adults with NP.

As a preliminary step towards understanding the mechanisms which contribute to the development of postural control deficits in older adults with NP, in addition to clinically relevant balance measures and standard centre-of-pressure (CoP) measures of postural control, we will also use analytical techniques of wavelet analysis. This is a technique that decomposes the postural sway data into multiple independent frequency distinct bandwidths where each bandwidth has been hypothesised to potentially be identified with physiological significance of postural movements associated with muscular proprioception (1.56-6.25 Hz) (Paillard et al., 2002), cerebellar (0.39-1.56 Hz) (Paillard et al., 2002), vestibular (0.10-0.39 Hz) (Oppenheim et al., 1999) and visual (<0.10 Hz) (Chagdes et al., 2009) systems.

Given the aforementioned background, in this cross-sectional, exploratory study, we sought to understand the mechanisms underlying NP-related postural control deficits in older adults with and without NP by (i) comparing several features that might relate to impaired postural stability but not directly related to the cervical spine to determine their influence, including level of physical-activity, lower limb, vestibular and visual function, as well as (ii) employing the use of wavelet analysis of standing balance. We hypothesized that there will be differences between groups in the level of physical-activity, lower limb, vestibular and visual function and that wavelet analysis will demonstrate changes in frequency measures in the NP group.

7.2 Methods

7.2.1 Participants

This cross-sectional study involved 84 older adults with (n=35, age 69.6 ± 6.3 years) and without (n=49, age 69.5 ± 4.9) idiopathic NP. Participants aged 60 years and older were recruited using convenience sampling. Participants were given an option of location of testing; either at the research laboratory or at their residence. Participants were included in the NP group if they reported chronic NP for ≥3 months, neck disability index (NDI) of ≥10% and (worst) neck-related pain intensity of ≥2/10 measured on the numeric rating scale and measured over the past 24 hours. Subjects were excluded if they had visual impairment not corrected by prescriptive lenses, trauma-induced NP such as whiplash injury, orthopaedic

surgery of the lower limb within the past year, diabetes, uncontrolled cardiorespiratory problems, known ongoing neurological or vestibular pathology, arthritis that requires active management and any acute musculoskeletal injuries. All participants provided informed consent as outlined by the Medical Ethics Committee of the University of Queensland and all procedures were conducted according to the Declaration of Helsinki. All procedures were supervised by the same physiotherapist (JQ) who has postgraduate qualifications and 15 years of clinical experience.

7.2.2 Questionnaires

Age, gender, co-morbidities (including musculoskeletal, heart, kidney and liver conditions and any psychological conditions such as depression), body mass index (BMI) and medication intake were included in demographic data. Activities-Specific Balance (ABC) scale was used to assess falls-related self-efficacy (Myers et al., 1998) and the level of physical activity of a typical week in the past 12 months was documented using a self-reported questionnaire (Leijon, 2002). This short questionnaire provides a general indication of overall activity levels and has previously been used in people with NP (Peolsson et al., 2007). Self-reported neck disability was measured using the Neck Disability Index (NDI) (Vernon, 2008; Vernon & Mior, 1991b) and the intensity of NP or NP pain measured on a 11-point numeric rating scale (NRS) (Jensen et al., 1999). Self-perceived handicap associated with dizziness was evaluated using the Dizziness Handicap Inventory (DHI)(Jacobson & Newman, 1990). Given that previous research found a significantly higher fear of falls in subjects who experienced a fall in the prior three months compared to those who did not fall (Li et al., 2003), and a high fear of fall has been associated with reduced postural control (Maki et al., 1991), we obtained a fall history for participants who sustained a fall within 3 months prior to data collection.

7.2.3 Lower limb function

Ankle range-of-motion was determined using a standard goniometer. Sensory testing using light touch and vibration sense were tested at the lateral malleolus of the participant's dominant foot using the Semmes-Weinstein Monofilaments (Aesthesio, San Jose, CA, USA) and a tuning fork (128 Hz) respectively. It is noted that current tools used to detect peripheral neuropathy have poor standardization of measurement which limit its use in clinical practice (Gelber et al., 1995; Kanji et al., 2010; Van Deursen et al., 2001). The sensation tests used in this study are by no means used for diagnostic purposes (as we excluded individuals with peripheral neuropathy during the screening process at recruitment), but to track the trend of

sensation specifically in light touch and vibration perception between older adults with and without NP.

Light touch was assessed in a descending order of the monofilaments and the final detectable monofilament was then confirmed by applying the monofilaments in an ascending order (Lord et al., 1991b). The monofilament was then recorded and converted to a logarithm scale for data analysis. If there was an inconsistency in results, the tests were repeated until a consistent result was obtained.

Vibration perception was measured as the duration of time from the moment the tuning fork contacted the foot to the point when the participant could no longer perceive the decreasing vibration stimulus (Hilz et al., 1998). The tuning fork has high specificity of 93.7-95.3% and moderate sensitivity of 55.8-62.5% in diabetic adults (Arshad & Alvi, 2016; Jayaprakash et al., 2011) compared to the gold standard of the neuro-esthesiometer which has higher sensitivity (61-80%) (Davis et al., 1997; Nelson et al., 2006) but lower specificity of 64-76%.

Amongst all lower limb muscles, we selected toe flexor strength because toe flexor strength has been shown to be an independent predictor of falls in older adults, over and above other known risk factors such as age, gender, fall risk score and strength of bigger muscle groups such as the quadriceps muscle (Mickle, Karen J et al., 2009). Toe flexor strength was measured using the Nintendo Wii balance board (NWBB)(Figure 7-1), using a set up demonstrated to be valid and reliable (Quek et al., 2015) and described in detail in Study 3. Torque produced from a maximal contraction was calculated, with the average of three trials used in the statistical analysis.

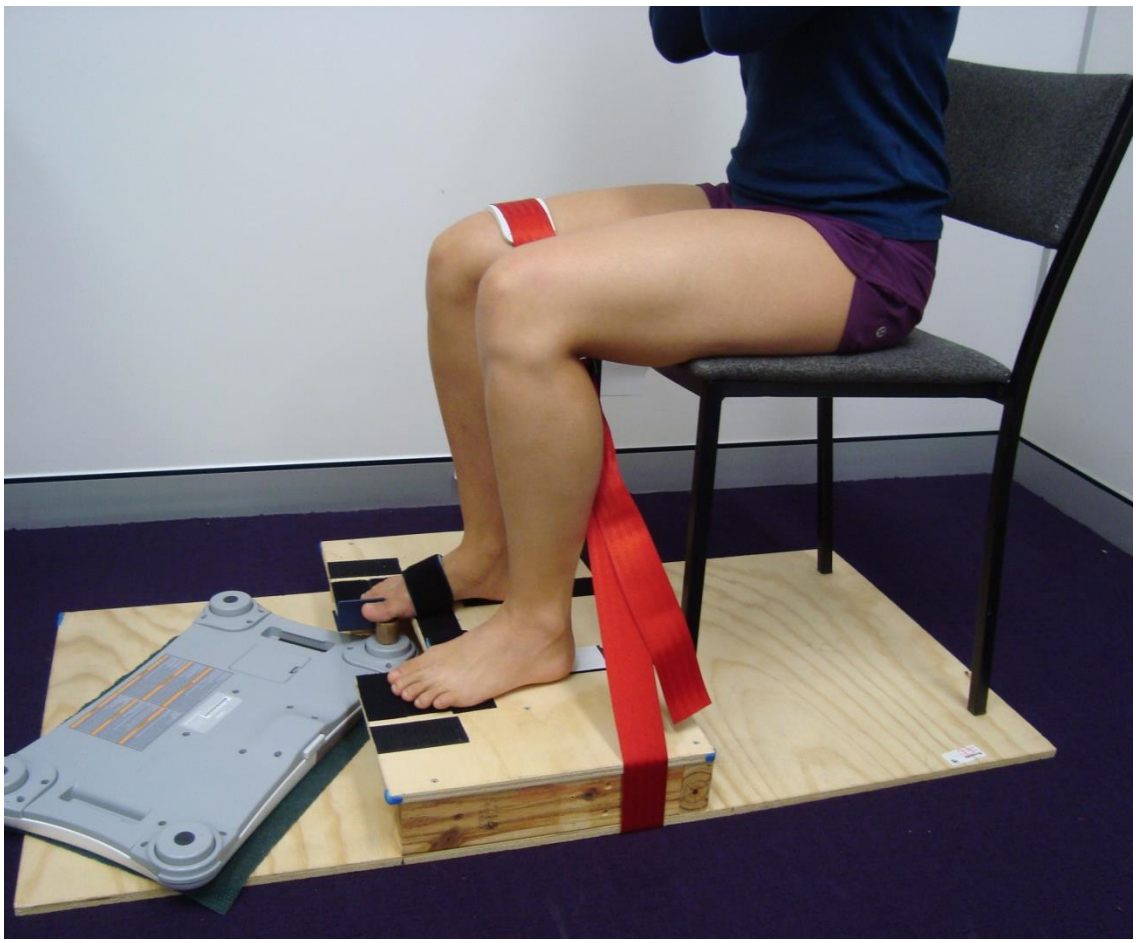


Figure 7-1. Experimental set-up with the NWBB

The NWBB is placed upside down on the wooden platform and the foot was secured using Velcro straps. Sticky Velcro was applied under the heel to prevent the heel from lifting off. The foot was positioned in such a way that the proximal metatarsophalangeal joint was at the edge of the platform and the sensor was placed under the interphalangeal joint of the big toe. Test trials where compensatory strategies were observed, such as toe curling and excessive trunk movements, were deemed invalid and repeated.

7.2.4 Vestibular function tests

To screen for subjects with vestibular hypofunction, we performed a clinical Dynamic Visual Acuity (DVA) test with a Snellen chart and the head impulse test (HIT). The protocol for both vestibular tests have been documented in previous studies (Dannenbaum et al., 2009; Schubert et al., 2004). To assess for active benign paroxysmal positional vertigo (BPPV), we performed the Dix-Hallpike manoeuvre to test for posterior semicircular canal BPPV, which is the most common form of BPPV. In all tests, the presence of saccades was determined by visual inspection.

7.2.5 Visual contrast sensitivity

Visual contrast sensitivity was evaluated using the Melbourne Edge Test (MET) (Australian Vision Charts, Forest Hill, Australia), with previous reports documenting excellent test-retest reliability (Haymes & Chen, 2004).

7.2.6 Balance

Dynamic balance was evaluated using the Dynamic Gait Index (DGI), a common clinical performance tool also used as a measure of fall risk, specifically obtaining a score of 19 or less out of a possible 24 is indicative of having a higher risk of falls (Shumway-Cook, A. et al., 1997). Static standing balance was evaluated using the Wii Balance Board (Nintendo, Kyoto, Japan) in a protocol previously validated against a laboratory force plate (Clark et al., 2010). Participants were instructed to stand "as still as possible" on the Wii Board in their habitual standing posture with arms by their side, feet hip-width apart, in their usual toe-out angle, looking straight ahead at a dot positioned at eye level on a plain background, approximately 1 meter away. For the balance testing performed at the participant's residence, the balance board was placed on a flat and even hard surface. To ensure the same feet placement for repeated trials, feet positions were traced. Two valid trials of 30-second duration of eyes open and closed were performed. Participants were given a rest if required in between trials. Center-of-pressure (CoP) displacement was used as a measure of postural sway (Winter, D. A., 1995). Standard measures of CoP amplitude (cm), velocity (path length divided by test time: cm/s) and SD (cm) were calculated on the anteroposterior (AP) axes. The zero position for CoP was set as the CoP position at the commencement of data collection during the trial. In addition, a Symlet-8 discrete wavelet transform was used to process the CoP data on the AP axis, separating the signal into four frequency bands as per previous study protocol (Quek et al., 2014): (1) moderate (1.56–6.25 Hz), (2) low (0.39–1.56 Hz), (3) very-low (0.10–0.39 Hz), and (4) ultralow (<0.10 Hz) frequencies. These bands were then individually analysed to obtain CoP velocity (cm/s) in each frequency range. This method, including how it was implemented and why the Symlet-8 was chosen, is described in detail by Clark et al (Clark et al., 2014) (see Appendix 9 for technical details).

7.3 Statistical Analysis

We used descriptive analyses to compare demographic and clinical characteristics between participants with and without NP. Wilcoxon-Mann-Whitney or Welch-t tests were used to compare the continuous data between groups. Fisher's Exact, Chi square or linear by linear tests was used to test for differences in proportions as the data did not fulfil the assumptions of normality. In order to adjust for other potential confounding variables (number of co-morbidities, BMI and fall history) regression analysis was performed. All statistical calculations were performed using the STATA version 11.0 statistical software. Statistical significance was defined as p values of <0.05.

7.4 Results

Table 7-1 compares the demographic and clinical characteristics for the NP group and healthy controls. The level of physical-activity, lower limb motor and sensory function, vestibular function and visual contrast sensitivity were similar in both groups ($p>0.05$). Older adults with NP obtained poorer scores in the ABC scale ($p=0.01$), lower DGI scores ($p=0.02$) and higher scores in the DHI ($p<0.01$). By design, older adults in the NP group showed significantly higher neck disability compared to healthy controls ($p<0.001$). Number of co-morbidities and BMI showed trends towards group differences and thus were included as co-variates in the regression analysis ($p=0.06$, Table 7-1).

When standard measures of postural control were compared between groups (Table 7-2) the NP group exhibited greater CoP velocity (overall and in the AP axis) in both eyes open and closed conditions as well as greater CoP amplitude and SD of path length in the AP direction in the eyes open condition. The results for wavelet transform are presented as absolute and percentages values (Table 7-2). In absolute terms, the NP group demonstrated significantly higher CoP velocity measures only in the moderate (1.56-6.25 Hz) and low (0.39-1.56 Hz) frequency bandwidths in both eyes open and closed conditions ($p<0.05$). All COP differences persisted after adjustment for number of co-morbidities and BMI. When the CoP data was analysed in percentages, there were no significant differences between groups across all frequency bandwidths (Table 7-2).

Table 7-1 Characteristics and comparison of Neck Pain and Healthy subjects (mean and standard deviation (SD) unless otherwise stated).

Clinical characteristics	NP (n = 35)	Healthy (n = 49)	*p*-Value
Age, years	69.6 (6.3)	69.4 (4.7)	0.92
Female Gender, n (%)	22 (63)	30 (61)	0.88
Body Mass Index	24.0 (3.9)	25.4 (3.9)	0.06
NDI (/100)	20.82 (7.14)	1.18 (1.63)	<0.001
NRS (Worst)	4.03 (2.0)	0 (0)	<0.001
ABC (/100)	91.25 (8.47)	95.57 (5.02)	0.01
DHI (/100)	8.69 (10.15)	2.32 (6.59)	0.002
Employment			
Full-time paid work, n (%)	4 (11.4)	3 (6)	
Part-time or casual paid work, n (%)	4 (11.4)	7 (14)	0.57
Retired, n (%)	27 (77.2)	39 (80)	
Number of co-morbidities, n (%)			
0	5 (14)	10 (20)	
1	7 (20)	17 (35)	0.06
≥2	23 (66)	22 (45)	
Medication, n (%)			
0-3	29 (83)	44 (90)	0.35
4-6	6 (17)	5 (10)	
Physical Activity, n(%)			
1 (no activity)	0 (0)	1 (2)	
2 (very little activity)	4 (12)	12 (24)	
3 (soft activities at least once/week)	19 (54)	20 (41)	0.34
4 (hard activities or competitions regularly)	12 (34)	16 (33)	
Visual Contrast Sensitivity (/24)	19.83 (1.84)	20.06 (1.67)	0.73
Lower Limb function			
Ankle ROM			
Inversion, degrees	31.85 (6.63)	31.31 (7.82)	0.88
Eversion, degrees	16.47 (7.20)	16.98 (7.36)	0.71
Sensation, logarithmic scale	1.88 (2.06)	1.54 (1.48)	0.35
Vibration sense, seconds	14.95 (5.66)	14.55 (4.29)	0.88
Big Toe torque, N-m	16.87 (16.3)	17.42 (12.94)	0.60
Vestibular function			
DVA	2.65 (1.63)	2.71 (1.54)	0.77
HIT- positive test, n (%)	30 (86)	45 (92)	0.63
Dix-Hallpike- positive test, n (%)	5 (14)	4 (8)	0.80
Place of testing			
Laboratory	24 (67)	32 (65)	0.82
Home	11 (31)	17 (35)	
Fall history 3 months prior, n (%)	2 (6)	3 (6)	0.94
DGI (mean, SD), (/24)	20.26 (2.98)	21.49 (1.98)	0.02**
DGI scores <19	15 (43)	10 (20)	0.03*

NDI: Neck Disability Index
NRS: Numeric Rating Scale
DGI: Dynamic Gait Index
ABC: Activities-specific Balance Confidence
DHI: Dizziness Handicap Inventory
DVA: Dynamic Visual Acuity
HIT: Head Impulse Test
**P-value after adjusting for body mass index and number of co-morbidities using logistic regression.*
***P-value after adjusting for body mass index and number of co-morbidities using ANCOVA.*

Table 7-2. Comparison of CoP measures between Neck Pain Subjects (n=35) and Healthy Controls (n=49)

CoP measures	Eyes Open		*P*-Value*	Cohen's d	Eyes Closed		*P*-Value*	Cohen's d
	Neck Pain	Healthy			Neck Pain	Healthy		
Standard measures								
Overall Velocity (cm/s)	0.97 ± 0.36	0.80 ± 0.18	0.007***	0.60	1.37 ± 0.61	1.13 ± 0.29	0.018**	0.50
AP Axis								
Velocity (cm/s)	0.81 ± 0.34	0.64 ± 0.17	0.006***	0.63	1.19 ± 0.57	0.97 ± 0.27	0.015**	0.49
Amplitude (cm)	1.97 ± 0.67	1.68 ± 0.46	0.007***	0.50	2.48 ± 0.75	2.35 ± 0.56	0.098	0.20
SD Path length (cm)	0.41 ± 0.17	0.35 ± 0.11	0.007***	0.42	0.50 ± 0.17	0.48 ± 0.13	0.254	0.13
Wavelet Analysis (Absolute)								
<0.10 Hz (cm/s)	0.065 ± 0.03	0.059 ± 0.03	0.146	0.2	0.075 ± 0.04	0.077 ± 0.04	0.549	0.05
0.10-0.39 Hz (cm/s)	0.20 ± 0.07	0.18 ± 0.05	0.141	0.33	0.31 ± 0.10	0.29 ± 0.08	0.137	0.22
0.39-1.56 Hz (cm/s)	0.55 ± 0.24	0.45 ± 0.13	0.008***	0.52	0.80 ± 0.38	0.67 ± 0.20	0.009***	0.42
1.56-6.25 Hz (cm/s)	0.54 ± 0.28	0.40 ± 0.13	0.013**	0.64	0.82 ± 0.48	0.62 ± 0.22	0.021**	0.54
Wavelet Analysis (%)								
<0.10 Hz	0.052 ± 0.02	0.054 ± 0.02	0.66	0.10	0.041 ± 0.02	0.047 ± 0.02	0.19	0.30
0.10-0.39 Hz	0.16 ± 0.05	0.17 ± 0.05	0.48	0.20	0.17 ± 0.06	0.18 ± 0.04	0.32	0.20
0.39-1.56 Hz	0.40 ± 0.05	0.41 ± 0.05	0.36	0.20	0.4 ± 0.06	0.4 ± 0.04	0.35	0.00
1.56-6.25 Hz	0.39 ± 0.07	0.36 ± 0.05	0.10	0.49	0.39 ± 0.07	0.37 ±0.06	0.10	0.31

Values are mean ± standard deviation
**P values after adjusting for body mass index (BMI) and number of co-morbidities using multiple regression.*
CoP: Center of pressure, SD: standard deviation, AP: anteroposterior.
EO: Eyes open, EC: Eyes closed.
***p<0.05*
****p<0.01*

7.5 Discussion

In this exploratory cross-sectional study, we compared various physical function tests and characteristics in older adults with and without NP. Contrary to our hypothesis, there were no significant differences in the levels of reported physical activity, big toe strength, ankle range-of-motion, lower limb light touch and vibration sense, vestibular function and visual contrast sensitivity. In addition, the NP group had lower balance confidence on the ABC scale ($p=0.01$) and greater dizziness handicap based on the DHI ($p<0.01$) compared to healthy controls. As expected, older adults with NP had poorer dynamic postural stability and swayed more during quiet stance compared to healthy controls. Further, wavelet analysis in absolute terms revealed that the NP group showed higher velocity CoP signal in the moderate and low frequencies in both eyes open and closed conditions.

Consistent with previous studies (Quek et al., 2014; Uthaikhup et al., 2012), the results of this study showed that older adults with NP demonstrated reduced postural stability compared to those without NP. The lack of significant differences in lower limb, vestibular or visual function and also physical activity suggest that the cause of postural instability observed in the NP group may be due to NP and directly-related impairments. This could manifest via altered cervical afferent input to the sensorimotor system (Treleaven, 2008).

Noteworthy, DGI scores of 19 or less have previously been shown to indicate increased fall risk in older adults (Shumway-Cook, A. et al., 1997). When we dichotomized the DGI scores to more than 19 (low fall risk) or 19 or less (high fall risk), we found that the NP group had twice the proportion of older adults in the group with higher fall risk compared to healthy controls, supporting previous assertions that older adults with NP are at a higher risk of falls (Quek et al., 2014). It is not surprising then that older adults with NP scored lower on the ABC scale, consistent with a previous study (Uthaikhup et al., 2012), indicating that this group of older adults demonstrate reduced balance confidence compared to older adults without NP. Our results reveal high scores (>90) on the ABC scale in both groups, and suggest that both groups demonstrate high balance confidence. Nevertheless, the significant differences between groups may be an early marker of decline in balance confidence in older adults with NP, and may suggest that strategies to improve balance confidence are needed to prevent future falls.

The results of the wavelet analysis showed that CoP velocity in the moderate and low frequency bandwidths was higher in the NP group compared to the healthy controls in both eyes open and eyes closed conditions. The higher velocity of the moderate frequency CoP

signal found in the NP group in this study is consistent with that found post neck muscle fatigue in young healthy controls (Liang et al., 2014). We agree with Liang et al (Liang et al., 2014) that increased weighting of the lower limb proprioceptive input to maintain the centre of gravity within the support base to compensate for cervical proprioceptive deficits is a possible explanation for these findings. This could take the form of increased stiffness of the lower limb and pelvis joints to decrease the time delay of proprioceptive feedback (Peterka, 2002). This proposition is further supported by the current study where older adults with NP did not demonstrate lower limb sensory or motor deficits. As for significant differences in the low frequency band (0.39-1.56 Hz) found in the current study, this may be due to a potential frequency band overlap. Previous authors have suggested signals of greater than 1 Hz are associated with proprioception input. Thus it is highly plausible that the moderate frequency range (1.56-6.25 Hz) used in this study may overlap with that of the bandwidth below, i.e. the low frequency (0.39-1.56 Hz) (Diener, H. C. et al., 1984). A less likely alternative may be that sensory reweighting was in place with an increase in cerebellar activity to improve postural stability (Paillard et al., 2002) in NP elders compared to healthy controls. However this speculation has weak evidence and can only be verified by further research.

On the other hand, our study results on wavelet analysis were not consistent with our previous study comparing postural control in older adults with and without NP (Quek et al., 2014). In the previous study, older adults with NP demonstrated a decrease in the proportion of CoP signal in the moderate frequency bandwidth and an increase in the very-low frequency bandwidth (0.10–0.39 Hz) compared with the control group. In that study, data was expressed in percentages to account for inter-subject variability. No significant differences were found between groups when comparing CoP measure in percentages. The use of a percentage is essentially converting the data into a ratio between the different bands, which has numerous flaws including obtaining the same value if the sway in each band goes up proportionately. A potential issue with this is that the majority of the signal occurs in the higher frequency bands, with little occurring in the lower frequency bands, and therefore a ratio method may mask the true findings if small but important changes are occurring in the lower frequency bands. Given the exploratory nature of our studies, it is unclear at this stage how best to divide the frequency bands and what each frequency band may represent. Further, the discrepancy between the results in study 4 and this study could potentially be due to the different postural control strategies employed by the older adults. In study 4, 95% of NP elders versus 65% in the control group reported more than 2 co-morbidities compared to 66% in the NP group versus 45% in the control group in the current

study. This difference may be due to fact that the method of calculation of comorbidities was different between both studies. It may also be possible that a greater percentage of elders in study 4 had more/worse lower limb deficits (in addition to reduced cervical spine proprioception), resulting in a lower proportion of velocity measures in the moderate frequency bandwidth in study 4. Participants may therefore have had to rely more on the vestibular system. However, more research is warranted if wavelet is to be used further for mechanistic purposes.

There were no differences between people with and without NP across a number of other measures including lower limb function (ankle ROM, big toe strength, tactile sensitivity and vibration sensation of the ankle), physical activity, vestibular and visual function. While this indicates that these factors may not be different between these groups, there is still a need to investigate other factors or use other measurement tools. For example, physical activity is often measured with accelerometers (Colley et al., 2011) and there are several longer questionnaires that have been validated in older adults (Washburn et al., 1993) and may be more sensitive to other aspects of physical activity not examined in this study, such as time spent in higher intensity physical activity, types of activities performed or avoided, or the pattern of activity accumulation. Similarly, a selection of measures of potential factors to influence postural control was chosen based on past literature, however for completeness, investigation of other measures (e.g. strength of other lower limb muscles or other visual functions such as acuity) should be performed, to conclusively indicate that there is no relationship between these constructs (e.g. of lower limb strength) with NP in older adults. In addition, vestibular testing was performed using visual inspection only to rate the presence of saccades, and the use of eye tracking and head velocity transducers would improve the accuracy of testing. The scores of both groups in the DHI (NP: 8.7/100, controls: 2.32/100) were well below that that reported for mild handicap (16-34/100), thus the high number of positive HIT findings need verification with objective measures. It should be noted that dizziness reported in the DHI could have been the result of complex interactions between the vestibular, visual, cervical spine and central processing of all these afferent inputs. This is discussed in section 8.7.1.7.

7.6 Limitations

The results of this study must be interpreted in the light of our study limitations. First, whilst the vestibular tests selected were clinically relevant, they may lack the precision that is required to detect subtle deficits in eye movement, and may increase the likelihood of under reporting vestibular impairments. Nevertheless, subjects with obvious vestibular

pathology were excluded from the study. Second, given the way the DHI was structured, it may be possible that the questions may have been misinterpreted to represent neck problem and not dizziness, resulting in over reporting of the level of handicap in participants with NP. However, DHI scores were not high and reflected mild disability as expected. Third, in order to increase the generalizability of the population, data collection was performed both in the laboratory or the participants' home. We were not able to consistently recreate the exact testing environment and this may affect the individual's performance. Performing balance tests in different environments may affect scores due to factors such as noise, visual input and deformation or non-levelness of the flooring. However, there were no group differences in the location of research testing (Table 7-1) and there were no statistical significant differences ($p>0.05$) in postural control measures between home and laboratory locations within each group. As a result, we believe that our findings are not biased with respect to this limitation. Fourth, we used the English version of a Swedish questionnaire to document the level of physical activity and this has not been validated. Further, future studies ought to include more details in physical activity measures in older adults with NP. Fifth, the physical function of the lower limb did not take into account the function of bigger joints such as the hip and knee joints and muscles such quadriceps and future studies may consider testing the physical function of the hip and knee. Lastly, even though we obtained data for a history of falls, we could not include the variable as a covariate in the analysis because the numbers were small.

7.7 Conclusion

In conclusion, the results of our study indicate that NP-related postural control deficits in older adults may not be associated with the level of physical-activity, lower limb motor and sensory function, vestibular function and visual contrast sensitivity. The changes in postural activity are most likely due to NP and associated musculoskeletal impairments altering cervical proprioceptive input to the sensorimotor control system. Wavelet analysis suggests that in an attempt to compensate for the deficits in neck proprioception, sensory reweighting was in place to engage lower limb proprioception. Given that older adults with NP had reduced balance confidence, poorer dynamic balance and a higher fall risk compared to healthy controls, future research is warranted to determine the underlying mechanisms underpinning NP-related postural control dysfunction.

Chapter 8: Manuscript preparation is in progress

Quek J, Clark RA, Brauer SG, Treleaven J

"The influence of neck pain on postural control in older adults"

Chapter 8: Study 6 The influence of neck pain on postural control in older adults

Previous research has suggested that cervical spine impairments may contribute to the postural control deficits observed in individuals with NP. As the next step towards understanding the mechanisms underpinning postural control deficits in older adults with NP, this study examined the factors that may potentially be associated with static and dynamic postural control in older adults with and without NP.

8.1 Introduction

Although evidence is accumulating to implicate the role of the cervical spine in influencing postural control, little is known about the mechanisms underpinning postural control deficits in individuals with NP. Previous cross-sectional studies have shown increased postural sway in static standing (Silva & Cruz, 2012) and decreased dynamic postural control (Quek et al., 2014) in older adults with NP compared with healthy controls. Importantly, empirical evidence suggests that older adults with NP may have higher risk of falls than those without cervical spine related symptoms (Kendall et al., 2016; Quek et al., 2014). Having a greater understanding of the factors contributing to postural control deficits in older adults with cervical spine dysfunction is important to developing management strategies to improve postural control and potentially reducing falls risk.

In chapter 6 we compared physical factors in older adults with and without NP and suggested that postural control deficits observed in older adults with NP are not due to differences in lower limb, vestibular and visual function compared to healthy controls. This supports the theories of altered cervical input to the postural control system as the primary contributor to these deficits (Treleaven, 2008), although altered biomechanics is also a consideration.

8.2 Altered cervical afferent input

Given that the cervical spine has high percentages of muscle spindles and extensive connections with the vestibular and central nervous systems, abnormal cervical afferent input may disrupt the integration of proprioceptive information and potentially affect standing postural control (Quek et al., 2013). Experimentally, neck muscle vibration, that is thought to stimulate muscle spindle afferents, resulted in increased postural sway in healthy older adults (Patel et al., 2009). Organically, altered cervical input can be due to several causes including pain (Treleaven, 2011), altered proprioception (Williams et al., 2017), muscle

fatigue (Liang et al., 2014) and asymmetry of range of motion (Quek et al., 2013). It is postulated that postural control changes may be a consequence of a mismatch between afferent signals from the altered cervical input and normal information from the vestibular, visual and central nervous systems (Treleaven, 2008). The following section details these various factors that may contribute to altered cervical afferent input and subsequent alterations to postural stability in those with NP.

8.2.1 Pain

Although studies have demonstrated associations between NP and increased postural sway (Treleaven, 2011), the presence of NP is not consistently associated with postural control disturbances (Pleguezuelos Cobo et al., 2009; Ruhe et al., 2011). Several mechanisms such as central modulation as well as subcortical and cortical reorganization of the somatosensory system has been postulated to explain the way in which pain may influence cervical input and possibly postural control (Tinazzi et al., 2000). Given that the presence of NP may potentially influence postural stability, assessing its severity may provide important insight into postural control mechanisms.

8.2.3 Proprioception

Joint position error (JPE) is the most commonly used measure of cervical proprioception and has been shown to a) be impaired in those with NP (de Vries et al., 2015), and b) contribute to postural control deficits in 14 adults with non-specific NP (Röijezon et al., 2008). Relatedly, previous studies have suggested that the neck torsion test is able to bias afferent input towards the cervical spine by moving the body on a stationary head (Chen & Treleaven, 2013). Accordingly, the effect of neck torsion on postural control has been demonstrated in patients with idiopathic NP (Williams et al., 2017) and in those with whiplash injury (Yu et al., 2011). However, to date no study has investigated the relationship between JPE and postural stability in older adults.

8.2.4 Range of motion asymmetry

A previous study has demonstrated that older adults with NP and upper cervical spine rotation range-of-motion asymmetry was associated with increased sway compared older adults with NP but without upper cervical spine asymmetry (Quek et al., 2013). The asymmetry was reasoned to alter proprioceptive input, leading to postural control changes.

8.2.5 Muscle fatigue

The influence of neck muscle fatigue on static postural control in young healthy subjects (Liang et al., 2014) and in adults with NP (Cheng et al., 2015) has been established

in previous studies, but no studies have been identified examining older adults with idiopathic NP. Ageing associated with progressive decline of general systems may place the older adult with NP at a greater proprioceptive disadvantage. Hence reduced neck muscle endurance could potentially contribute to postural instability in older adults with cervical spine dysfunction.

8.3 Biomechanical factors

Given the biomechanical link between cervicothoracic spinal alignment and neck function (Quek et al., 2012), it is biologically plausible that older adults with NP may modify their spinal posture in response to pain and deficits in proprioception and this may in turn influence postural stability. Relatedly, lumbar lordosis has been found to be associated with postural instability in older adults with osteoporosis (Ishikawa et al., 2009). Even though the spine is typically categorized as three regions: cervical, thoracic and lumbar spine, each region should not be considered in isolation from each other. Therefore, it is possible that craniovertebral angle, or commonly known as forward head posture (FHP), thoracic kyphosis and lumbar lordosis may be important dimensions to take into consideration when assessing postural control in NP.

Thus, it is highly possible that these postural control deficits are due to cervical spine impairments but no studies have been done to comprehensively examine these associations. This study aimed to identify which of the above potential contributors most significantly influence postural control in older adults with NP in this cross-sectional, exploratory study. Further, healthy controls were included to also evaluate the moderating effects of NP on cervical spine impairments associated with postural instability. As part of the exploratory nature of this study, we also included the use of discrete wavelet transform to gain further insights into the mechanisms underlying NP induced postural control impairments. We hypothesized that proprioceptive deficits in the cervical spine as differentially expressed by various outcome measures such as joint position error, asymmetry, cervical muscle fatigue and/or altered biomechanics will be associated with reduced postural control in older adults with NP, and that wavelet analysis will reveal some new insights into postural instability in people with NP.

8.4 Methods

8.4.1 Participants

The study sample comprised 84 community-dwelling older adults with (mean age = 69.6 ± 6.3 years) and without (mean age = 69.4 ± 4.7 years) idiopathic NP living in

Queensland, Australia. Elders aged 60 years and older were recruited using convenience sampling. Participants were included in the study if they reported chronic NP for ≥3 months, neck disability index (NDI) of ≥10% (Vernon & Mior, 1991a) and a neck-related pain intensity of ≥2/10 measured on the numeric rating scale (Jensen et al., 1999). To minimize the influence of potential confounders, subjects were excluded if they had a history of falls of less than three months, visual deficits that were not corrected by prescriptive lenses, NP of traumatic origin such as whiplash injury, recent orthopaedic surgery, diabetes, uncontrolled cardiorespiratory problems, known ongoing neurological or vestibular pathology, arthritis that required active management and any acute musculoskeletal injuries. All participants provided informed consent as outlined by the Medical Ethics Committee of the University of Queensland and all procedures were conducted according to the Declaration of Helsinki. All procedures were supervised by the same physiotherapist (JQ) who has postgraduate qualifications and 15 years of clinical experience.

8.4.2 Self-reported Questionnaires (Appendix 8)

Given the exploratory nature of this study, in addition to age, gender, body mass, co-morbidities and medication intake, we also included in our measurements, (i) self-reported neck disability, measured using the Neck Disability Index (NDI) (Vernon, 2008; Vernon & Mior, 1991a), (ii) falls-related self-efficacy, assessed by the Activities-Specific Balance Confidence (ABC) scale (Myers et al., 1998), (iii) intensity of NP or neck-related pain measured on a 11-point numeric rating scale (Jensen et al., 1999), (iv) self-perceived handicap associated with dizziness, evaluated using the Dizziness Handicap Inventory (DHI)(Jacobson & Newman, 1990), fear of movement assessed using the Pictorial fear of activity scale for the cervical spine (PFActS-C) (Turk et al., 2008) and the (v) level of physical activity (Leijon, 2002).

8.4.3 NP-related impairments

8.4.3.1 Cervical Joint Position Error

In order to reduce the influence of the vestibular afferents and to isolate neck afferents, the joint position error test with neck torsion was used in this study to measure cervical spine proprioception (Chen & Treleaven, 2013). The laser sensor was fixed on the centre of the sternum of each participant using a sticky tape. Participants were instructed to sit on foam that was placed on a standardised chair positioned 90 cm away from the chart. With vision occluded and head in neutral and stationary throughout the procedure, participants were asked to focus on the neutral resting trunk position for a few seconds, and

then actively rotate the trunk as far as possible, and finally returning to trunk neutral as accurately as possible. If required, the examiner gently held the participant's head to ensure that the head remained still. The participants verbally indicated when they thought they returned to the original starting position and the difference between the starting and end position was recorded in cm and then converted to degrees (Chen & Treleaven, 2013). Figure 8-1 shows the chart used in this experiment with the angles labelled. Before commencing the next repetition, the examiner passively repositioned the head/trunk to the centre of the target. No feedback or verbal cues were given. All participants were given at least one test trial to ensure that they understood the instructions of the procedure. Joint position error measurements were calculated from the laser sensor position indicated on the chart (see figure 8-1). Six trials of each direction (right and left trunk rotation) were completed and the average of the six scores was used in the analysis.

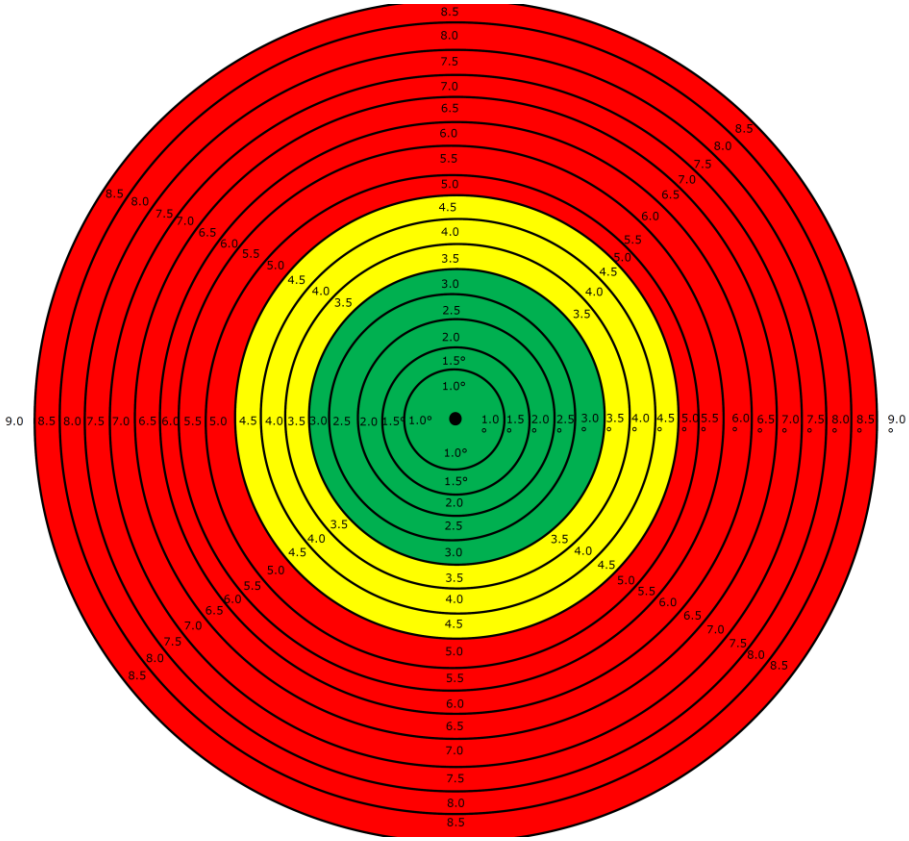


Figure 8-1 Chart indicating the joint position error labelled in degrees.

The position on which the laser light lands is recorded as the joint position error of the trial.

8.4.3.2 Cervical Range-of-Motion Asymmetry

Range-of-motion (ROM) of the cervical spine was measured using the CROM device (Performance Attainment Associates, St. Paul, MN), which has established validity and reliability (Capuano-Pucci et al., 1991; Hall et al., 2008; Tousignant et al., 2000; Tousignant et al., 2002). Specifically, active-assisted cervical rotation range-of-motion was performed with participants seated fastened on a chair using a belt (Mulligan Mobilization Belt) and passive upper cervical rotation ROM was measured using a previously established protocol (Quek et al., 2012). For upper cervical rotation ROM, the examiner determined the limit of ROM when a firm resistance was felt or when pain was first perceived. Three measurements were obtained for each movement direction (right rotation, left rotation, upper cervical rotation right and left) and the average of the three was recorded and the absolute difference between sides for both cervical rotation and upper cervical rotation were used for data analysis. The CROM was used in this study instead of the smart phone because rotation ROM measurements demonstrated poor validity and reliability (chapter 3).

8.4.3.3 Cervical muscle endurance

The muscle endurance tests used for both the cervical spine flexor and extensor muscles were adapted from previous study (see details below) and both tests have demonstrated good to excellent reliability (ICC=0.88 to 0.93) (Edmondston et al., 2008). Before the commencement of each test, participants were given a “trial test” in order to ensure that they understood the test procedures. For both cervical flexor and extensor endurance measurements, the time to fatigue was recorded and rating of perceived exertion as well as a discomfort score (0-10) was documented.

8.4.3.3.1 Cervical flexors

The cervical flexor muscle endurance test was performed with subjects lying supine on the plinth. The examiner guided the participant’s cervical spine into slight upper cervical flexion and instructed the participant to lift the head just above the plinth and to maintain this position for as long as possible. The test was terminated if the subject was unable to maintain their standardized position or when they chose to stop the test due to exhaustion.

8.4.3.3.2 Cervical extensors

To test the endurance of the cervical extensors, participants were positioned in prone lying with arms by the side and their heads over the end of the plinth. In order to stabilise the upper thoracic spine, an inelastic belt (Mulligan belt) was secured between T4-T6. A band with weight attached (3kg for males and 2 kg for females) was placed around the participant's head. The participant's head and neck were positioned in neutral and the test started when the weight was applied. Instructions were given to hold this position for as long as possible. The test was terminated when the participant was no longer able to maintain this position due to discomfort or fatigue. Even though an inclinometer was used to detect a drop in head position as used in previous study (Edmondston et al., 2008), we found that the inclinometer was not useful to detect a drop in head-height in the absence of a cervical sagittal flexion ie. during a cervical protraction, which was the common position adopted when the muscles were fatigued. Consequently, we resorted to visual estimation and gave verbal feedback to participants to re-position their head when they deviated from the neutral position. The test would be terminated when participants were not able to maintain a neutral head and neck posture.

8.4.3.4 Forward Head Posture (FHP)

FHP was assessed using a previously described method (Quek et al., 2012). We quantified FHP by measuring the craniovertebral angle from a digitized, lateral-view photograph of the subject (see figure 8-1). Specifically, CVA was calculated from the angle between the line connecting the tragus of the ear to C7 and the horizontal line passing through C7 using the software Image J (Schneider et al., 2012). Noteworthy, to minimize image distortion, we placed a spirit level on the top of the camera to ensure that the camera was perpendicular to the horizontal. Previous studies have demonstrated good test-retest reliability (0.88-0.98) for FHP measurements (Brunton et al., 2003; Raine & Twomey, 1997). Greater craniovertebral angle indicates less forward head posture.

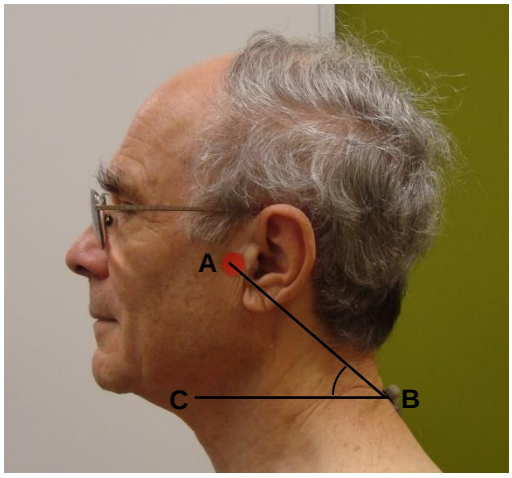


Figure 8-2 Craniovertebral angle is defined as the acute angle subtended by the lines AB & BC.

8.4.3.5 Thoracic Kyphosis, Lumbar Lordosis

In study 4 (chapter 5), the Microsoft Kinect demonstrated excellent validity and intra-rater reliability to measure thoracic kyphosis in standing and in sitting. Given the advantages of the Microsoft Kinect (overall ease of use, quick data processing time and ability to produce almost instant results), it would have been useful for this study for the researcher. However, calibration of the Microsoft Kinect is necessary whenever the position of the device is altered, adding to the length of the total data collection time. Moreover the Kinect needs a power supply and this may be a problem in some homes depending on the home set up. Given that we had to perform data collection in participants' home, and bearing in mind the possibility of participant fatigue, we decided to use the flexicurve instead. Furthermore, the flexicurve is able to obtain both thoracic and lumbar lordosis measurements at the same time whereas the preliminary data shows that the Microsoft Kinect is not reliable to measure lumbar lordosis (not reported). Hence, thoracic kyphosis and lumbar lordosis were assessed using the flexicurve method, a well-established technique that is freely accessible (Quek et al., 2012; Rajabi et al., 2008). Moreover, the validity and reliability of the measurements obtained from the flexicurve has been established in previous studies (Arnold et al., 2000; Greendale et al., 2011; Hart & Rose, 1986; Rajabi et al., 2008; Seidi et al., 2009). Participants were instructed to stand in their usual posture whilst the examiner placed the flexicurve over the spinous processes of the spine from C7 to S2. The shape of the flexicurve was conformed to the curvature of the spine. The flexicurve was then carefully placed on the table and a digital image of the flexicurve imprint was captured using a 7.2 megapixels

digital camera (Sony DSC-W110). Next, the kyphosis and lordosis index were processed using Image J (Schneider et al., 2012), as described in Figure 4-1.

8.4.4 Vestibular function

Known vestibular dysfunction was an exclusion criteria, however, given that vestibular function may play an important role in postural stability in older adults with NP (Quek et al., 2014), we included 3 clinical vestibular tests to screen for (subclinical) vestibular hypofunction and included them as potential covariates - dynamic visual acuity test using the Snellen Chart (Dannenbaum et al., 2009), head impulse test (Schubert et al., 2004) and the Dix-Hallpike to assess posterior benign paroxysmal positional vertigo (Fife, 2009). In this study, we defined a positive response to Dix-Hallpike test as the presence of nystagmus and/or symptoms such as dizziness or nausea. To clarify, because we did not use specialised equipment such as the Frenzel goggles for testing, we were unable to objectively determine the direction and quality of nystagmus. Hence, we conservatively recorded the presence of any nystagmus, regardless of direction and fatigability, as positive and negative if none was visually detected.

8.4.5 Standing Balance

Static standing balance was assessed using the Wii Balance Board (Nintendo, Kyoto, Japan), a portable and accessible balance board which has been previously validated against a laboratory force plate (Clark et al., 2010) and described in studies 1 and 5. Participants were asked to stand “as still as possible” on the Wii Balance Board in their habitual standing posture with arms by their side, feet positioned hip-width apart, in their usual toe-out angle, eyes looking straight ahead at a dot positioned at eye level on a plain background, approximately 1-meter away. Feet positions were traced so as to standardize feet placement for repeated trials. Two valid trials of 30-second duration were performed for both eyes open and eyes closed conditions. CoP velocity and amplitude of the anteroposterior (AP) axes were obtained as measures of postural sway. Further, discrete wavelet transform was used to process the CoP data, separating the signal into four frequency bands as previously reported in our study protocol (Quek et al., 2014): (1) moderate (1.56–6.25 Hz), (2) low (0.39–1.56 Hz), (3) very-low (0.10–0.39 Hz), and (4) ultralow (<0.10 Hz) frequencies (see Appendix 9 for technical details). Moderate and low frequency bands were selected to be the focus of the wavelet analysis because our previous study (Chapter 6) showed differences in CoP frequency measures only in these two frequency bandwidths between older adults with and without NP. Lastly, Dynamic Gait Index (DGI) was used to measure dynamic balance and is a common clinical performance tool to

measure fall risk. Scores range from 0-24 with larger scores indicating less impairment, and a score of ≤19 indicative of a higher fall risk (Shumway-Cook, A. et al., 1997)

8.5 Statistical Analysis

A series of separate univariate linear regression models were constructed within each group to examine each independent variable with static and dynamic postural control measures, and wavelet CoP frequency measures as the dependent variables. Based on the results of the univariate analysis, variables with $p<0.05$ were used in separate multivariable regression models to evaluate the associations of the various variables with the postural control measures respectively, adjusting for age. To avoid model overload, stepwise regression as well as backward elimination of variables with $p<0.1$ were used within each group. We used robust regression to account for potential outliers or heteroscedasticity (Verardi & Croux, 2009). Analysis of residuals of the regression model was employed to examine the distribution of the residuals and when required, appropriate data transformation was applied. Additionally multicollinearity was assessed using the variance inflation factor (Katz, 2006) showing that there was no evidence of multicollinearity. Subsequently, moderation analysis was employed to determine the moderating effects of NP on the variables that emerged as significant predictors in the individual multivariate stepwise regression models. All statistical calculations were performed using STATA version 13.0 statistical software. Statistical significance was defined as p values of <0.05.

8.6 Results

Table 8-1 shows demographic and clinical characteristics of the study participants. Table 8-2 & 8-3 show the results of univariate analysis and the variables that were statistically significant with the respective postural control measures. After adjusting for age, multivariable linear regression results within the NP group indicate that forward head posture and a positive response to the Dix-Hallpike test were consistently and positively associated with both CoP path velocity ($P<0.05$) and amplitude ($P<0.05$) (Table 8-4). Higher age and physical activity were covariates that were positively associated with path velocity. These models explained 36% (with amplitude as the dependent variable) to 62% (with path velocity as the dependent variable) of the variability of static postural control in NP. For the regression model with DGI as the dependent variable, dizziness handicap, PFActS-C scores and age were significantly associated with DGI ($P<0.05$). This model explained 52% of the variability of dynamic postural control in NP. Table 8-5 shows the results of the multivariate regression models within the control group, subsequently used in the moderation analysis. In order to assess the moderating effects of NP on the factors influencing postural control,

the interaction terms (NP X CVA), (NP X Dix-Hallpike), (NP X PA), (NP X Age) and (NP X DHI) were added respectively to the final multiple regression models. Figures 8-(1-4) plot the conditional effect of NP on path velocity across the values of each predictor variable. The results of moderation analysis showed that NP moderated the relationships between the 4 variables and path velocity (Table 8-6): CVA (β= -0.031, p=.013) and a positive Dix-Hallpike test (β= 0.46, p=.022), age (β= 0.035, p=.021) and the level of physical activity (β= 0.26, p=.017).

In terms of the wavelet analysis results, multivariable linear regression results within the NP group indicated that a positive Dix-Hallpike test, age and the level of physical activity were associated with the CoP velocity in the moderate frequency range (1.56–6.25 Hz) and craniovertebral angle and a positive Dix-Hallpike test were associated with the CoP velocity in the low frequency range (0.39–1.56 Hz).

Table 8-1. Characteristics and comparison of all participants with and without neck pain (mean and standard deviation (SD) unless otherwise stated)

Clinical characteristics	NP (n = 35)	Healthy (n=49)	P-Value
Age, years	69.6, range 60-88 (6.3)	69.4, range 61-82 (4.7)	0.92
Female Gender, n (%)	22 (63)	30 (61)	0.88
Height, cm	166.6 (7.6)	166.8 (8.5)	0.94
Weight, kg	66.9 (13.4)	70.9 (13.8)	0.13
Employment			
Full-time paid work, n (%)	4 (11.4)	3 (6)	0.57
Part-time or casual paid work, n (%)	4 (11.4)	7 (14)	
Retired, n (%)	27 (77.2)	39 (80)	
NDI (/100)	20.8 (7.1)	1.18 (1.63)	<0.001
NRS (Worst)	4.0 (2.0)	0 (0)	<0.001
ABC (/100)	91.3 (8.5)	95.57 (5.02)	0.01
DHI (/100)	8.7 (10.2)	2.32 (6.59)	0.002
Number of co-morbidities, n (%)			
0	5 (14)	10 (20)	
1	7 (20)	17 (35)	0.055
≥2	23 (65)	22 (45)	
Medication, n (%)			
0-3	29 (83)	44 (90)	0.24
4-6	6 (17)	5 (10)	
Physical Activity, n(%)			
1 (no activity)	0 (0)	1 (2)	
2 (very little activity)	4 (12)	12 (24)	0.34
3 (soft activities at least once/week)	19 (54)	20 (41)	
4 (hard activities/competitions regularly)	12 (34)	16 (33)	
Place of testing			
Laboratory	24 (69)	32 (65)	0.82
Home	11 (31)	17 (35)	
PFActS-C (fear avoidance)	35.8 (51.8)	NA	NA
Craniovertebral angle	45.1 (6.8)	41.6 (7.6)	0.055
Kyphosis index	13.0 (3.5)	13.6 (3.5)	0.45
Lordosis angle	10.6 (3.5)	10.3 (3.6)	0.39
Joint position sense right	3.6 (1.8)	3.1 (1.1)	0.12
Joint position sense left	3.3 (1.8)	2.7 (1.1)	0.10
Joint Position Sense total	3.4 (1.4)	2.9 (0.9)	0.045
Endurance Neck Flexors (sec)	59.7 (53.8)	60.0 (48.7)	0.65
Endurance Neck Extensors (sec)	180.0 (174.2)	241.1 (178.9)	0.052
Rate of Perceived Exertion Flexors	6.2 (1.7)	6.1 (2.4)	0.89
Rate of Perceived Exertion Extensors	5.9 (2.0)	4.8 (2.1)	0.006
Discomfort Flexors (/10)	5.7 (2.1)	4.9 (2.3)	0.13
Discomfort Extensors (/10)	5.9 (2.0)	4.3 (2.0)	0.005
Dix-Hallpike(%)			
Negative	30 (86)	45 (92)	0.80
Positive	5 (14)	4 (8)	
DVA	2.7 (1.6)	2.7 (1.5)	0.77
HIT			
No	21 (60)	26 (53)	0.63
Yes	14 (40)	23 (47)	
Cervical Rotation ROM (^{0})	119.3 (19.9)	118.2 (17.5)	0.57
Upper Cervical Rotation ROM (^{0})	53.8 (14.7)	55.3 (11.4)	0.78
Cervical Rotation ROM difference (^{0})	7.2 (6.2)	6.0 (4.8)	0.43
Upper Cervical Rotation ROM difference (^{0})	5.2 (3.8)	4.4 (3.8)	0.30
DGI (mean, SD), (/24)	20.3 (3.0)	21.49 (2.0)	0.024
AP Path velocity	1.19 (0.6)	0.97 (0.3)	0.015
AP amplitude	2.48 (0.8)	2.35 (0.6)	0.098

NDI: Neck Disability Index, NRS: Numeric Rating Scale, ABC: Activities-specific Balance Confidence, DHI: Dizziness Handicap Inventory, PFActS-C: Pictorial Fear of Activity Scale- Cervical, DVA: Dynamic Visual Acuity, HIT: Head Impulse Test, DGI: Dynamic Gait Index, AP: Antero-posterior

Figure 8-3: Interaction of neck pain and craniovertebral angle predicting path velocity. (error bars indicate standard deviation)

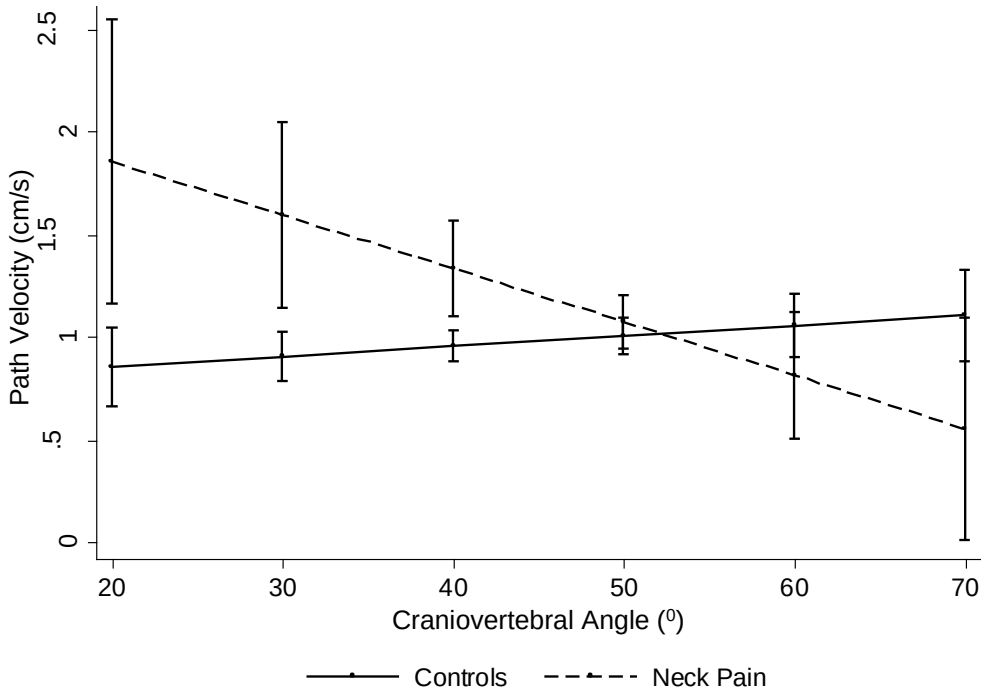


Figure 8-4 Interaction of neck pain and hallpike predicting path velocity.

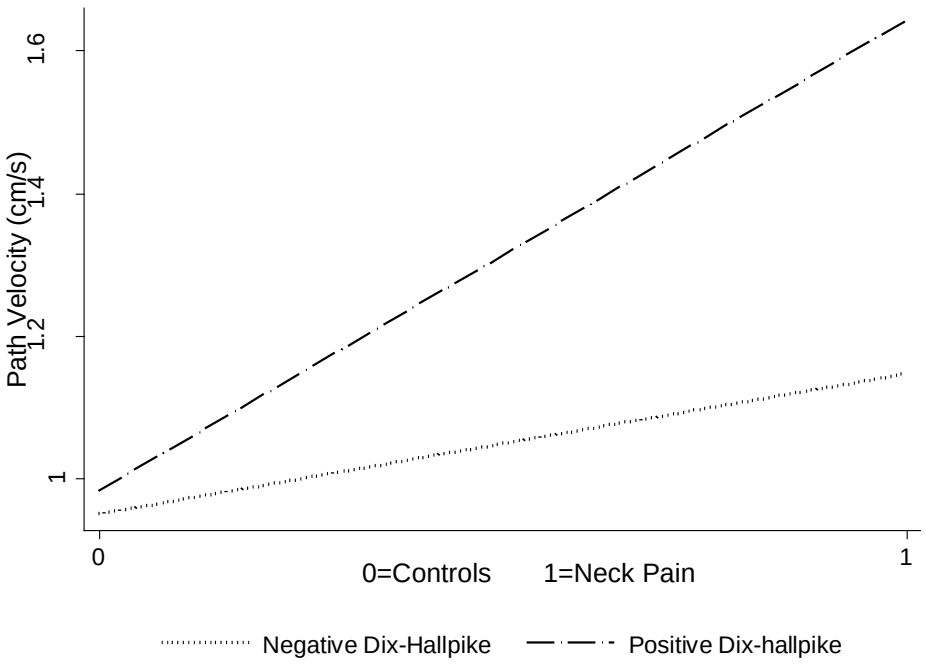


Figure 8-5 Interaction of neck pain and age predicting path velocity.
(error bars indicate standard deviation)

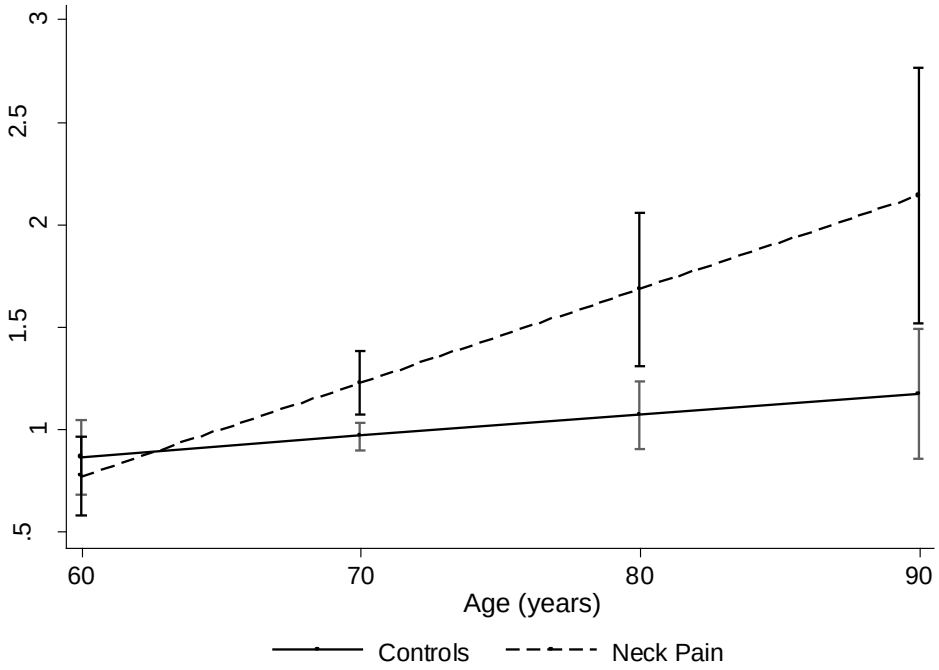


Figure 8-6 Interaction of neck pain and level of physical activity predicting path velocity.
(error bars indicate standard deviation)

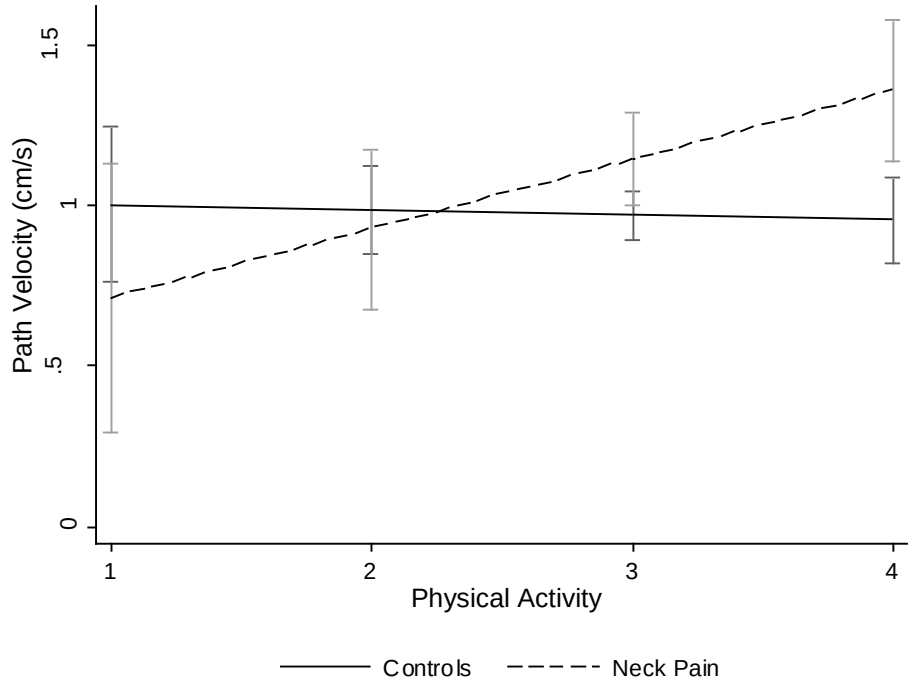


Table 8-2. Univariate regression analysis of variables on Path Velocity, Amplitude and Dynamic Gait Index (DGI) within the neck pain group (n=35).

	Path velocity as DV		Amplitude as DV		DGI as DV	
	Coefficient β	P-Value	Coefficient β	P-Value	Coefficient β	P-Value
Age	0.06	0.006	0.04	0.07	-0.18	0.023
Height	0.026	0.044				
Physical Activity	0.33	0.031				
CVA	-0.05	0.022	-0.05	0.008		
Dix-Hallpike	0.63	0.021	0.8	0.026		
NDI			0.036	0.046	-0.17	0.017
ABC					0.16	0.006
DHI					-0.14	0.004
PFActS-C					-0.03	0.001

ABC: Activities-specific Balance Confidence
CVA: Craniovertebral angle
DHI: Dizziness Handicap Inventory
DV: Dependent variable
NDI: Neck Disability Index
PFActS-C: Pictorial Fear of Activity Scale- Cervical

Table 8-3. Univariate regression analysis of variables on Path Velocity, Amplitude and Dynamic Gait Index (DGI) within the healthy controls (n=49).

	Path velocity as DV		Amplitude as DV		DGI as DV	
	Coefficient β	P-Value	Coefficient β	P-Value	Coefficient β	P-Value
Age	0.006	0.50	0.0002	0.99	-0.045	0.46
Height	0.017	<0.001	0.02	0.031	0.06	0.097
Weight	0.011	<0.001	0.017	0.002	0.008	0.70
Gender	0.23	0.003	0.31	0.06	1.09	0.059
ABC	0.012	0.13	0.24	0.14	0.13	0.025
Dix-Hallpike	-0.03	0.85	0.32	0.27	-2.44	0.017
Flexors endurance	0.002	0.005	0.002	0.21	0.007	0.26

ABC: Activities of Balance Confidence
DV: Dependent variable
DGI: Dynamic Gait index

Table 8-4. Multiple regression analysis of association between path velocity (DV), amplitude (DV), dynamic gait index (DV) and independent predictors within the NP group (n=35).

	Regression coefficient	SE of Regression coefficient	P Value	95% CI	R^2
Path velocity					
Age	0.028	0.011	0.019	0.005 to 0.05	
CVA	-0.03	0.008	0.003	-0.044 to -0.010	
Physical Activity	0.20	0.096	0.043	0.007 to 0.400	
Dix-Hallpike	0.62	0.14	<0.001	0.342 to 0.905	0.62
Amplitude					
Age	-0.010	0.016	0.55	-0.04 to 0.02	
CVA	-0.06	0.014	<0.001	-0.09 to -0.03	
Dix-Hallpike	0.90	0.23	<0.001	0.44 to 1.36	0.41
DGI					
Age	-0.14	0.05	0.014	-0.25 to 0.03	
PFActS-C	-0.026	0.011	0.025	-0.05 to -0.003	
DHI	-0.10	0.042	0.019	-0.19 to -0.018	0.52

CVA: Craniovertebral angle
DHI: Dizziness Handicap Inventory
DV: Dependent variable
PFActS-C: Pictorial Fear of Activity Scale- Cervical

Table 8-5. Multiple regression analysis of association between path velocity (DV), amplitude (DV), dynamic gait index (DV) and independent predictors within the healthy controls (n=49).

	Regression coefficient	SE of Regression coefficient	P Value	95% CI	R^2
Path velocity					
Age	0.011	0.007	0.145	-0.004 to 0.025	
Weight	0.010	0.002	<0.001	0.006 to 0.014	
Flexors	0.001	0.0005	0.031	0.0001 to 0.002	0.37
Amplitude					
Age	0.01	0.018	0.57	-0.026 to 0.046	
Weight	0.018	0.006	0.004	0.006 to 0.030	0.19
DGI					
Age	-0.07	0.042	0.10	-0.15 to 0.014	
ABC	0.13	0.053	0.016	0.027 to 0.24	
Dix-Hallpike	-2.67	1.10	0.019	-4.87 to -0.46	0.27

ABC: Activities of Balance Confidence
DV: Dependent variable

Table 8-6. Multiple regression analysis of association between path velocity (DV), and independent predictors with neck pain and controls (n=84).

Path velocity as DV	Regression coefficient	SE of Regression coefficient	P Value	95% CI	R^2
Model 1					
NP X CVA	-0.031	0.012	0.013	-0.055 to -0.007	
Age	0.023	0.007	0.002	0.008 to 0.038	
CVA	0.005	0.003	0.202	-0.002 to 0.013	
Physical Activity	0.018	0.050	0.73	-0.088 to 0.125	
Dix-Hallpike	0.292	0.114	0.012	0.066 to 0.518	
NP	1.62	0.59	0.008	0.440 to 2.80	
Weight	0.009	0.003	0.004	0.003 to 0.0149	
Flexors	0.0007	0.0007	0.286	-0.0006 to 0.002	0.50
Model 2					
NP X Hallpike	0.462	0.198	0.022	0.067 to 0.857	
Age	0.026	0.009	0.005	0.008 to 0.044	
CVA	-0.004	0.005	0.428	-0.015 to 0.006	
Physical Activity	0.077	0.055	0.166	-0.033 to 0.186	
Dix-Hallpike	0.032	0.103	0.752	-0.172 to 0.234	
NP	0.196	0.096	0.044	0.006 to 0.387	
Weight	0.011	0.003	0.005	0.008 to 0.044	
Flexors	0.0004	0.0007	0.005	0.008 to 0.044	0.47
Model 3					
NP X Age	0.035	0.015	0.021	0.005 to 0.065	
Age	0.010	0.008	0.205	-0.006 to 0.026	
CVA	-0.002	0.005	0.736	-0.012 to 0.008	
Physical Activity	0.056	0.052	0.281	-0.047 to 0.159	
Dix-Hallpike	0.214	0.114	0.006	-0.013 to 0.441	
NP	0.241	0.085	0.006	0.073 to 0.410	
Weight	0.010	0.003	<0.001	0.005 to 0.015	
Flexors	0.0006	0.0006	0.331	-0.0006 to 0.002	0.49
Model 4					
NP X Physical Activity	0.265	0.109	0.017	0.048 to 0.482	
Age	0.028	0.008	0.001	0.013 to 0.044	
CVA	0.0003	0.005	0.948	-0.009 to 0.010	
Physical Activity	-0.016	0.055	0.770	-0.125 to 0.093	
Dix-Hallpike	0.323	0.119	0.008	0.086 to 0.560	
NP	-0.612	0.347	0.082	-1.303 to 0.079	
Weight	0.010	0.003	0.001	0.004 to 0.016	
Flexors	0.0007	0.0007	0.310	-0.0007 to 0.002	0.48

CVA: Craniovertebral angle
DV: Dependent variable
NP= Neck Pain

8.7 Discussion

This study explored the associations between cervical spine impairments with static and dynamic postural control measures in older adults with and without idiopathic NP. Stepwise multivariate regression analysis demonstrated that greater forward head posture and a positive Dix-Hallpike test, greater age and physical activity are associated with increase postural sway ($p<0.05$) and higher dizziness handicap, fear avoidance (Pfacts) and greater age are associated with reduced dynamic postural control ($p<0.05$) in the NP group. Further, moderation analysis revealed that NP significantly moderated the relationship between path velocity and 4 variables- forward head posture, a positive Dix-Hallpike test, age and physical activity.

Reviewing the literature, we were unable to find any studies that comprehensively investigated the factors associated with postural control in older adults with idiopathic NP. Our study revealed that, amongst all the cervical impairments considered, only FHP was associated with static postural control. Interestingly, moderation analysis results demonstrated that NP moderated the relationship between FHP and static balance. In other words, this relationship exists only in the presence of NP and did not hold true for the healthy controls. Further, a similar pattern of results was observed for three covariates: a positive Dix-hallpike test, age and physical activity. In this sample of older adults, a positive response to the Dix-hallpike test, being older and being more active were significant predictors of increased CoP velocity in static standing with eyes closed in the NP group but not in the healthy group. Our results suggest that altered postural control in older adults with NP is not merely a matter of identifying specific local cervical spine impairments. Rather these changes may be a complex function of delicate interplay between afferent and efferent mechanisms.

8.7.1 Static postural control

8.7.1.1 Forward head posture

It is biologically plausible that assuming a greater forward head posture may affect the postural alignment by displacing the body's centre of mass anteriorly and consequently imposing a perturbing influence on postural sway. However, this biomechanical factor cannot adequately explain the effect of forward head posture on static postural control because this relationship did not exist in the healthy controls. Importantly, there were also no statistically significant differences in forward head posture values between NP and control groups ($p>0.05$). This result is consistent with that of Silva et al. (2009) who found

no statistical differences in forward head posture between non-traumatic NP and healthy controls in adults (age range 51-68 years). Our study provides circumstantial evidence of the link between head posture and postural control and it may explain why previous research failed to find any effect of FHP on static postural control in healthy controls (Silva & Johnson, 2013), because our results indicate that NP moderated this relationship. On the other hand, another study performed in healthy computer workers demonstrated significant associations between forward head posture and static and dynamic balance as measured by the NeuroCom (Kang et al., 2012). This study unfortunately measured the craniovertebral angle of the participant in sitting after 2 hours of computer work (which reflects dynamic control of spinal posture) as opposed to the current study, where craniovertebral angle was measured in standing and therefore their results may not accurately represent the true physiological responses of the effect of forward head posture on postural sway in standing.

8.7.1.2 Kyphosis and Lordosis

On the other hand, thoracic kyphosis and lumbar lordosis did not demonstrate any association with both static and dynamic postural control. Contrasting our results with studies that found increased kyphosis was associated with greater postural sway and dynamic balance measures (Katzman et al., 2011; Lynn et al., 1997), it may be reasonable to speculate that the degree of kyphosis in this group of adults was not severe enough to significantly influence postural control. However, our results is consistent with previous studies which found that thoracic kyphosis is not associated with postural control impairment (Eum et al., 2013; Greig et al., 2007). Another possible explanation may be that the effect of spinal curvature on postural control may be more complicated than initially envisaged. Previous EMG studies revealed that the level of muscle activity of the extensor back muscles was different depending on the combinations of thoracolumbar and lumbar curves (Claus et al., 2009), and lumbar extensor muscle fatigue has been associated with postural sway (Davidson et al., 2004). Rather than merely focusing on individual segments of the spine, future research may need to explore the complex interaction between spinal segments on postural control.

One may question why FHP, not thoracic kyphosis influenced postural control in NP? Theoretically, FHP may have a greater potential to alter cervical spine proprioception than thoracic kyphosis. Although our study results did not demonstrate any differences between NP and controls in JPE in cervical rotation, we did not measure JPE in the sagittal plane (ie. cervical flexion and extension). It may be possible that the JPE is altered in the sagittal plane affecting postural sway in standing. Alternatively, it may be plausible that poorer endurance

of the neck extensor muscles in NP mediated the relationship between FHP and postural sway. Our results demonstrated that the NP group had a trend towards a lower neck extensor muscle endurance compared to the controls (180 sec in NP, 241 sec in controls, p=0.052) and previous research has demonstrated the effect of neck muscle fatigue on postural control. As mentioned, in chapter 8 (study 6), it may be possible that this study was limited by the mild to moderate nature of NP and therefore unable to demonstrate direct effects of neck muscle endurance on postural control but may have an indirect influence on postural sway via FHP. Future research should consider evaluating the mediating effects of JPE in the sagittal plane and muscle fatigue on FHP and postural control and recruiting subjects with greater pain and disability.

8.7.1.3 Joint position error and neck muscle fatigue

Contrary to our hypothesis, cervical spine impairments of joint position error and neck muscle fatigue were not associated with any postural control measures (p>0.05). Whilst overall altered JPE is seen to be consistently associated with NP (Cheng et al., 2010; Kristjansson et al., 2003; Sá & Silva, 2017), this is not always demonstrated (de Vries et al., 2015; Grip et al., 2007; Sjölander et al., 2008; Uthaikhup et al., 2012). Given that the threshold for abnormal joint position error is known to be 4.5^0 (Revel et al., 1991), the mean values in the current study (2.7^0-3.4^0) suggest that JPE was not a significant finding in most participants. Although we had no previous study with the same population of older adults with idiopathic NP to compare with, joint position error of the cervical spine in patients with whiplash was also not highly correlated with reduced postural control (Treleaven et al., 2003). It may be possible that the measurement of conscious proprioception of JPE is not relevant for unconscious measures such as balance (Röijezon et al., 2015). An alternative explanation for the lack of significant findings in JPE in older adults in the NP group may be that the levels of pain and disability reported in this group were not high enough to elicit deficits in proprioception in the cervical spine. Although deficits in JPE generally exist in idiopathic NP, there are some inconsistencies reported in the literature showing some studies demonstrate positive findings but some don't (de Vries et al., 2015; Stanton et al., 2016). Nevertheless, we think that the JPE measures used in this study is sufficient to detect differences between idiopathic NP and control groups (Chen & Treleaven, 2013). Table 8-1 shows that there are statistical differences between groups (p=0.045) but this difference may not be clinically significant for the reasons stated above.

Likewise, cervical spine flexor and extensor muscle endurance were not associated with postural control, contrary to our expectations. Interestingly, both neck flexor and

extensor muscle endurance did not differ significantly between older adults with and without NP in this study. Our study was consistent with previous studies which did not find any significant differences in neck flexor (Wirth et al., 2014) and extensor (Edmondston et al., 2011) muscle endurance between those with and without NP. This is in contrast to other studies who found that adults with NP demonstrated reduced neck flexor (Martins et al., 2017) and extensor endurance (Lee et al., 2005) in people with NP compared to healthy controls. It is unclear why there are discrepancies in the literature. Some authors have suggested that the large variability of test performance may influence the results (Edmondston et al., 2011). It may also be possible that our sample of older adults could be subjected to participation bias. Given that endurance tests are highly influenced by the level of motivation of the individual (Moreau et al., 2001), it may be possible that our sample population included older adults who were more motivated compared to the general population with NP. Similar to JPE, these tests of muscle fatigue were perhaps not a specific measure of proprioception and further research may consider using vibration of targeted cervical muscles (Beinert et al., 2015) to stimulate the muscle spindles of the cervical spine or electromyography (Stapley et al., 2006) to determine the effects of altered proprioception and postural control in older adults with idiopathic NP. In addition, it may also be possible that the lack of group differences in neck muscle endurance tests was due to the mild to moderate nature of pain and disability in the NP group.

From a methodological perspective, we selected the population of idiopathic NP and excluded those with trauma such as whiplash so as to limit the influence of trauma related vestibular deficits on postural control. However, in this group of idiopathic NP, impairments are less and not always identified. As such, it is likely that this group of older adults with idiopathic NP did not demonstrate great deficits in postural control, perhaps due to the stringent recruitment criteria applied. Thus it was difficult to find clear associations between impairments and postural control measures.

8.7.1.4 Dix-Hallpike

Regarding the association between a positive Dix-Hallpike test and standing postural sway in older adults with NP, we were surprised at this finding because these older adults with NP had a positive response to Dix-Hallpike test did not report any a current history of BPPV or neurological diseases, nor did they exhibit any symptoms of dizziness that affected their daily function. Interestingly this association was only true for the NP group, despite a similar number of subjects in the healthy control group having a positive response to the Dix-Hallpike test. It is unclear at this stage whether the criteria used in our study for a positive

response to the Dix-Hallpike ie any positional nystagmus (regardless of the direction or fatigue) and/or symptoms evoked, indicates an early manifestation of disease onset via disruption of central pathways (Macdonald et al., 2017) or peripheral vestibular hypofunction (Büttner et al., 1999). Even though there is no literature to support or refute our findings, this is an interesting discovery that may contribute to the understanding of the mechanisms underpinning NP-related postural control deficits. Noteworthy, we acknowledge that because our findings were based on a very small number of subjects with positive Dix-Hallpike test (5 in NP group and 4 in the control group), it is difficult to make conclusive inferences and clearly points to further research in this area.

8.7.1.5 Age

Similarly, age was only a significant predictor of static postural sway in the presence of NP but not in the control group in our study sample. The results of our study is consistent with the experimental evidence of Patel et al (2010) where the authors found a significant change in movement coordination patterns in older adults when vibrating the neck muscles but no change was observed in the young adults. The authors interpreted these findings to indicate that postural control was more challenging for the older adult as compared to the young adult during disturbance of the neck proprioceptors. Accordingly, these findings may explain why age had a significant effect on postural control only in the presence of NP and not in the control group. In contrast, previous study comparing postural control in older adults with and without NP did not show significant differences in age between the 2 groups (Poole et al., 2008). However, this study did not comprehensively examine the associations of multiple variables of postural control in individuals with and without NP and therefore cannot be directly compared with the results of our study.

8.7.1.6 Physical Activity

Our results indicate that the level of physical activity was positively associated with postural sway in static standing. This was counter-intuitive as a previous study has shown that sedentary older adults had increased postural sway compared to active older adults, (Prioli et al., 2005) and we thought that people with NP would either show no difference in physical activity levels compared to healthy adults (as per study 7) or reduced levels. In our analysis, we detected 2 outliers that skewed the data and the association between CoP velocity and the level of physical activity became insignificant when these 2 outliers were removed. Perhaps this unexpected finding is a consequence of participation bias and may not truly reflect the association between the level of physical activity and postural sway in

the general population of older adults with NP. On the other hand, it is possible that the magnitude of postural sway may not a good reflection of postural control. Previous study has suggested that an increase in postural sway may be an exploratory strategy used by the CNS to gain information about the environment, rather than a manifestation of impaired postural control (Carpenter et al., 2010).

8.7.1.7 Mechanisms underpinning postural control deficits in neck pain

An intriguing question that remains unsolved is the underlying mechanisms underpinning postural control deficits in older adults with NP. Bringing all the results together, it is conceivable that a likely explanation for our findings is that NP induced postural deficits are not just a result of specific cervical spine impairments at a peripheral level but a sensorimotor mismatch in the integration of sensory inputs (Treleaven, 2008). It may be possible that sensory integration at the central level is compromised as a result of deterioration of proprioceptive input from the cervical spine. This is biologically plausible given the intricate anatomical central and reflex connections the cervical spine afferents have with the vestibular, visual and central nervous systems (Treleaven, 2008). Specifically, it has been suggested that damaged cervical joint receptors in the upper cervical spine results in abnormal afferent input to the vestibular nuclei of the brainstem, and potentially a cause of cervicogenic dizziness (Ryan & Cope, 1955).

Although there is currently no research available (to our knowledge) to support this postulation, a recent neuro imaging study demonstrated an indirect link between decreased integrity of the superior cerebellar peduncle and proprioceptive sensory data processing in individuals with low back pain (Pijnenburg et al., 2014). In this study, the authors showed that compared to healthy controls, individuals with chronic low back pain had significantly reduced integrity of the superior cerebellar peduncle, and this was associated with an increased standing CoP postural sway post vibration to the triceps surae muscles. The results imply an increased reliance on ankle muscle proprioceptive signals and therefore a weaker proprioceptive weighting capacity. As such, it is possible that individuals with NP may have proprioceptive deficits as a result of peripheral and central changes. Consequently, any compromise to the efficiency of the other elements involved in the postural control system such as subclinical vestibular hypofunction or subclinical central degradation, increased age or a change in head posture may result in increased postural sway. However, future research with a focus on neuro-imaging in NP and postural control deficits is warranted to confirm this proposition.

Another suggested theory to explain NP-related postural control changes include a neurovascular hypothesis where the degenerative changes in the cervical spine could cause mechanical irritation of the sympathetic plexus surrounding the vertebral arteries, in turn producing reflexive vasoconstriction in the vertebrobasilar system resulting in symptoms of disequilibrium (Barré, 1926). However, these theories remain to be proven and point to a need for more research to be done to understand the mechanisms underpinning NP related postural control deficits.

8.7.2 Dynamic postural control

As previously stated, dizziness, fear avoidance and greater age in older adults with NP were associated with reduced dynamic balance. These findings are important as it implies that older adults with NP who demonstrate dizziness and high fear avoidance may be at a higher risk of falls. Our study results are analogous to previous findings which showed that suffering from neck or back pain and anxiety were significant mediators of the relationship between dizziness and falls (Menant et al., 2013). It is possible that dizziness experienced by the older adults with NP in this study may be due to sensory conflicts between the cervical spine and vestibular afferents (Hikosaka & Maeda, 1973) which in turn increased their fear of movement. Further, previous study showed that the efficiency of postural regulation diminishes with age (Maitre & Paillard, 2017). Our study provides a basis for future interventional studies to determine whether addressing the anxiety of the fear of neck movements and treating the cervical spine dysfunction will improve dynamic postural control and potentially reduce the risk of falls. Noteworthy, dizziness is a symptom often related to NP (Magnusson & Malmstrom, 2016) and treatment directed at musculoskeletal deficits may be needed to help reduce dizziness (Malmström et al., 2007).

8.7.3 Wavelet analysis

When considering results of the wavelet analysis, consistent with the opinion of Maitre et al. (2013) (Maitre & Paillard, 2017), age was positively associated with the CoP velocity within the moderate frequency. However, it is difficult to meaningfully interpret the rest of the results of the wavelet analysis as our results did not give clarity or give further insights to the complex mechanisms that underlie postural control deficits in NP. It may be possible that wavelet analysis may not be an effective means to enhance our understanding of postural control mechanisms in the NP population studied here.

8.8 Implications

Our study results have several important clinical and research implications. Firstly, given that testing for BPPV is currently not a routine practice in the management of NP, especially when patients do not complain of ongoing symptoms, therapists may want to consider testing for BPPV in older adults with NP. This would be particularly important especially for those who have known vestibular problems. More research is needed to better understand how a positive Dix-hallpike test in asymptomatic BPPV influences postural control in older adults with NP. Secondly, interventional studies are also needed to determine if addressing forward head posture in older adults with NP and treatment of vestibular hypofunction will improve postural control. Thirdly, given the results of the study, therapists ought to be alerted when NP patients present with some form of dizziness, have signs of the fear of movement and are advanced in age as these patients may be at risk of reduced dynamic balance and hence be predisposed to falls. Fourthly, given the complex nature of postural instability in older adults with NP, the findings of this study raise the question of whether specific postural control exercises may be needed to address altered postural control in older adults with NP (Beinert & Taube, 2013). Lastly, an important implication of this study is the potential role the central nervous system plays in influencing postural control in older adults with NP and points to the need for neuro-imaging research to be done.

8.9 Limitations

The findings of this study need to be interpreted in the context of its limitations. First, this study is cross-sectional in nature and therefore cannot infer causation. Second, even though the vestibular tests selected were clinically relevant, they did not have the precision that is required to detect subtle deficits in eye movement and may result in under reporting of vestibular impairments. Third, because we chose to use very strict criteria to recruit older adults with NP and excluded those with other significant physical issues such as other musculoskeletal disorders and vestibular dysfunction, the distribution of the patients in our study may not reflect the general population of older adults who potentially may demonstrate multiple concurrent comorbidities. Fourth, the physical activity questionnaire used in this study has not been validated in older adults with NP and might not be sufficiently sensitive to reflect different physical activity levels of these older adults. Future studies ought to include more details in validated physical activity measures in older adults with NP. Lastly, as an exploratory study, our results demonstrated a modest number of participants that were

tested positive in Dix-hallpike: 5 in the NP group, and 4 in the control group. Future studies might consider replicating the study in larger sample size.

8.9 Conclusion

In conclusion, this study identified the factors associated with static and dynamic postural control in older adults with NP. The results showed that greater forward head posture angles, testing positive on the Dix-hallpike manoeuvre, being of advanced age and higher levels of physical activity are associated with greater postural sway in static standing. Further, greater dizziness disability, fear of movement and age are associated with poor dynamic postural control. Our study suggests that the mechanisms underpinning postural control deficits in NP are complex and provides a basis for future studies to explore the role of the central nervous system and its integration of somatosensory input in maintaining postural stability in older adults with NP.

Chapter 9: Summary and implications of findings, future research directions and conclusions

The overall objectives of this thesis were to i) explore new measurement tools and technique related to cervical spine impairments and postural control that may be potentially useful in research and in the clinical setting (studies 1 to 3) and ii) to better understand the mechanisms underpinning NP-related postural control deficits in older adults (studies 4 to 6). This chapter aims to bring together the work of this thesis and to integrate the findings to a broader context.

9.1 Brief summary of the findings of each study

Study 1 (chapter 3) investigated the validity and reliability of an Android smart phone to measure cervical spine range-of-motion in sitting in healthy adults. The results demonstrated that an Android phone is valid and reliable to measure cervical range-of-motion for the sagittal plane (ie. flexion and extension) and the coronal plane (ie. lateral flexion) but not the transverse plane (ie. rotation). This study implies that an Android phone may not be useful to measure cervical range-of-motion in both clinical and research purposes where movements involving rotation in sitting are required.

Study 2 (chapter 4) assessed the validity and reliability of the Microsoft Kinect for measuring thoracic kyphosis. The findings show that the Microsoft Kinect is valid and reliable to measure thoracic kyphosis. Given the ease of use and relative affordability, the Microsoft Kinect may have the potential to facilitate the routine evaluation of thoracic kyphosis in the clinical setting. Future research may consider developing advanced software programs to improve the speed of calibration and faster processing time to help facilitate the ease of use and speed of obtaining thoracic kyphosis measurements for clinical use.

Study 3 (chapter 5) examined the intra-rater reliability of the Nintendo Wii Balance Board to measure hallux flexor muscle strength. The results of the study demonstrate that this new method reliably measures hallux flexor strength and has the potential to be useful in the context of research and clinical practice. This study demonstrates that there is great potential for the Nintendo Wii Balance Board to be used in a wider scope, and calls for future studies to explore strength testing in other muscle groups.

Study 4 (chapter 6) explored possible mechanisms of standing postural control using novel analytical techniques of time-frequency (wavelet analysis) and complexity (sample

entropy) in older adults with and without NP. This study highlighted the potential use of wavelet analysis to reveal new insights into postural control mechanisms. Specifically, the results showed an increased sway signal within the very low frequency band (0.1 to 0.39 Hz) and a decrease in sway signal within the moderate frequency band (1.56 to 6.25 Hz) in older adults with NP compared to healthy controls. Given the physiological associations of the centre-of-pressure signal movements of the very low and moderate frequencies with the vestibular system and muscular proprioceptive input respectively, it is postulated that because older adults with NP demonstrated a diminished ability to recruit the proprioceptive system compared to the healthy controls, they recruited the vestibular system for postural stability. On the other hand, sample entropy results did not allow for meaningful conclusions to be made.

Study 5 (chapter 7) sought to understand the mechanisms underlying postural control deficits associated with NP by comparing visual, vestibular and lower limb function as well as the level of physical activity between older adults with and without NP. This study also explored the use of wavelet analysis to gain further insights into these mechanisms. The findings reveal that there were no differences in visual, vestibular and lower limb function and the level of physical activity in older adults with NP compared to the healthy controls. The results of this study suggest that postural control changes in NP are likely due to altered cervical proprioceptive input to the sensorimotor system and its associations with the cervical spine. Wavelet analysis demonstrated sensory reweighting but further research needs to be done to better define the physiological significance of the CoP signal content within the frequency bands.

Study 6 (chapter 8) identified the factors associated with static and dynamic postural control in older adults with NP. The findings of the study demonstrated that greater forward head posture angles, exhibiting a positive response on Dix-hallpike manoeuvre, being of advanced age and higher levels of physical activity are associated with greater postural sway in static standing. In addition, greater dizziness disability, fear of movement and age are associated with poor dynamic postural control. The results of this study suggest that the mechanisms underpinning postural control deficits in NP are complex. Moreover, it highlights a need for future studies to explore the role of the central nervous system and its integration of somatosensory input in maintaining postural stability in older adults with NP.

9.2 Implications of this thesis for the use of commercially-available technology in assessment in research and clinical practice

Performing accurate and reliable objective measurements in the research and clinical settings are often limited by the availability and accessibility of resources and measurement tools. This thesis explored the validity and/or reliability of three new methods to measure impairments associated with cervical spine and postural control that are not routinely assessed objectively because of reasons such as practicality, cost and accessibility. Specifically, the Android phone application was developed to measure cervical range-of-motion, the Nintendo Wii Balance Board application was developed to measure the hallux flexor strength and the Microsoft Kinect was assessed to measure thoracic kyphosis.

9.2.1 The Android phone application

The results of study 1 showed that the Android phone is only valid and reliable to measure cervical range-of-motion in the sagittal (ie. flexion and extension) and coronal planes (ie. lateral flexion) but not in the transverse plane (ie. rotation) in sitting. It is interesting to note the reliability of the 3DMA was not particularly good for rotation range-of-motion measurements. As mentioned in study 1, it was not possible to determine whether the poor reliability results of the 3DMA were due to intra-day subject variation or equipment-related measurement error. If it was the former reason, it would explain the poor reliability results for the phone. If it was the latter, the phone reliability results would not be affected, Given that the results of our study is consistent with that of the previous study (Tousignant-Laflamme et al., 2013), which also demonstrated poor reliability results for cervical rotation range-of-motion using the iphone, it is highly likely that the poor reliability results for cervical rotation measurements are influenced by magnetic field interference. Therefore, it may not be a useful tool for therapists and researchers for cervical range-of-motion evaluation since rotation range-of-motion forms a significant part of the assessment in cervical spine disorders. Alternatively, the Android phone may be useful if cervical rotation ROM testing is done in supine, since cervical rotation ROM measurement performed in this position does not depend on the magnetometer. However, the supine position may not be functional. Therefore, it is because of this reason that we did not use the Android phone to assess the cervical range-of-motion in studies 5 & 6. However this application may be useful for some situations, particularly where rotation measurement in sitting is not crucial. Future studies are warranted to determine if the Android phone is valid and reliable to measure cervical rotation ROM in the supine position.

Practically, we made minor modifications to a bicycle helmet in testing to affix the phone firmly. This could be easily done in clinical practice. We also used a customised APP to measure range of motion. While this was accurate and simple to use, it is not readily available to all therapists. The development of technology needs to be accompanied by a translation plan to permit clinicians to access and use the latest versions of data collection programs.

9.2.2 Nintendo Wii Balance Board

The Nintendo Wii Balance Board application reliably measures hallux flexor strength and shows great potential for future research and clinical use. Moreover, the Nintendo Wii Balance Board application is inexpensive and straightforward to set up. Consequently, the Nintendo Wii Balance Board was used in studies 5 & 6. However, one criticism of testing the big toe strength with the subject in sitting is that this position may not be directly applicable to standing postural control. The sitting position was selected as part of the setup using the NWBB because the setup allowed minimisation of compensatory strategies from the ankle and the trunk, which would not be possible to detect if the test was performed in standing. Moreover, toe flexor muscle strength tests performed in a non-weightbearing position in another study was sufficient to demonstrate that the ability to generate force from the hallux and second toe flexor muscles was associated with the incidence of falls in the elderly (Mickle, K. J. et al., 2009).

More studies need to be completed using the Nintendo Wii Balance Board application on populations with balance and foot problems. Furthermore, given that the Nintendo Wii Balance Board is accurate and reliable using embedded load cells to measure force output, this study serves as a platform for future studies to explore strength testing in other body parts.

Practically, to be reliable, we constructed a customised frame linked to the chair and the Nintendo Wii Board to ensure repeatable isolated movements that minimised the ability to compensate with other muscle groups. This would need to be constructed or replicated in a similar manner by therapists to ensure similar levels of repeatability. Noteworthy, the customised software is freely available -- http://www.rehabtools.org/strength.html and the time taken for strength measurement including the set up takes no more than 10 minutes.

9.2.3 Microsoft Kinect

Lastly, compared to the flexicurve, the Microsoft Kinect is valid and reliable to measure thoracic kyphosis. The flexicurve is cheaper than the Kinect, is portable and easy to use. However, obtaining the results is not instant like the Kinect and a substantial greater

amount of time and effort is needed to process the data for the flexicurve compared to the Kinect. Given its relative affordability and ease of use, the Microsoft Kinect may enhance the routine evaluation of thoracic kyphosis, especially important in the older population. Please see table 9.1 for the comparison between flexicurve and the Microsoft Kinect. This study forms the basis for future study to consider assessing the validity of the Microsoft Kinect against the gold standard of radiological images. Even though the findings of this study support the use of the Microsoft Kinect to measure thoracic kyphosis in studies 5 & 6, we decided to use the flexicurve instead for good reasons. The Kinect would have been ideal if data collection was contained within the laboratory as it would not require repeated calibration as long as the position of the Kinect did not change. However, due to the nature of the research, data collection also involved going to participant's homes which we anticipated would significantly add to the total length of research testing time, hence increasing the risk of fatigue for the participant. Moreover the Kinect needs a power supply and this may be a problem in some homes depending on the home set up. Therefore, all things considered, we decided not to use the Kinect for study 6. Nevertheless, given the advantages of immediate availability of results, easy access and storage of the data electronically and the potential for remote distance assessment, incorporating technology into physiotherapy practice may enhance clinical practice.

Table 9-1 Comparison between the Flexicurve and the Kinect

	Flexicurve	**Kinect**
Portability	Light and portable	Portable but more bulky compared to flexicurve
Affordability	Extremely affordable US$15	Fairly affordable US$150
Power source needed	No	Yes
Calibration needed	No	Yes, 5 minutes
Processing time	Significantly greater than Kinect, 20 minutes	Very minimum, 30 seconds
Software needed	No	Yes
Overall ease of use	Fair	Very good

9.2.4 Limitations

A major limitation of these studies that explored technology is that only healthy participants were examined, hence restricting the generalizability of the results.

Consequently, future studies ought to consider replicating the studies in older adults with NP and other populations of interest.

It must also be noted that the systems used as part of this thesis will not be around forever. The Nintendo Wii Balance Board is becoming harder to purchase new, and does not appear to be in the future plans of Nintendo. The Microsoft Kinect is now considered a failure from a sales standpoint and smartphones evolve every year. However, even if these systems become obsolete in the near future the findings of this thesis indicate that there may be a role for low cost technology in the assessment of NP-related physical function.

9.3 Implications for understanding mechanisms underpinning postural control deficits in older adults with NP

Static and dynamic postural control deficits are consistently more pronounced in older adults with NP when compared to healthy controls (studies 4 and 5). This implied alteration in postural control associated with NP is complex and cannot be explained simply by examining the differences in function or impairments between older adults with and without NP (study 5). Rather, the findings of studies 5 & 6 suggest that altered postural control may not be a result of a single variable but more likely an interaction of multiple factors. Furthermore, these postural control deficits may not be viewed merely from a peripheral or spinal perspective but should also be considered from a supra-spinal perspective. However, no neuro-imaging research has been done in this area and future studies are required to validate these postulations.

It is not possible to establish if postural control deficits were a consequence of the multiple factors identified in study 6 or that these factors such as our criteria used for a positive response to Dix-hallpike test, forward head posture or dizziness were present prior to the changes in postural control. Further investigations including longitudinal studies are warranted.

9.4 Implications of this thesis for the use of wavelet analysis

It is unclear which method of calculation and the exact frequency band ranges most accurately reflects the physiological reality of systems representation in postural control. Study 4 used proportions and study 5 incorporated both proportions and absolute values. The results of study 4 demonstrated a lower proportion of moderate frequency content (1.56 to 6.25Hz) in the CoP signal and a higher proportion in the very low frequency band (0.1 to 0.39 Hz) in older adults with NP compared to the healthy controls. Noteworthy, the use of a

percentage is essentially converting the data into a ratio between the different bands, which has numerous flaws including obtaining the same value if the sway in each band goes up proportionately. A potential issue with this is that the majority of the signal occurs in the higher frequency bands, with little occurring in the lower frequency bands, and therefore a ratio method may mask the true findings if small but important changes are occurring in the lower frequency bands.

On the other hand, study 5 showed a higher CoP velocity signal in the moderate frequency (1.56 to 6.25 Hz) and lower in the low frequency band (0.39 to 1.56 Hz). It is important to note that the methods of calculation are different in studies 4 and 5 for the reasons stated above. However, when we analysed our results using proportion in study 5 (same method used in study 4), we did not obtain consistent results with that of study 4. Further, even though various authors have suggested physiological links that the CoP signals in the lower frequencies are associated with visual (Chagdes et al., 2009) and vestibular (Oppenheim et al., 1999) activities and that the higher frequencies are associated with the muscular proprioceptive (Lacour et al., 2008; Paillard et al., 2002) and central nervous system (Paillard et al., 2002) activities, apart from the ultralow frequency (<0.1 Hz) (Chagdes et al., 2009) there is currently no definitive empirical evidence that exists to validate these assertions. Given the paucity of evidence and the inconsistent results in studies 4 and 5, it may be premature at this stage to propose firm conclusions regarding the usefulness of wavelet analysis in revealing mechanistic insights into postural control in this population. More research clearly needs to be done.

9.5 Clinical implications for older adults with NP

Current treatments of NP in older adults do not focus on the assessment and management of postural control. These studies suggest that older adults with NP demonstrate altered postural control in standing with eyes open (studies 4 & 5), reduced dynamic balance ability as measured with the clinical balance tests of the TUG and the DGI (studies 4 & 5) and lower balance confidence (study 5) compared to healthy controls. The average DGI performance in both studies for people with NP was at a level that placed these adults at risk of falling. As such we would recommend that clinicians consider adding the DGI to their assessment routine for people with NP, particularly if they are concerned about possible postural instability or an increased risk of falls in their patient.

We suggest that Dix-hallpike manoeuvre form part of the cervical spine assessment even in the absence of any symptoms of dizziness. A positive response to the test (nystagmus regardless of direction or pattern in addition to symptoms of dizziness or

nausea) should indicate further assessment. Further, a combination of high fear of movement and symptoms of dizziness in older adults with NP may call for a need for individualised fall risk assessment and management.

The results of the thesis imply that craniovertebral angle may be considered as a predictive measure of postural instability (increased sway) in quiet standing in older adults with NP. It is notable that many cervical spine impairments were not predictive of reduced postural control in standing. For a complete assessment, these impairments may be present in older adults with NP and therefore important to be assessed to ascertain the levels of ability, but in this study, it was not related to postural control.

9.6 Methodological implications

Although the strengths and limitations of each study have been mentioned within the respective chapters, this section gives an overview of some important issues that require consideration.

9.6.1 Selection of participants

All recruitment and data collection was completed by a single assessor (JQ). Although there are advantages to this approach, specifically removing inter-rater measurement error, a limitation of this approach is the possibility of bias as the investigator could not be blinded to group allocation (NP vs healthy controls). A strength of the research design was that a strict criteria was employed during the recruitment process to eliminate any potential confounders. In particular, many older adults with significant musculoskeletal pain such as back and lower limb pain, traumatic NP and vestibular problems were excluded. As a result, the findings of the thesis may be limited only to relatively healthy older adults with and without NP and cannot be generalized to the broader population of older adults or to all older adults with NP.

9.6.2 Sample size and data analysis

In study 5, the a priori sample size calculation based on two-tailed hypothesis using Cohen's d = 0.5, alpha = 0.05 was 64 per group. Our sample of 35 in the NP and 49 in the control groups were unfortunately below the targeted sample size. This was due to a couple of reasons. First, it was very challenging recruiting older adults with minimal co-morbidities. Further, we had to exclude many who had NP of traumatic origin and those with significant co-morbidities because of their potential influence on postural control. We also had to exclude several participants (12) that did not quite meet the criteria of both NDI of >11% and

a VAS of at least 2/10. Consequently, a small sample size increases the chance of a type 2 error.

In study 6, an a priori sample size estimate of 70 subjects (in total including NP and controls) was calculated based on conservative estimates using Cohen's f^2 method of effect size determination (f^2=0.2) and a maximum of 5 predictor variables to achieve 80% power. Noteworthy, multiple regression models with a minimum of 10-15 observations per predictor variable has been shown to reveal stable estimates (Babyak, 2004). In light of this evidence, multivariate regression models in Tables 8-4 and 8-5 consisted of mostly 3 variables (one model had 4 variables) for sample size of 35 (NP group) and 49 (control group) respectively. In the moderation analysis in Table 8-6, there was a maximum of 8 predictor variables for a sample size of 84. As it turns out, our a priori sample size calculation was conservative and therefore we think that the sample size obtained for the purpose of this study was mostly sufficient.

9.7 Future research directions

This section highlights a number of design issues that limit the interpretation and the generalizability of our results. Due to the cross-sectional design of studies 4, 5 and 6, it is not possible to infer causation of NP on postural control. Longitudinal prospective studies on the influence of NP and associated impairments are needed to identify the causes and contributors of postural control deficits in NP.

This thesis provides a first step towards bridging the research to practice (equipment) gap and understanding the mechanisms underpinning NP induced postural control deficits. With respect to the application of newly developed technology for both research and clinical purposes, the Wii Balance Board application proves to be of great potential to be used as an assessment tool to measure hallux flexor strength (study 3), an important muscle needed to maintain postural stability in older adults (Mickle, K. J. et al., 2009). This study forms the basis for more investigations to determine the inter-rater reliability and the ease of use in the clinical setting. In addition, given that the Microsoft Kinect is shown to be valid and reliable to measure thoracic kyphosis when compared to the flexicurve (study 4), more investigation could be performed to validate the Microsoft Kinect against the gold standard of radiological images as well as the inter-rater reliability to measure thoracic kyphosis. As indicated earlier, future studies are needed to determine if mobile phones can be used to accurately measure cervical spine rotation in other positions, as their ready availability could make them a feasible tool to improve objectivity of clinical measures.

Studies 4 & 5 provide a basis for future research to identify how best to use wavelet analysis to facilitate understanding of postural control mechanisms. Specifically, more research is required to bridge the translational gap between the specific frequency bands and physiological domains in order to extract clinically meaningful data. Assessing postural control under conditions where one system must be preferentially used could be a way to verify the links between the energy in certain frequency bands and systems used in postural control. For example, future research may consider using vibration to stimulate the muscle spindles of targeted cervical muscles as it is thought to alter cervical spine proprioception (Beinert et al., 2015). When this is performed with eyes closed in standing, sensory information from the proprioceptive and visual systems is attenuated and reweighed to engage more vestibular input for postural stability.

It can be implied that the mechanisms underlying NP postural control deficits are complex (studies 5 & 6) and more research needs to be undertaken further to explore the influence of cervical spine dysfunction on the vestibular system and how this impacts postural control in older adults. Future research may consider recruiting young and older adults with NP to further strengthen the preliminary evidence found in this study regarding the impact of age on postural control in NP. Also, JPE in the sagittal plane and muscle fatigueability ought to be assessed and the relationship with FHP and postural sway should be further explored. Whether older adults with NP actually have a greater risk of falling than their otherwise healthy counterparts is clearly an important issue, but would require high numbers of participants to be adequately powered.

Clearly, there is a paucity of mechanistic research and more investigations are required to understand the complex integration of the afferent and efferent mechanisms involved in the maintenance of postural stability in older adults with NP. Understanding these mechanisms will help researchers and clinicians to develop management strategies to improve postural stability and potentially reduce risk of falls. Similar to the suggestion above, developing studies where participants with NP are forced to use certain systems for postural control may also assist in understanding the importance of individual systems for postural control, and thus contribute to an understanding of underpinning mechanisms.

If our findings can be replicated in adequately powered studies, future interventional studies (e.g. RCTs) could be warranted to determine if improving underlying impairments such as forward head posture or vestibular function can improve postural sway, and if reducing dizziness and fear of movement could increase dynamic stability in older adults with NP. An ultimate study would be to investigate the effect of interventions to reduce the risk of falls in older adults with NP.

9.8 Conclusion

In conclusion, this thesis explored the use of newly developed technology to bridge the research to practice gap and highlights the paucity of research in NP-related postural control impairments. The results provide evidence to use the Wii Balance Board application to measure hallux flexor strength, the Microsoft Kinect to measure thoracic kyphosis, and the Android phone to measure cervical range-of-motion in the sagittal and coronal planes sitting. In addition, it was found that static and dynamic postural control was altered in older adults with NP compared to healthy controls. Greater forward head posture angles, a positive Dix-hallpike test, being advanced in age and higher physical activity levels were associated with increased static postural sway. Higher dizziness disability, fear of movement and age were associated with poorer dynamic postural control. Overall, this thesis provides evidence that the mechanisms underpinning postural control deficits observed in older adults with NP are complex and highlights the need for extended investigation such as neuro-imaging research to further understand the potential role the central nervous system plays in the development and modulation of postural control impairment in this population.

References

Adkin, A. L., Frank, J. S., Carpenter, M. G., & Peysar, G. W. (2002). Fear of falling modifies anticipatory postural control. *Experimental Brain Research, 143*(2), 160-170.

Alin, K. K., Grahn Kronhed, A.-C., & Salminen, H. (2016). The association between spinal curvature and balance in elderly women at high risk of osteoporotic fractures in primary health care. *European Journal of Physiotherapy, 18*(4), 226-232.

Allet, L., Armand, S., Golay, A., Monnin, D., De Bie, R., & De Bruin, E. (2008). Gait characteristics of diabetic patients: a systematic review. *Diabetes/metabolism research and reviews, 24*(3), 173-191.

Allum, J., Honegger, F., & Schicks, H. (1994). The influence of a bilateral peripheral vestibular deficit on postural synergies. *Journal of vestibular research: equilibrium & orientation*.

Arnold, C., Beatty, B., Harrison, E., & W., O. (2000). The reliability of five clinical postural alignment measures for women with osteoporosis. *Physiotherapy Canada, 52*(4), 286-294.

Arshad, A. R., & Alvi, K. Y. (2016). Diagnostic Accuracy of Clinical Methods for Detection of Diabetic Sensory Neuropathy. *Journal of the College of Physicians and Surgeons Pakistan, 26*(5), 374-379.

Babyak, M. A. (2004). What you see may not be what you get: a brief, nontechnical introduction to overfitting in regression-type models. *Psychosomatic medicine, 66*(3), 411-421.

Barré, J. (1926). Sur un syndrome sympathique cervical posterieur et sa cause frequente: l'arthrite cervical. *Revue neurologique, 33*, 1246-1248.

Barrett, E., McCreesh, K., & Lewis, J. (2014). Reliability and validity of non-radiographic methods of thoracic kyphosis measurement: a systematic review. *Manual therapy, 19*(1), 10-17.

Beinert, K., Keller, M., & Taube, W. (2015). Neck muscle vibration can improve sensorimotor function in patients with neck pain. *The Spine Journal, 15*(3), 514-521.

Beinert, K., & Taube, W. (2013). The effect of balance training on cervical sensorimotor function and neck pain. *Journal of motor behavior, 45*(3), 271-278.

Bent, L. R., Inglis, J. T., & McFadyen, B. J. (2004). When is vestibular information important during walking? *Journal of neurophysiology, 92*(3), 1269-1275.

Bergin, P., Bronstein, A. M., Murray, N., Sancovic, S., & Zeppenfeld, D. (1995). Body sway and vibration perception thresholds in normal aging and in patients with polyneuropathy. *Journal of Neurology, Neurosurgery & Psychiatry, 58*(3), 335-340.

Black, F., Shupert, C., Horak, F., & Nashner, L. (1988). Abnormal postural control associated with peripheral vestibular disorders. *Progress in brain research, 76*, 263-275.

Black, F. O., Wall, C., Rockette, H. E., & Kitch, R. (1982). Normal subject postural sway during the Romberg test. *American journal of Otolaryngology, 3*(5), 309-318.

Bland, J. M., & Altman, D. G. (1986). Statistical Methods for Assessing Agreement between Two Methods of Clinical Measurement. *Lancet, 1*(8476), 307-310.

Bland, J. M., & Altman, D. G. (1999). Measuring agreement in method comparison studies. *Statistical Methods in Medical Research, 8*(2), 135-160.

Borg, F. G., & Laxaback, G. (2010). Entropy of balance--some recent results. *Journal of Neuroengineering and Rehabilitation, 7*, 38.

Boucher, P., Descarreaux, M., & Normand, M. C. (2008). Postural control in people with osteoarthritis of the cervical spine. *J Manipulative Physiol Ther, 31*(3), 184-190.

Boudreau, S. A., & Falla, D. (2014). Chronic neck pain alters muscle activation patterns to sudden movements. *Experimental Brain Research, 232*(6), 2011-2020.

Boyd-Clark, L. C., Briggs, C. A., & Galea, M. P. (2002). Muscle spindle distribution, morphology, and density in longus colli and multifidus muscles of the cervical spine. *Spine (Phila Pa 1976), 27*(7), 694-701.

Boyle, J. J., Milne, N., & Singer, K. P. (2002). Influence of age on cervicothoracic spinal curvature: an ex vivo radiographic survey. *Clin Biomech (Bristol, Avon), 17*(5), 361-367.

Braith, R. W., Graves, J. E., Leggett, S. H., & Pollock, M. L. (1993). Effect of training on the relationship between maximal and submaximal strength. *Medicine and Science in Sports and Exercise, 25*(1), 132-138.

Brandt, T., Strupp, M., Benson, J., & Dieterich, M. (2001). Vestibulopathic gait. Walking and running. *Advances in neurology, 87*, 165.

Brunton, J., Brunton, E., & Mhuiri, A. N. (2003). Reliability of measuring natural head posture using the craniovertebral angle. *Irish Ergonomics Review*, 37-41.

Bush, K. W., Collins, N., Portman, L., & Tillett, N. (2000). Validity and intertester reliability of cervical range of motion using inclinometer measurements. *Journal of Manual & Manipulative Therapy, 8*(2), 52-61.

Büttner, U., Helmchen, C., & Brandt, T. (1999). Diagnostic criteria for central versus peripheral positioning nystagmus and vertigo: a review. *Acta oto-laryngologica, 119*(1), 1-5.

Campbell, A. J., Borrie, M. J., Spears, G. F., Jackson, S. L., Brown, J. S., & Fitzgerald, J. L. (1990). Circumstances and consequences of falls experienced by a community population 70 years and over during a prospective study. *Age Ageing, 19*(2), 136-141.

Capuano-Pucci, D., Rheault, W., Aukai, J., Bracke, M., Day, R., & Pastrick, M. (1991). Intratester and intertester reliability of the cervical range of motion device. *Arch Phys Med Rehabil, 72*(5), 338-340.

Carpenter, M. G., Frank, J. S., Silcher, C. P., & Peysar, G. W. (2001). The influence of postural threat on the control of upright stance. *Experimental Brain Research, 138*(2), 210-218.

Carpenter, M. G., Murnaghan, C. D., & Inglis, J. T. (2010). Shifting the balance: evidence of an exploratory role for postural sway. *Neuroscience, 171*(1), 196-204.

Carr, J. H., & Shepherd, R. B. (2000). *Movement science : foundations for physical therapy in rehabilitation* (2nd ed.). Gaithersburg, Md.: Aspen Publishers.

Chagdes, J. R., Rietdyk, S., Haddad, J. M., Zelaznik, H. N., Raman, A., Rhea, C. K., & Silver, T. A. (2009). Multiple timescales in postural dynamics associated with vision and a secondary task are revealed by wavelet analysis. *Experimental Brain Research, 197*(3), 297-310.

Chen, X., & Treleaven, J. (2013). The effect of neck torsion on joint position error in subjects with chronic neck pain. *Manual therapy, 18*(6), 562-567.

Cheng, C.-H., Chien, A., Hsu, W.-L., Yen, L.-W., Lin, Y.-H., & Cheng, H.-Y. K. (2015). Changes of postural control and muscle activation pattern in response to external perturbations after neck flexor fatigue in young subjects with and without chronic neck pain. *Gait & posture, 41*(3), 801-807.

Cheng, C. H., Wang, J. L., Lin, J. J., Wang, S. F., & Lin, K. H. (2010). Position accuracy and electromyographic responses during head reposition in young adults with chronic neck pain. *J Electromyogr Kinesiol, 20*(5), 1014-1020.

Choy, N. L., Brauer, S., & Nitz, J. (2003). Changes in postural stability in women aged 20 to 80 years. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 58*(6), M525-M530.

Clark, R. A., Bryant, A. L., Pua, Y., McCrory, P., Bennell, K., & Hunt, M. (2010). Validity and reliability of the Nintendo Wii Balance Board for assessment of standing balance. *Gait Posture, 31*(3), 307-310.

Clark, R. A., Howells, B., Pua, Y.-H., Feller, J., Whitehead, T., & Webster, K. E. (2014). Assessment of standing balance deficits in people who have undergone anterior cruciate ligament reconstruction using traditional and modern analysis methods. *Journal of biomechanics, 47*(5), 1134-1137.

Clark, R. A., McGough, R., & Paterson, K. (2011). Reliability of an inexpensive and portable dynamic weight bearing asymmetry assessment system incorporating dual Nintendo Wii Balance Boards. *Gait & posture, 34*(2), 288-291.

Clark, R. A., Pua, Y.-H., Bryant, A. L., & Hunt, M. A. (2013). Validity of the Microsoft Kinect for providing lateral trunk lean feedback during gait retraining. *Gait and Posture, 38*(4), 1064-1066.

Clark, R. A., Pua, Y.-H., Fortin, K., Ritchie, C., Webster, K. E., Denehy, L., & Bryant, A. L. (2012). Validity of the Microsoft Kinect for assessment of postural control. *Gait & posture, 36*(3), 372-377.

Clark, R. A., Pua, Y. H., Fortin, K., Ritchie, C., Webster, K. E., Denehy, L., & Bryant, A. L. (2012). Validity of the Microsoft Kinect for assessment of postural control. *Gait Posture, 36*(3), 372-377.

Claus, A. P., Hides, J. A., Moseley, G. L., & Hodges, P. W. (2009). Different ways to balance the spine: subtle changes in sagittal spinal curves affect regional muscle activity. *Spine, 34*(6), E208-E214.

Cleland, J. A., Glynn, P., Whitman, J. M., Eberhart, S. L., MacDonald, C., & Childs, J. D. (2007). Short-term effects of thrust versus nonthrust mobilization/manipulation directed at the thoracic spine in patients with neck pain: a randomized clinical trial. *Phys Ther, 87*(4), 431-440.

Colley, R. C., Garriguet, D., Janssen, I., Craig, C. L., Clarke, J., & Tremblay, M. S. (2011). Physical activity of Canadian adults: accelerometer results from the 2007 to 2009 Canadian Health Measures Survey. *Health reports, 22*(1), 7.

Courtemanche, R., Teasdale, N., Boucher, P., Fleury, M., Lajoie, Y., & Bard, C. (1996). Gait problems in diabetic neuropathic patients. *Archives of physical medicine and rehabilitation, 77*(9), 849-855.

D'Anna, C., Schmid, M., Bibbo, D., Bertollo, M., Comani, S., & Conforto, S. (2015). The Effect of continuous and discretized presentations of concurrent augmented visual biofeedback on postural control in quiet stance. *PloS one, 10*(7), e0132711.

Dall'Alba, P. T., Sterling, M. M., Treleaven, J. M., Edwards, S. L., & Jull, G. A. (2001). Cervical range of motion discriminates between asymptomatic persons and those with whiplash. *Spine, 26*(19), 2090-2094.

Dannenbaum, E., Paquet, N., Chilingaryan, G., & Fung, J. (2009). Clinical evaluation of dynamic visual acuity in subjects with unilateral vestibular hypofunction. *Otology & Neurotology, 30*(3), 368-372.

Dault, M. C., Yardley, L., & Frank, J. S. (2003). Does articulation contribute to modifications of postural control during dual-task paradigms? *Brain Res Cogn Brain Res, 16*(3), 434-440.

Davidson, B. S., Madigan, M. L., & Nussbaum, M. A. (2004). Effects of lumbar extensor fatigue and fatigue rate on postural sway. *European journal of applied physiology, 93*(1-2), 183-189.

Davis, E., Jones, T., Walsh, P., & Byrne, G. (1997). The use of biothesiometry to detect neuropathy in children and adolescents with IDDM. *Diabetes Care, 20*(9), 1448-1453.

de Vries, J., Ischebeck, B., Voogt, L., van der Geest, J., Janssen, M., Frens, M., & Kleinrensink, G. J. (2015). Joint position sense error in people with neck pain: a systematic review. *Manual therapy, 20*(6), 736-744.

Di Bari, M., Chiarlone, M., Matteuzzi, D., Zacchei, S., Pozzi, C., Bellia, V., Tarantini, F., Pini, R., Masotti, G., & Marchionni, N. (2004). Thoracic kyphosis and ventilatory

dysfunction in unselected older persons: an epidemiological study in Dicomano, Italy. *J Am Geriatr Soc, 52*(6), 909-915.

Diener, H. C., Dichgans, J., Bacher, M., & Gompf, B. (1984). Quantification of postural sway in normals and patients with cerebellar diseases. *Electroencephalography and clinical neurophysiology, 57*(2), 134-142.

Diener, H. C., Dichgans, J., Guschlbauer, B., & Mau, H. (1984). The significance of proprioception on postural stabilization as assessed by ischemia. *Brain Res, 296*(1), 103-109.

DiPietro, L. (2001). Physical activity in aging changes in patterns and their relationship to health and function. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 56*(suppl 2), 13-22.

Edmondston, S., Björnsdóttir, G., Pálsson, T., Solgård, H., Ussing, K., & Allison, G. (2011). Endurance and fatigue characteristics of the neck flexor and extensor muscles during isometric tests in patients with postural neck pain. *Manual therapy, 16*(4), 332-338.

Edmondston, S. J., Wallumrød, M. E., MacLéid, F., Kvamme, L. S., Joebges, S., & Brabham, G. C. (2008). Reliability of isometric muscle endurance tests in subjects with postural neck pain. *Journal of manipulative and physiological therapeutics, 31*(5), 348-354.

Ernst, M. J., Rast, F. M., Bauer, C. M., Marcar, V. L., & Kool, J. (2013). Determination of thoracic and lumbar spinal processes by their percentage position between C7 and the PSIS level. *BMC research notes, 6*(1), 58.

Eum, R., Leveille, S. G., Kiely, D. K., Kiel, D. P., Samelson, E. J., & Bean, J. F. (2013). Is kyphosis related to mobility, balance and disability? *American journal of physical medicine & rehabilitation/Association of Academic Physiatrists, 92*(11), 980.

Falla, D., O'leary, S., Farina, D., & Jull, G. (2011). Association between intensity of pain and impairment in onset and activation of the deep cervical flexors in patients with persistent neck pain. *The Clinical journal of pain, 27*(4), 309-314.

Fejer, R., Kyvik, K. O., & Hartvigsen, J. (2006). The prevalence of neck pain in the world population: a systematic critical review of the literature. *European spine journal, 15*(6), 834-848.

Field, S., Treleaven, J., & Jull, G. (2008). Standing balance: a comparison between idiopathic and whiplash-induced neck pain. *Man Ther, 13*(3), 183-191.

Fife, T. D. (2009). *Benign paroxysmal positional vertigo.* Paper presented at the Seminars in neurology.

Fleiss, J. L. (1986). *The design and analysis of clinical experiments*. New York: Wiley.

Fletcher, J. P., & Bandy, W. D. (2008). Intrarater reliability of CROM measurement of cervical spine active range of motion in persons with and without neck pain. *J Orthop Sports Phys Ther, 38*(10), 640-645.

Friedrich, M., Grein, H.-J., Wicher, C., Schuetze, J., Mueller, A., Lauenroth, A., Hottenrott, K., & Schwesig, R. (2008). Influence of pathologic and simulated visual dysfunctions on the postural system. *Experimental Brain Research, 186*(2), 305-314.

Garth JR, W. P., & Miller, S. T. (1989). Evaluation of claw toe deformity, weakness of the foot intrinsics, and posteromedial shin pain. *The American journal of sports medicine, 17*(6), 821-827.

Gelber, D. A., Pfeifer, M. A., Broadstone, V. L., Munster, E. W., Peterson, M., Arezzo, J. C., Shamoon, H., Zeidler, A., Clements, R., & Greene, D. A. (1995). Components of variance for vibratory and thermal threshold testing in normal and diabetic subjects. *Journal of Diabetes and its Complications, 9*(3), 170-176.

Gil-Gómez, J.-A., Lloréns, R., Alcañiz, M., & Colomer, C. (2011). Effectiveness of a Wii balance board-based system (eBaViR) for balance rehabilitation: a pilot randomized clinical trial in patients with acquired brain injury. *Journal of Neuroengineering and Rehabilitation, 8*(1), 30.

Goble, D. J., Coxon, J. P., Wenderoth, N., Van Impe, A., & Swinnen, S. P. (2009). Proprioceptive sensibility in the elderly: degeneration, functional consequences and plastic-adaptive processes. *Neuroscience & Biobehavioral Reviews, 33*(3), 271-278.

Golomer, E., & Dupui, P. (2000). Spectral analysis of adult dancers' sways: Sex and interaction vision-proprioception. *International Journal of Neuroscience, 105*(1-4), 15-26.

Goodvin, C., Park, E. J., Huang, K., & Sakaki, K. (2006). Development of a real-time three-dimensional spinal motion measurement system for clinical practice. *Med Biol Eng Comput, 44*(12), 1061-1075.

Gosselin, G., Rassoulian, H., & Brown, I. (2004). Effects of neck extensor muscles fatigue on balance. *Clin Biomech (Bristol, Avon), 19*(5), 473-479.

Greendale, G. A., Nili, N. S., Huang, M. H., Seeger, L., & Karlamangla, A. S. (2011). The reliability and validity of three non-radiological measures of thoracic kyphosis and their relations to the standing radiological Cobb angle. *Osteoporos Int, 22*(6), 1897-1905.

Greig, A., Bennell, K., Briggs, A., Wark, J., & Hodges, P. (2007). Balance impairment is related to vertebral fracture rather than thoracic kyphosis in individuals with osteoporosis. *Osteoporosis International, 18*(4), 543-551.

Grip, H., Sundelin, G., Gerdle, B., & Karlsson, J. S. (2007). Variations in the axis of motion during head repositioning–a comparison of subjects with whiplash-associated disorders or non-specific neck pain and healthy controls. *Clinical Biomechanics, 22*(8), 865-873.

Haibach, P. S., Slobounov, S. M., Slobounova, E. S., & Newell, K. M. (2007). Aging and time-to-postural stability following a visual perturbation. *Aging clinical and experimental research, 19*(6), 438-443.

Hall, T. M., Robinson, K. W., Fujinawa, O., Akasaka, K., & Pyne, E. A. (2008). Intertester reliability and diagnostic validity of the cervical flexion-rotation test. *J Manipulative Physiol Ther, 31*(4), 293-300.

Hart, D. L., & Rose, S. J. (1986). Reliability of a noninvasive method for measuring the lumbar curve*. *J Orthop Sports Phys Ther, 8*(4), 180-184.

Hartholt, K. A., van Beeck, E. F., Polinder, S., van der Velde, N., van Lieshout, E. M., Panneman, M. J., van der Cammen, T. J., & Patka, P. (2011). Societal consequences of falls in the older population: injuries, healthcare costs, and long-term reduced quality of life. *Journal of Trauma and Acute Care Surgery, 71*(3), 748-753.

Hartvigsen, J., Christensen, K., & Frederiksen, H. (2004). Back and neck pain exhibit many common features in old age: a population-based study of 4,486 Danish twins 70–102 years of age. *Spine, 29*(5), 576-580.

Hartvigsen, J., Frederiksen, H., & Christensen, K. (2006). Back and neck pain in seniors—prevalence and impact. *European spine journal, 15*(6), 802-806.

Hausdorff, J. M., Rios, D. A., & Edelberg, H. K. (2001). Gait variability and fall risk in community-living older adults: a 1-year prospective study. *Archives of Physical Medicine and Rehabilitation, 82*(8), 1050-1056.

Haymes, S. A., & Chen, J. (2004). Reliability and validity of the Melbourne Edge Test and high/low contrast visual acuity chart. *Optometry and Vision Science, 81*(5), 308-316.

Herdman, S. J., Blatt, P., Schubert, M. C., & Tusa, R. J. (2000). Falls in patients with vestibular deficits. *Otology & Neurotology, 21*(6), 847-851.

Herman, T., Inbar-Borovsky, N., Brozgol, M., Giladi, N., & Hausdorff, J. M. (2009). The Dynamic Gait Index in healthy older adults: The role of stair climbing, fear of falling and gender. *Gait & posture, 29*(2), 237-241.

Hikosaka, O., & Maeda, M. (1973). Cervical effects on abducens motoneurons and their interaction with vestibulo-ocular reflex. *Experimental Brain Research, 18*(5), 512-530.

Hilz, M. J., Axelrod, F. B., Hermann, K., Haertl, U., Duetsch, M., & Neundörfer, B. (1998). Normative values of vibratory perception in 530 children, juveniles and adults aged 3–79 years. *Journal of the neurological sciences, 159*(2), 219-225.

Hlavacka, F., & Njiokiktjien, C. (1985). Postural responses evoked by sinusoidal galvanic stimulation of the labyrinth: influence of head position. *Acta oto-laryngologica, 99*(1-2), 107-112.

Hole, D. E., Cook, J. M., & Bolton, J. E. (1995). Reliability and concurrent validity of two instruments for measuring cervical range of motion: effects of age and gender. *Man Ther, 1*(1), 36-42.

Hood, W., & Hood, M. (2016). Can eyes cause neck pain? *International Journal of Therapy and Rehabilitation, 23*(10), 499-504.

Horak, F., Nashner, L., & Diener, H. (1990). Postural strategies associated with somatosensory and vestibular loss. *Experimental Brain Research, 82*(1), 167-177.

Horak, F., Shupert, C., Dietz, V., & Horstmann, G. (1994). Vestibular and somatosensory contributions to responses to head and body displacements in stance. *Experimental Brain Research, 100*(1), 93-106.

Horak, F. B., Shupert, C. L., & Mirka, A. (1989). Components of postural dyscontrol in the elderly: a review. *Neurobiol Aging, 10*(6), 727-738.

Ishikawa, Y., Miyakoshi, N., Kasukawa, Y., Hongo, M., & Shimada, Y. (2009). Spinal curvature and postural balance in patients with osteoporosis. *Osteoporosis International, 20*(12), 2049-2053.

Jack, C., Smith, T., Neoh, C., Lye, M., & McGalliard, J. (1995). Prevalence of low vision in elderly patients admitted to an acute geriatric unit in Liverpool: elderly people who fall are more likely to have low vision. *Gerontology, 41*(5), 280-285.

Jacobson, G. P., & Newman, C. W. (1990). The development of the dizziness handicap inventory. *Archives of Otolaryngology–Head & Neck Surgery, 116*(4), 424-427.

Jahn, K., Strupp, M., Schneider, E., Dieterich, M., & Brandt, T. (2000). Differential effects of vestibular stimulation on walking and running. *Neuroreport, 11*(8), 1745-1748.

Jayaprakash, P., Bhansali, A., Bhansali, S., Dutta, P., Anantharaman, R., Shanmugasundar, G., & Ravikiran, M. (2011). Validation of bedside methods in evaluation of diabetic peripheral neuropathy. *The Indian journal of medical research, 133*(6), 645.

Jensen, M. P., Turner, J. A., Romano, J. M., & Fisher, L. D. (1999). Comparative reliability and validity of chronic pain intensity measures. *Pain, 83*(2), 157-162.

Johansson, R., Magnusson, M., & Fransson, P.-A. (1995). Galvanic vestibular stimulation for analysis of postural adaptation and stability. *IEEE Transactions on Biomedical Engineering, 42*(3), 282-292.

Jorgensen, M. B., Skotte, J. H., Holtermann, A., Sjogaard, G., Petersen, N. C., & Sogaard, K. (2011). Neck pain and postural balance among workers with high postural demands - a cross-sectional study. *BMC Musculoskelet Disord, 12*, 176.

Juul-Kristensen, B., Clausen, B., Ris, I., Vikaer Jensen, R., Fischer Steffensen, R., Samir Chreiteh, S., Birk Jorgensen, M., & Sogaard, K. (2013). Increased Neck Muscle Activity and Impaired Balance Among Females with Whiplash-Related Chronic Neck Pain: A Cross-Sectional Study. *Journal of Rehabilitation Medicine, 45*(4), 376-384.

Kado, D. M., Huang, M. H., Barrett-Connor, E., & Greendale, G. A. (2005). Hyperkyphotic posture and poor physical functional ability in older community-dwelling men and women: the Rancho Bernardo study. *J Gerontol A Biol Sci Med Sci, 60*(5), 633-637.

Kado, D. M., Lui, L. Y., Ensrud, K. E., Fink, H. A., Karlamangla, A. S., & Cummings, S. R. (2009). Hyperkyphosis predicts mortality independent of vertebral osteoporosis in older women. *Ann Intern Med, 150*(10), 681-687.

Kalisch, T., Ragert, P., Schwenkreis, P., Dinse, H. R., & Tegenthoff, M. (2008). Impaired tactile acuity in old age is accompanied by enlarged hand representations in somatosensory cortex. *Cerebral Cortex, 19*(7), 1530-1538.

Kang, J.-H., Park, R.-Y., Lee, S.-J., Kim, J.-Y., Yoon, S.-R., & Jung, K.-I. (2012). The effect of the forward head posture on postural balance in long time computer based worker. *Annals of rehabilitation medicine, 36*(1), 98-104.

Kanji, J. N., Anglin, R. E., Hunt, D. L., & Panju, A. (2010). Does this patient with diabetes have large-fiber peripheral neuropathy? *JAmA, 303*(15), 1526-1532.

Karlsson, A., & Frykberg, G. (2000). Correlations between force plate measures for assessment of balance. *Clinical Biomechanics, 15*(5), 365-369.

Katz, M. H. (2006). Relationship of independent variables to one another. *Multivariable Analysis A Practical Guide for Clinicians, 2*, 71-72.

Katzman, W., Vittinghoff, E., & Kado, D. (2011). Age-related hyperkyphosis, independent of spinal osteoporosis, is associated with impaired mobility in older community-dwelling women. *Osteoporosis International, 22*(1), 85-90.

Kavounoudias, A., Gilhodes, J. C., Roll, R., & Roll, J. P. (1999). From balance regulation to body orientation: two goals for muscle proprioceptive information processing? *Exp Brain Res, 124*(1), 80-88.

Kendall, J. C., Boyle, E., Hartvigsen, J., Hvid, L. G., Azari, M. F., Skjødt, M., & Caserotti, P. (2016). Neck pain, concerns of falling and physical performance in community-dwelling Danish citizens over 75 years of age: A cross-sectional study. *Scandinavian Journal of Public Health*, 1403494816666414.

Kendall, J. C., Hartvigsen, J., French, S. D., & Azari, M. F. (2015). Is there a role for neck manipulation in elderly falls prevention?–An overview. *The Journal of the Canadian Chiropractic Association, 59*(1), 53.

Kenshalo Sr, D. R. (1986). Somesthetic sensitivity in young and elderly humans. *Journal of gerontology, 41*(6), 732-742.

Kobayashi, R., Hosoda, M., Minematsu, A., Sasaki, H., Maejima, H., Tanaka, S., Kanemura, N., Matsuo, A., Shirahama, K., & Ueda, T. (2001). Effects of toe grasp training for the aged on spontaneous postural sway. *Journal of Physical Therapy Science, 11*(1), 31-34.

Kojima, G., Masud, T., Kendrick, D., Morris, R., Gawler, S., Treml, J., & Iliffe, S. (2015). Does the timed up and go test predict future falls among British community-dwelling older people? Prospective cohort study nested within a randomised controlled trial. *BMC geriatrics, 15*(1), 38.

Koski, K., Luukinen, H., Laippala, P., & Kivela, S. L. (1996). Physiological factors and medications as predictors of injurious falls by elderly people: a prospective population-based study. *Age Ageing, 25*(1), 29-38.

Koumantakis, G. A., Winstanley, J., & Oldham, J. A. (2002). Thoracolumbar proprioception in individuals with and without low back pain: intratester reliability, clinical applicability, and validity. *Journal of Orthopaedic & Sports Physical Therapy, 32*(7), 327-335.

Kowal, P., & Dowd, J. E. (2001). Definition of an older person. Proposed working definition of an older person in Africa for the MDS Project. Geneva: World Health Organisation.

Kristjansson, E., Dall'Alba, P., & Jull, G. (2003). A study of five cervicocephalic relocation tests in three different subject groups. *Clin Rehabil, 17*(7), 768-774.

Kulkarni, V., Chandy, M. J., & Babu, K. S. (2001). Quantitative study of muscle spindles in suboccipital muscles of human foetuses. *Neurol India, 49*(4), 355-359.

Kwon, O., Tuttle, L., Johnson, J., & Mueller, M. (2009). Muscle imbalance and reduced ankle joint motion in people with hammer toe deformity. *Clinical Biomechanics, 24*(8), 670-675.

Lacour, M., Bernard-Demanze, L., & Dumitrescu, M. (2008). Posture control, aging, and attention resources: models and posture-analysis methods. *Neurophysiologie Clinique, 38*(6), 411-421.

Lajoie, Y., & Gallagher, S. (2004). Predicting falls within the elderly community: comparison of postural sway, reaction time, the Berg balance scale and the Activities-specific Balance Confidence (ABC) scale for comparing fallers and non-fallers. *Archives of gerontology and geriatrics, 38*(1), 11-26.

Lau, H. M., Wing Chiu, T. T., & Lam, T. H. (2011). The effectiveness of thoracic manipulation on patients with chronic mechanical neck pain - a randomized controlled trial. *Manual therapy, 16*(2), 141-147.

Lau, K. T., Cheung, K. Y., Chan, K. B., Chan, M. H., Lo, K. Y., & Chiu, T. T. (2010). Relationships between sagittal postures of thoracic and cervical spine, presence of neck pain, neck pain severity and disability. *Manual therapy, 15*(5), 457-462.

Laughton, C. A., Slavin, M., Katdare, K., Nolan, L., Bean, J. F., Kerrigan, D. C., Phillips, E., Lipsitz, L. A., & Collins, J. J. (2003). Aging, muscle activity, and balance control: physiologic changes associated with balance impairment. *Gait & posture, 18*(2), 101-108.

Lee, H., Nicholson, L. L., & Adams, R. D. (2005). Neck muscle endurance, self-report, and range of motion data from subjects with treated and untreated neck pain. *Journal of manipulative and physiological therapeutics, 28*(1), 25-32.

Leijon, M. (2002). Östgötens hälsa och miljö. In Ekberg, K., Noorlind Brage, H. & Dastserri, M. (Eds.). Landstinget i Östergötland: Folhälsovetenskapligt Centrum.

Li, F., Fisher, K. J., Harmer, P., McAuley, E., & Wilson, N. L. (2003). Fear of falling in elderly persons: association with falls, functional ability, and quality of life. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences, 58*(5), P283-P290.

Liang, Z., Clark, R., Bryant, A., Quek, J., & Pua, Y. H. (2014). Neck musculature fatigue affects specific frequency bands of postural dynamics during quiet standing. *Gait & posture, 39*(1), 397-403.

Lord, S. R., Clark, R. D., & Webster, I. W. (1991a). Postural stability and associated physiological factors in a population of aged persons. *Journal of gerontology, 46*(3), M69-M76.

Lord, S. R., Clark, R. D., & Webster, I. W. (1991b). Postural stability and associated physiological factors in a population of aged persons. *J Gerontol, 46*(3), M69-76.

Lord, S. R., Clark, R. D., & Webster, I. W. (1991c). Visual acuity and contrast sensitivity in relation to falls in an elderly population. *Age and ageing, 20*(3), 175-181.

Lord, S. R., & Ward, J. A. (1994). Age-associated differences in sensori-motor function and balance in community dwelling women. *Age and Ageing, 23*(6), 452-460.

Low Choy, N. L., Brauer, S. G., & Nitz, J. C. (2007). Age-Related Changes in Strength and Somatosensation during Midlife. *Annals of the New York Academy of Sciences, 1114*(1), 180-193.

Ludbrook, J. (1997). Special article comparing methods of measurement. *Clinical and Experimental Pharmacology and Physiology, 24*(2), 193-203.

Ludbrook, J. (2002). Statistical techniques for comparing measurers and methods of measurement: a critical review. *Clinical and Experimental Pharmacology and Physiology, 29*(7), 527-536.

Lynn, S. G., Sinaki, M., & Westerlind, K. C. (1997). Balance characteristics of persons with osteoporosis. *Arch Phys Med Rehabil, 78*(3), 273-277.

Macdonald, N. K., Kaski, D., Saman, Y., Sulaiman, A. A.-S., Anwer, A., & Bamiou, D.-E. (2017). Central Positional Nystagmus: A Systematic Literature Review. *Frontiers in neurology, 8*.

Macpherson, J. M., & Inglis, J. T. (1993). Stance and balance following bilateral labyrinthectomy. *Progress in brain research, 97*, 219-228.

Madeleine, P., Nielsen, M., & Arendt-Nielsen, L. (2011). Characterization of postural control deficit in whiplash patients by means of linear and nonlinear analyses - A pilot study. *Journal of Electromyography and Kinesiology, 21*(2), 291-297.

Magnusson, M., Enbom, H., Johansson, R., & Wiklund, J. (1990). Significance of pressor input from the human feet in lateral postural control: The effect of hypothermia on galvanically induced body-sway. *Acta oto-laryngologica, 110*(5-6), 321-327.

Magnusson, M., & Malmstrom, E. M. (2016). The conundrum of cervicogenic dizziness. *Handb Clin Neurol, 137*, 365-369.

Maitre, J., & Paillard, T. (2017). Vestibular Adaptations Induced by Gentle Physical Activity Are Reduced Among Older Women. *Frontiers in aging neuroscience, 9*.

Maki, B. E., Holliday, P. J., & Topper, A. K. (1991). Fear of falling and postural performance in the elderly. *Journal of gerontology, 46*(4), M123-M131.

Malmström, E.-M., Karlberg, M., Melander, A., Magnusson, M., & Moritz, U. (2007). Cervicogenic dizziness–musculoskeletal findings before and after treatment and long-term outcome. *Disability and rehabilitation, 29*(15), 1193-1205.

Mancini, M., Salarian, A., Carlson-Kuhta, P., Zampieri, C., King, L., Chiari, L., & Horak, F. B. (2012). ISway: a sensitive, valid and reliable measure of postural control. *Journal of neuroengineering and rehabilitation, 9*(1), 59.

March, L. M., Brnabic, A. J. M., Skinner, J. C., Schwarz, J. M., Finnegan, T., Druce, J., & Brooks, P. M. (1998). Musculoskeletal disability among elderly people in the community. *Medical Journal of Australia, 168*(9), 439-442.

Mariani, B., Hoskovec, C., Rochat, S., Büla, C., Penders, J., & Aminian, K. (2010). 3D gait assessment in young and elderly subjects using foot-worn inertial sensors. *Journal of biomechanics, 43*(15), 2999-3006.

Martins, F., Bento, A., & Silva, A. G. (2017). Within session and between session reliability, construct validity and comparison between individuals with and without neck pain of four neck muscle tests. *PM&R*.

McGaugh, J., Brismee, J., Dedrick, G., Jones, E., & Sizer, P. (2007). Comparing the anatomical consistency of the posterior superior iliac spine to the iliac crest as reference landmarks for the lumbopelvic spine: a retrospective radiological study. *Clinical Anatomy, 20*(7), 819-825.

McIlroy, W., & Maki, B. (1997). Preferred placement of the feet during quiet stance: development of a standardized foot placement for balance testing. *Clinical Biomechanics, 12*(1), 66-70.

McKeon, P. O., Hertel, J., Bramble, D., & Davis, I. (2014). The foot core system: a new paradigm for understanding intrinsic foot muscle function. *British Journal of Sports Medicine, 0*, 1-9.

McPartland, J. M., Brodeur, R. R., & Hallgren, R. C. (1997). Chronic neck pain, standing balance, and suboccipital muscle atrophy--a pilot study. *J Manipulative Physiol Ther, 20*(1), 24-29.

Mecagni, C., Smith, J. P., Roberts, K. E., & O'Sullivan, S. B. (2000). Balance and ankle range of motion in community-dwelling women aged 64 to 87 years: a correlational study. *Physical therapy, 80*(10), 1004-1011.

Melzer, I., Benjuya, N., & Kaplanski, J. (2001). Age-related changes of postural control: effect of cognitive tasks. *Gerontology, 47*(4), 189-194.

Melzer, I., Kurz, I., & Oddsson, L. I. (2010). A retrospective analysis of balance control parameters in elderly fallers and non-fallers. *Clinical Biomechanics (Bristol, Avon), 25*(10), 984-988.

Menant, J. C., Wong, A., Sturnieks, D. L., Close, J. C., Delbaere, K., Sachdev, P. S., Brodaty, H., & Lord, S. R. (2013). Pain and anxiety mediate the relationship between dizziness and falls in older people. *Journal of the American Geriatrics Society, 61*(3), 423-428.

Mentiplay, B. F., Clark, R. A., Mullins, A., Bryant, A. L., Bartold, S., & Paterson, K. (2013). Reliability and validity of the Microsoft Kinect for evaluating static foot posture. *Journal of foot and ankle research, 6*(1), 14.

Menz, H. B., Morris, M. E., & Lord, S. R. (2006a). Foot and ankle risk factors for falls in older people: a prospective study. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 61*(8), 866-870.

Menz, H. B., Zammit, G. V., Munteanu, S. E., & Scott, G. (2006b). Plantarflexion strength of the toes: age and gender differences and evaluation of a clinical screening test. *Foot & ankle international, 27*(12), 1103-1108.

Michaelson, P., Michaelson, M., Jaric, S., Latash, M. L., Sjolander, P., & Djupsjobacka, M. (2003). Vertical posture and head stability in patients with chronic neck pain. *J Rehabil Med, 35*(5), 229-235.

Mickle, K. J., Munro, B. J., Lord, S. R., Menz, H. B., & Steele, J. R. (2009). ISB Clinical Biomechanics Award 2009: toe weakness and deformity increase the risk of falls in older people. *Clinical biomechanics, 24*(10), 787-791.

Mickle, K. J., Munro, B. J., Lord, S. R., Menz, H. B., & Steele, J. R. (2009). ISB Clinical Biomechanics Award 2009: toe weakness and deformity increase the risk of falls in older people. *Clin Biomech (Bristol, Avon), 24*(10), 787-791.

Misu, S., Doi, T., Asai, T., Sawa, R., Tsutsumimoto, K., Nakakubo, S., Yamada, M., & Ono, R. (2014). Association between toe flexor strength and spatiotemporal gait parameters in community-dwelling older people. *Journal of Neuroengineering and Rehabilitation, 11*(1), 143.

Mok, N. W., Brauer, S. G., & Hodges, P. W. (2004). Hip strategy for balance control in quiet standing is reduced in people with low back pain. *Spine, 29*(6), E107-E112.

Mok, N. W., Brauer, S. G., & Hodges, P. W. (2011). Postural recovery following voluntary arm movement is impaired in people with chronic low back pain. *Gait & posture, 34*(1), 97-102.

Moreau, C. E., Green, B. N., Johnson, C. D., & Moreau, S. R. (2001). Isometric back extension endurance tests: a review of the literature. *Journal of Manipulative and Physiological Therapeutics, 24*(2), 110-122.

Mueller, M. J., Minor, S. D., Sahrmann, S. A., Schaaf, J. A., & Strube, M. J. (1994). Differences in the gait characteristics of patients with diabetes and peripheral neuropathy compared with age-matched controls. *Physical therapy, 74*(4), 299-308.

Mulligan, E. P., & Cook, P. G. (2013). Effect of plantar intrinsic muscle training on medial longitudinal arch morphology and dynamic function. *Manual Therapy, 18*(5), 425-430.

Murray, C. J., & Lopez, A. D. (1996). Evidence-based health policy--lessons from the Global Burden of Disease Study. *Science, 274*(5288), 740-743.

Myers, A. M., Fletcher, P. C., Myers, A. H., & Sherk, W. (1998). Discriminative and evaluative properties of the activities-specific balance confidence (ABC) scale. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 53*(4), M287-M294.

Nelson, D., Mah, J. K., Adams, C., Hui, S., Crawford, S., Darwish, H., Stephure, D., & Pacaud, D. (2006). Comparison of conventional and non-invasive techniques for the early identification of diabetic neuropathy in children and adolescents with type 1 diabetes. *Pediatric diabetes, 7*(6), 305-310.

O'Leary, T., Sterling, Jull. (2008). Whiplash, headache, and neck pain : research-based directions for physical therapies. Edinburgh: Churchill Livingstone.

Oie, K. S., Kiemel, T., & Jeka, J. J. (2002). Multisensory fusion: simultaneous re-weighting of vision and touch for the control of human posture. *Cognitive Brain Research, 14*(1), 164-176.

Oppenheim, U., Kohen-Raz, R., Alex, D., Kohen-Raz, A., & Azarya, M. (1999). Postural characteristics of diabetic neuropathy. *Diabetes Care, 22*(2), 328-332.

Ostrowska, B., Rożek-Mróz, K., & Giemza, C. (2003). Body posture in elderly, physically active males. *The Aging Male, 6*(4), 222-229.

Paillard, T., Costes-Salon, C., Lafont, C., & Dupui, P. (2002). Are there differences in postural regulation according to the level of competition in judoists? *British Journal of Sports Medicine, 36*(4), 304-305.

Palmgren, P. J., Andreasson, D., Eriksson, M., & Hagglund, A. (2009). Cervicocephalic kinesthetic sensibility and postural balance in patients with nontraumatic chronic neck pain--a pilot study. *Chiropr Osteopat, 17*, 6.

Palmieri, R. M., Ingersoll, C. D., Stone, M. B., & Krause, B. A. (2002). Center-of-pressure parameters used in the assessment of postural control. *Journal of Sport Rehabilitation, 11*(1), 51-66.

Papegaaij, S., Taube, W., Baudry, S., Otten, E., & Hortobágyi, T. (2014). Aging causes a reorganization of cortical and spinal control of posture. *Frontiers in aging neuroscience, 6*.

Patel, M., Fransson, P. A., Karlberg, M., Malmstrom, E. M., & Magnusson, M. (2010). Change of body movement coordination during cervical proprioceptive disturbances with increased age. *Gerontology, 56*(3), 284-290.

Patel, M., Fransson, P. A., & Magnusson, M. (2009). Effects of ageing on adaptation during vibratory stimulation of the calf and neck muscles. *Gerontology, 55*(1), 82-91.

Peolsson, A., Almkvist, C., Dahlberg, C., Lindqvist, S., & Pettersson, S. (2007). Age-and sex-specific reference values of a test of neck muscle endurance. *Journal of manipulative and physiological therapeutics, 30*(3), 171-177.

Perriman, D. M., Scarvell, J. M., Hughes, A. R., Lueck, C. J., Dear, K. B., & Smith, P. N. (2012). Thoracic hyperkyphosis: a survey of Australian physiotherapists. *Physiotherapy Research International, 17*(3), 167-178.

Peterka, R. J. (2002). Sensorimotor integration in human postural control. *J Neurophysiol, 88*(3), 1097-1118.

Peterka, R. J., & Loughlin, P. J. (2004). Dynamic regulation of sensorimotor integration in human postural control. *Journal of neurophysiology, 91*(1), 410-423.

Pijnenburg, M., Caeyenberghs, K., Janssens, L., Goossens, N., Swinnen, S. P., Sunaert, S., & Brumagne, S. (2014). Microstructural integrity of the superior cerebellar peduncle is associated with an impaired proprioceptive weighting capacity in individuals with non-specific low back pain. *PloS one, 9*(6), e100666.

Pleguezuelos Cobo, E., Garcia-Alsina, J., Garcia Almazan, C., Ortiz Fandino, J., Perez Mesquida, M. E., Guirao Cano, L., Samitier Pastor, B., Perucho Pont, C., Coll Serra, E., Matarrubias, C., & Reveron, G. (2009). [Postural control disorders in initial phases of whiplash]. *Medicina Clínica, 132*(16), 616-620.

Podsiadlo, D., & Richardson, S. (1991a). The timed “Up & Go”: a test of basic functional mobility for frail elderly persons. *Journal of the American geriatrics Society, 39*(2), 142-148.

Podsiadlo, D., & Richardson, S. (1991b). The timed" Up & Go": a test of basic functional mobility for frail elderly persons. *Journal of the American Geriatrics Society, 39*(2), 142.

Pollock, A. S., Durward, B. R., Rowe, P. J., & Paul, J. P. (2000). What is balance? *Clinical rehabilitation, 14*(4), 402-406.

Poole, E., Treleaven, J., & Jull, G. (2008). The influence of neck pain on balance and gait parameters in community-dwelling elders. *Manual therapy, 13*(4), 317-324.

Prioli, A. C., Freitas Júnior, P., Barela, J., & Angelo, e. (2005). Physical activity and postural control in the elderly: coupling between visual information and body sway. *Gerontology, 51*(3), 145-148.

Quek, J., Brauer, S., Clark, R., & Treleaven, J. (2014). New insights into neck-pain-related postural control using measures of signal frequency and complexity in older adults. *Gait & posture, 39*(4), 1069-1073.

Quek, J., Pua, Y.-H., Clark, R. A., & Bryant, A. L. (2012). Effects of thoracic kyphosis and forward head posture on cervical range of motion in older adults. *Manual therapy*.

Quek, J., Treleaven, J., Brauer, S. G., O'Leary, S., & Clark, R. A. (2015). Intra-rater reliability of hallux flexor strength measures using the Nintendo Wii Balance Board. *Journal of foot and ankle research, 8*(1), 48.

Quek, J. M. T., Pua, Y.-H., Bryant, A. L., & Clark, R. A. (2013). The influence of cervical spine flexion-rotation range-of-motion asymmetry on postural stability in older adults. *Spine, 38*(19), 1648-1655.

Raine, S., & Twomey, L. T. (1997). Head and shoulder posture variations in 160 asymptomatic women and men. *Arch Phys Med Rehabil, 78*(11), 1215-1223.

Rajabi, R., Seidi, F., & Mohamadi, F. (2008). Which method is accurate when using the flexible ruler to measure the lumbar curvature angle? deep point or mid point of arch. *World Applied Sciences Journal, 4*(6), 849-852.

Ramdani, S., Seigle, B., Lagarde, J., Bouchara, F., & Bernard, P. L. (2009). On the use of sample entropy to analyze human postural sway data. *Medical Engineering and Physics, 31*(8), 1023-1031.

Rheault, W., Albright, B., Beyers, C., Franta, M., Johnson, A., Skowronek, M., & Dougherty, J. (1992). Intertester reliability of the cervical range of motion device. *J Orthop Sports Phys Ther, 15*(3), 147-150.

Riley, M. A., & Clark, S. (2003). Recurrence analysis of human postural sway during the sensory organization test. *Neuroscience letters, 342*(1), 45-48.

Rix, G. D., & Bagust, J. (2001). Cervicocephalic kinesthetic sensibility in patients with chronic, nontraumatic cervical spine pain. *Arch Phys Med Rehabil, 82*(7), 911-919.

Roerdink, M., Hlavackova, P., & Vuillerme, N. (2011). Effects of plantar-flexor muscle fatigue on the magnitude and regularity of center-of-pressure fluctuations. *Experimental Brain Research, 212*(3), 471-476.

Röijezon, U., Björklund, M., Bergenheim, M., & Djupsjöbacka, M. (2008). A novel method for neck coordination exercise–a pilot study on persons with chronic non-specific neck pain. *Journal of neuroengineering and rehabilitation, 5*(1), 36.

Röijezon, U., Björklund, M., & Djupsjöbacka, M. (2011). The slow and fast components of postural sway in chronic neck pain. *Manual Therapy, 16*(3), 273-278.

Röijezon, U., Clark, N. C., & Treleaven, J. (2015). Proprioception in musculoskeletal rehabilitation. Part 1: Basic science and principles of assessment and clinical interventions. *Manual therapy, 20*(3), 368-377.

Rosenhall, U., & Rubin, W. (1975). Degenerative changes in the human vestibular sensory epithelia. *Acta oto-laryngologica, 79*(1-2), 67-80.

Rowlands, R., Campbell, I., & Kenyon, G. (2009). Otological and vestibular symptoms in patients with low grade (Quebec grades one and two) whiplash injury. *The Journal of Laryngology & Otology, 123*(02), 182-185.

Rubenstein, L. Z. (2006). Falls in older people: epidemiology, risk factors and strategies for prevention. *Age and ageing, 35*(suppl_2), ii37-ii41.

Ruhe, A., Fejer, R., & Walker, B. (2011). Altered postural sway in patients suffering from non-specific neck pain and whiplash associated disorder - A systematic review of the literature. *Chiropractic and Manual Therapies, 19*(1), 13.

Ryan, G., & Cope, S. (1955). Cervical vertigo. *The Lancet, 266*(6905), 1355-1359.

Sá, S., & Silva, A. G. (2017). Repositioning error, pressure pain threshold, catastrophizing and anxiety in adolescents with chronic idiopathic neck pain. *Musculoskeletal Science and Practice, 30*, 18-24.

Schieppati, M., Nardone, A., & Schmid, M. (2003). Neck muscle fatigue affects postural control in man. *Neuroscience, 121*(2), 277-285.
Schneider, C. A., Rasband, W. S., & Eliceiri, K. W. (2012). NIH Image to ImageJ: 25 years of image analysis. *Nature methods, 9*(7), 671.
Schubert, M. C., Tusa, R. J., Grine, L. E., & Herdman, S. J. (2004). Optimizing the sensitivity of the head thrust test for identifying vestibular hypofunction. *Physical therapy, 84*(2), 151-158.
Seidi, F., Rajabi, R., Ebrahimi, I., Alizadeh, M. H., & Minoonejad, H. (2014). The efficiency of corrective exercise interventions on thoracic hyper-kyphosis angle. *Journal of Back and Musculoskeletal Rehabilitation, 27*(1), 7-16.
Seidi, F., Rajabi, R., Ebrahimi, T., Tavanai, A., & Moussavi, S. (2009). The Iranian flexible ruler reliability and validity in lumbar lordosis measurements. *World journal of sport sciences, 2*(2), 95-99.
Seidler, R. D., Bernard, J. A., Burutolu, T. B., Fling, B. W., Gordon, M. T., Gwin, J. T., Kwak, Y., & Lipps, D. B. (2010). Motor control and aging: links to age-related brain structural, functional, and biochemical effects. *Neuroscience & Biobehavioral Reviews, 34*(5), 721-733.
Senda, M., Takahara, Y., Yagata, Y., Yamamoto, K., Nagashima, H., Tukiyama, H., & Inoue, H. (1999). Measurement of the muscle power of the toes in female marathon runners using a toe dynamometer. *Acta Med Okayama, 53*(4), 189-191.
Shumway-Cook, A., Baldwin, M., Polissar, N. L., & Gruber, W. (1997). Predicting the probability for falls in community-dwelling older adults. *Physical therapy, 77*(8), 812-819.
Shumway-Cook, A., Brauer, S., & Woollacott, M. (2000). Predicting the probability for falls in community-dwelling older adults using the Timed Up & Go Test. *Physical therapy, 80*(9), 896-903.
Shumway-Cook, A., Gruber, W., Baldwin, M., & Liao, S. (1997). The effect of multidimensional exercises on balance, mobility, and fall risk in community-dwelling older adults. *Physical therapy, 77*(1), 46-57.
Shumway-Cook, A., & Woollacott, M. H. Motor control: theory and practical applications. 2001. *Philadelphia, Williams and Wilkins Google Scholar*.
Shumway-Cook, A., & Woollacott, M. H. (2001). *Motor control : theory and practical applications* (2nd ed.). Philadelphia: Lippincott Williams & Wilkins.
Shumway-Cook, A., & Woollacott, M. H. (2017). Motor Control: Translating Research into Clinical Practice.
Silva, A. G., & Cruz, A. L. (2012). Standing balance in patients with whiplash-associated neck pain and idiopathic neck pain when compared with asymptomatic participants: A systematic review. *Physiotherapy Theory and Practice*, 1-18.
Silva, A. G., & Johnson, M. I. (2013). Does forward head posture affect postural control in human healthy volunteers? *Gait & posture, 38*(2), 352-353.
Silva, A. G., Punt, T. D., Sharples, P., Vilas-Boas, J. P., & Johnson, M. I. (2009). Head posture and neck pain of chronic nontraumatic origin: a comparison between patients and pain-free persons. *Archives of physical medicine and rehabilitation, 90*(4), 669-674.
Sinaki, M., Brey, R. H., Hughes, C. A., Larson, D. R., & Kaufman, K. R. (2005). Balance disorder and increased risk of falls in osteoporosis and kyphosis: significance of kyphotic posture and muscle strength. *Osteoporos Int, 16*(8), 1004-1010.
Sinaki, M., Brey, R. H., Hughes, C. A., Larson, D. R., & Kaufman, K. R. (2005). *Significant reduction in risk of falls and back pain in osteoporotic-kyphotic women through a Spinal Proprioceptive Extension Exercise Dynamic (SPEED) program.* Paper presented at the Mayo Clinic Proceedings.

Sitthipornvorakul, E., Janwantanakul, P., & Lohsoonthorn, V. (2015). The effect of daily walking steps on preventing neck and low back pain in sedentary workers: a 1-year prospective cohort study. *European spine journal, 24*(3), 417-424.

Sjolander, P., Michaelson, P., Jaric, S., & Djupsjobacka, M. (2008). Sensorimotor disturbances in chronic neck pain--range of motion, peak velocity, smoothness of movement, and repositioning acuity. *Man Ther, 13*(2), 122-131.

Sjölander, P., Michaelson, P., Jaric, S., & Djupsjöbacka, M. (2008). Sensorimotor disturbances in chronic neck pain—range of motion, peak velocity, smoothness of movement, and repositioning acuity. *Manual therapy, 13*(2), 122-131.

Soma, M., Murata, S., Kai, Y., Nakae, H., & Satou, Y. (2014). An Examination of Limb Position for Measuring Toe-grip Strength. *J Phys Ther Sci, 26*(12), 1955.

Soysa, A., Hiller, C., Refshauge, K., & Burns, J. (2012). Importance and challenges of measuring intrinsic foot muscle strength. *Journal of foot and ankle research, 5*(1), 29.

Spink, M. J., Fotoohabadi, M. R., & Menz, H. B. (2009). Foot and ankle strength assessment using hand-held dynamometry: reliability and age-related differences. *Gerontology, 56*(6), 525-532.

Spink, M. J., Fotoohabadi, M. R., & Menz, H. B. (2010). Foot and ankle strength assessment using hand-held dynamometry: reliability and age-related differences. *Gerontology, 56*(6), 525-532.

Spink, M. J., Fotoohabadi, M. R., Wee, E., Hill, K. D., Lord, S. R., & Menz, H. B. (2011). Foot and ankle strength, range of motion, posture, and deformity are associated with balance and functional ability in older adults. *Arch Phys Med Rehabil, 92*(1), 68-75.

Stanton, T. R., Leake, H. B., Chalmers, K. J., & Moseley, G. L. (2016). Evidence of impaired proprioception in chronic, idiopathic neck pain: systematic review and meta-analysis. *Physical therapy, 96*(6), 876-887.

Stapley, P. J., Beretta, M. V., Dalla Toffola, E., & Schieppati, M. (2006). Neck muscle fatigue and postural control in patients with whiplash injury. *Clin Neurophysiol, 117*(3), 610-622.

Sturnieks, D. L., St George, R., & Lord, S. R. (2008). Balance disorders in the elderly. *Neurophysiologie Clinique/Clinical Neurophysiology, 38*(6), 467-478.

Sundermier, L., Woollacott, M. H., Jensen, J. L., & Moore, S. (1996). Postural sensitivity to visual flow in aging adults with and without balance problems. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 51*(2), M45-M52.

Takahashi, T., Ishida, K., Hirose, D., Nagano, Y., Okumiya, K., Nishinaga, M., Matsubayashi, K., Doi, Y., Tani, T., & Yamamoto, H. (2005). Trunk deformity is associated with a reduction in outdoor activities of daily living and life satisfaction in community-dwelling older people. *Osteoporos Int, 16*(3), 273-279.

Teng, C. C., Chai, H., Lai, D. M., & Wang, S. F. (2007). Cervicocephalic kinesthetic sensibility in young and middle-aged adults with or without a history of mild neck pain. *Man Ther, 12*(1), 22-28.

Tinazzi, M., Fiaschi, A., Rosso, T., Faccioli, F., Grosslercher, J., & Aglioti, S. M. (2000). Neuroplastic changes related to pain occur at multiple levels of the human somatosensory system: A somatosensory-evoked potentials study in patients with cervical radicular pain. *Journal of Neuroscience, 20*(24), 9277-9283.

Tinetti, M. E., & Williams, C. S. (1998). The effect of falls and fall injuries on functioning in community-dwelling older persons. *Journal of Gerontology A Biological Sciences Medical Sciences, 53*(2), M112-119.

Toglia, J., Rosenberg, P., & Ronis, M. (1969). Vestibular and audiological aspects of whiplash injury and head trauma. *Journal of Forensic Sciences, 14*(2), 219-226.

Tousignant-Laflamme, Y., Boutin, N., Dion, A. M., & Vallee, C. A. (2013). Reliability and criterion validity of two applications of the iPhone to measure cervical range of motion in healthy participants. *J Neuroeng Rehabil, 10*(1), 69.

Tousignant, M., de Bellefeuille, L., O'Donoughue, S., & Grahovac, S. (2000). Criterion validity of the cervical range of motion (CROM) goniometer for cervical flexion and extension. *Spine (Phila Pa 1976), 25*(3), 324-330.

Tousignant, M., Duclos, E., Lafleche, S., Mayer, A., Tousignant-Laflamme, Y., Brosseau, L., & O'Sullivan, J. P. (2002). Validity study for the cervical range of motion device used for lateral flexion in patients with neck pain. *Spine (Phila Pa 1976), 27*(8), 812-817.

Tran, T., Wing, D., Davis, A., Bergstrom, J., Schousboe, J., Nichols, J., & Kado, D. (2016). Correlations among four measures of thoracic kyphosis in older adults. *Osteoporosis International, 27*(3), 1255-1259.

Treleaven, J. (2008). Sensorimotor disturbances in neck disorders affecting postural stability, head and eye movement control. *Manual therapy, 13*(1), 2-11.

Treleaven, J. (2011). Dizziness, unsteadiness, visual disturbances, and postural control: implications for the transition to chronic symptoms after a whiplash trauma. *Spine, 36*, S211-S217.

Treleaven, J., Clamaron-Cheers, C., & Jull, G. (2011). Does the region of pain influence the presence of sensorimotor disturbances in neck pain disorders? *Manual therapy, 16*(6), 636-640.

Treleaven, J., Jull, G., & Lowchoy, N. (2005a). Standing balance in persistent whiplash: a comparison between subjects with and without dizziness. *J Rehabil Med, 37*(4), 224-229.

Treleaven, J., Jull, G., & LowChoy, N. (2006). The relationship of cervical joint position error to balance and eye movement disturbances in persistent whiplash. *Man Ther, 11*(2), 99-106.

Treleaven, J., Jull, G., & Sterling, M. (2003). Dizziness and unsteadiness following whiplash injury: characteristic features and relationship with cervical joint position error. *Journal of Rehabilitation Medicine, 35*(1), 36-43.

Treleaven, J., LowChoy, N., Darnell, R., Panizza, B., Brown-Rothwell, D., & Jull, G. (2008). Comparison of sensorimotor disturbance between subjects with persistent whiplash-associated disorder and subjects with vestibular pathology associated with acoustic neuroma. *Arch Phys Med Rehabil, 89*(3), 522-530.

Treleaven, J., Murison, R., Jull, G., LowChoy, N., & Brauer, S. (2005b). Is the method of signal analysis and test selection important for measuring standing balance in subjects with persistent whiplash? *Gait Posture, 21*(4), 395-402.

Tsao, H., Galea, M., & Hodges, P. (2008). Reorganization of the motor cortex is associated with postural control deficits in recurrent low back pain. *Brain, 131*(8), 2161-2171.

Turk, D. C., Robinson, J. P., Sherman, J. J., Burwinkle, T., & Swanson, K. (2008). Assessing fear in patients with cervical pain: development and validation of the Pictorial Fear of Activity Scale-Cervical (PFActS-C). *Pain, 139*(1), 55-62.

Unger, C. L., & Wooden, M. J. (2000). Effect of foot intrinsic muscle strength training on jump performance. *The Journal of Strength & Conditioning Research, 14*(4), 373-378.

Uthaikhup, S., Jull, G., Sungkarat, S., & Treleaven, J. (2012). The influence of neck pain on sensorimotor function in the elderly. *Arch Gerontol Geriatr, 55*(3), 667-672.

Uthaikhup, S., Sunkarat, S., Khamsaen, K., Meeyan, K., & Treleaven, J. (2014). The effects of head movement and walking speed on gait parameters in patients with chronic neck pain. *Manual therapy, 19*(2), 137-141.

Van Deursen, R. W. M., Sanchez, M., Derr, J., Becker, M., Ulbrecht, J., & Cavanagh, P. R. (2001). Vibration perception threshold testing in patients with diabetic neuropathy: ceiling effects and reliability. *Diabetic medicine, 18*(6), 469-475.

Verardi, V., & Croux, C. (2009). Robust Regression in Stata. *Stata Journal, 9*(3), 439-453.

Vernon, H. (2008). The Neck Disability Index: state-of-the-art, 1991-2008. *Journal of manipulative and physiological therapeutics, 31*(7), 491-502.

Vernon, H., & Mior, S. (1991a). The Neck Disability Index: a study of reliability and validity. *Journal of manipulative and physiological therapeutics, 14*(7), 409-415.
Vernon, H., & Mior, S. (1991b). The Neck Disability Index: a study of reliability and validity. *Journal of Manipulative and Physiological Therapeutics, 14*(7), 409-415.
Viccaro, L. J., Perera, S., & Studenski, S. A. (2011). Is Timed Up and Go Better Than Gait Speed in Predicting Health, Function, and Falls in Older Adults? *Journal of the American Geriatrics Society, 59*(5), 887-892.
Visser, J. E., Carpenter, M. G., van der Kooij, H., & Bloem, B. R. (2008). The clinical utility of posturography. *Clinical Neurophysiology, 119*(11), 2424-2436.
Walston, J., Hadley, E. C., Ferrucci, L., Guralnik, J. M., Newman, A. B., Studenski, S. A., Ershler, W. B., Harris, T., & Fried, L. P. (2006). Research agenda for frailty in older adults: toward a better understanding of physiology and etiology: summary from the American Geriatrics Society/National Institute on Aging Research Conference on Frailty in Older Adults. *Journal of the American Geriatrics Society, 54*(6), 991-1001.
Walter, S., Eliasziw, M., & Donner, A. (1998). Sample size and optimal designs for reliability studies. *Statistics in Medicine, 17*(1), 101-110.
Washburn, R. A., Smith, K. W., Jette, A. M., & Janney, C. A. (1993). The Physical Activity Scale for the Elderly (PASE): development and evaluation. *Journal of clinical epidemiology, 46*(2), 153-162.
Westcott, S. L., Lowes, L. P., & Richardson, P. K. (1997). Evaluation of postural stability in children: current theories and assessment tools. *Physical therapy, 77*(6), 629-645.
Williams, K., Tarmizi, A., & Treleaven, J. (2017). Use of neck torsion as a specific test of neck related postural instability. *Musculoskeletal Science and Practice, 29*, 115-119.
Winter, D. A. (1995). *ABC (anatomy, biomechanics and control) of balance during standing and walking*: Waterloo Biomechanics.
Winter, D. A. (1995). Human balance and postural control during standing and walking. *Gait Posture, 3*, 193-214.
Winter, D. A., Patla, A. E., & Frank, J. S. (1990). Assessment of balance control in humans. *Med prog technol, 16*(1-2), 31-51.
Wirth, B., Amstalden, M., Perk, M., Boutellier, U., & Humphreys, B. (2014). Respiratory dysfunction in patients with chronic neck pain–Influence of thoracic spine and chest mobility. *Manual therapy, 19*(5), 440-444.
Yahia, A., Ghroubi, S., Jribi, S., Malla, J., Baklouti, S., Ghorbel, A., & Elleuch, M. H. (2009). Chronic neck pain and vertigo: Is a true balance disorder present? *Ann Phys Rehabil Med, 52*(7-8), 556-567.
Ylinen, J., Salo, P., Nykänen, M., Kautiainen, H., & Häkkinen, A. (2004). Decreased isometric neck strength in women with chronic neck pain and the repeatability of neck strength measurements. *Archives of physical medicine and rehabilitation, 85*(8), 1303-1308.
Yu, L. J., Stokell, R., & Treleaven, J. (2011). The effect of neck torsion on postural stability in subjects with persistent whiplash. *Manual Therapy, 16*(4), 339-343.

Appendix

Appendix 1- URL Link to Study 1

https://jneuroengrehab.biomedcentral.com/articles/10.1186/1743-0003-11-65

Appendix 2- URL Link to Study 2

http://journals.lww.com/intjrehabilres/Abstract/publishahead/The_concurrent_validity_and_intrarater_reliability.99548.aspx

Appendix 3- URL Link to Study 3

https://jfootankleres.biomedcentral.com/articles/10.1186/s13047-015-0104-7

Appendix 4- URL Link to Study 4

http://www.sciencedirect.com/science/article/pii/S0966636214000289

Appendix 5- URL Link to Study 5

http://www.sciencedirect.com/science/article/pii/S0966636217310159?_rdoc=1&_fmt=high&_origin=gateway&_docanchor=&md5=b8429449ccfc9c30159a5f9aeaa92ffb

Appendix 6- Ethics Approval

THE UNIVERSITY OF QUEENSLAND

Institutional Human Research Ethics Approval

Project Title:	The Influence Of Cervical Spine Dysfunction On Postural Control
Chief Investigator:	Ms June Quek
Supervisor:	Prof Sandy Brauer, Dr Julia Treleaven, Dr Ross Clark
Co-Investigator(s):	Prof Sandy Brauer, Dr Julia Treleaven, Dr Ross Clark
School(s):	School of Health and Rehabilitation
Approval Number:	2013001596
Granting Agency/Degree:	PhD
Duration:	31st December 2016

Comments/Conditions:

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 15.1.14

Appendix 7- Participant Information Sheet

School of Health and Rehabilitation Sciences

Division of Physiotherapy
Head: Professor Sandra Brauer
PhD, BPhty (Hons 1)

CRICOS PROVIDER NUMBER 00025B

PARTICIPANT INFORMATION SHEET

TITLE: The Influence of Cervical Spine Dysfunction on Postural Control.

LAY TITLE: The Influence of Neck Pain on Balance

INVESTIGATORS: **June Quek**
PhD Candidate, Division of Physiotherapy, The University of Queensland
Prof. Sandy Brauer
Division of Physiotherapy, The University of Queensland
Dr. Julia Treleaven
Division of Physiotherapy, The University of Queensland
Dr. Ross Clark
Australian Catholic University, Melbourne

1. Participant selection and purpose of the study
The aim of this study is to investigate how factors related to neck pain influences balance. It will help us to understand the potential factors associated with balance deficits in individuals with neck pain. The information gathered will direct further research in this area and ultimately help to guide the management of this condition. You are invited to participate in this study.

2. Description of study and risks:
If you agree to participate in the study you will be asked to perform several tasks including:

☐ Complete a form asking general personal details (e.g. date of birth, occupation, known medical conditions), information about your neck pain, medications etc.
☐ Complete questionnaires related to neck disability, falls, fear of movement, dizziness and physical activity. These may be mailed to you before the testing session.
☐ Stand on a balance board for 30 seconds with eyes open and eyes closed in comfortable and feet together foot positions with and without vibration to the calf and neck muscles.
☐ Perform basic walking tasks such as walking a short distance with and without head turns, climb steps and step over small obstacles.
☐ Read a chart to assess your vision, with and without the examiner moving your head.
☐ Perform head movements while wearing a pair of goggles that have virtual reality games.
☐ Perform neck, trunk and ankle movements in sitting and lying down.
☐ Wear a pair of glasses connected to a computer and align a line to vertical by using a mouse.
☐ Being tested on your ability to feel in your leg using a feather-like and vibration equipment.
☐ Stand while a photo is taken from a side and back view to capture your posture. You will be asked to expose your back. This will be done in a screened area and you will be given a gown to wear.
☐ Sit on a chair to watch a 10-minute movie clip. At the end of the movie, you will be asked 3 questions on the movie.

- ☐ Lie on your back with a light weight placed on your forehead. You will be asked to lift your head off the bed by approximately 1cm and hold this position as long as you can. You will then be asked to lie facing down, with your head off the bed. A light weight will be placed on the head and you will be asked to hold the weight as long as you can.
- ☐ Perform eye movements while the examiner moves your head.
- ☐ Keep your eyes open while the examiner assists you to move from a sitting position to a lying position while supporting your head. This is one of the tests of vestibular function.

There are minimal risks associated with this study. All tests are non-invasive and tasks are not designed to cause physical harm. Some participants may experience a small amount of pain or dizziness associated with their condition and adequate rest periods will be provided to all participants upon request. All tests will be terminated if participants experience severe pain or discomfort.

This study will last approximately 1.5-2 hours, for one session. The experiment will be conducted either at your home, at a nearby hall/facility or at Therapies Building (84A) at The University of Queensland, St Lucia Campus. We cannot and do not guarantee that you will receive any benefits from this study, but the participant may have a greater appreciation of their balance, visual, vestibular and neck function. No reimbursement will be provided for participating in this study.

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission or except as required by law. If you give us permission by signing the consent form, we plan to publish the results in international scientific journals. In any publication, information will be provided in such a way that you cannot be identified. On your request, a summary of the overall results and conclusions from the study will be available at the completion of the study.

Your decision whether or not to participate will not prejudice your future relations with The University of Queensland and its teaching hospitals. If you decided to participate you are free to withdraw your consent and to discontinue your participation at any time without prejudice.

This study has been cleared by one of the human ethics committees of 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 at anytime:

June Quek contactable on 0431005641

If you would like to speak to an officer of the University not involved in the study, you may contact the Ethics Officer on 3365 3924

You will be given a copy of this form to keep. We would like to thank you for considering participating in the above mentioned study.

Appendix 8- Participant Consent Form

School of Health and Rehabilitation Sciences

Division of Physiotherapy
Head: Professor Sandra Brauer
PhD, BPhty (Hons 1)

CRICOS PROVIDER NUMBER 00025B

PARTICIPANT CONSENT FORM

TITLE: The Influence of Cervical Spine Dysfunction on Postural Control.

LAYTITLE: The Influence of Neck Pain on Balance

INVESTIGATORS: **June Quek**
PhD Candidate, Division of Physiotherapy, The University of Queensland
Prof. Sandy Brauer
Division of Physiotherapy, The University of Queensland
Dr. Julia Treleaven
Division of Physiotherapy, The University of Queensland
Dr. Ross Clark
Australian Catholic University, Melbourne

1. I, _____ (PLEASE PRINT) hereby consent to take part in the research project titled: "The Influence of Cervical Spine Dysfunction on Postural Control".

2. I have read, understood and initialed the Information sheet and have received a copy, which I can keep. The project, so far as it affects me, has been explained to my satisfaction. I freely consent to my participation in the project.

3. The procedures have been explained to me, including the anticipated length of time the experiment will take, the frequency with which the tasks and procedures will be performed, and an indication of any discomfort or possible risks which may be expected. I understand that I will be asked to do tasks and/or undergo the procedures (as described in detail in the Information sheet).

4. Although I understand that the purpose of this research is to improve the quality of medical care, I understand that this is a research project and not a treatment program. My involvement may not be of any direct benefit to me.

5. I understand that I am free to withdraw from the project at any stage without penalty.

6. The information obtained in this experiment will be treated confidentially as no personal information or results will be published in a way that the participant's identity will be identifiable.

Signed: _____ Name: _____ Date: _____
(Participant)

Signed: _____ Name: _____ Date: _____
(Investigator)

Signed: _____ Name: _____ Date: _____
(Witness)

Appendix 9- Participant Questionnaires

Date: _____

Name:

Address:

Contact number:

Personal Data and Demographics

Height: _____ cm/feet **Weight:** _____ kg/lbs

Gender: Male/Female (please circle) **Date of** _____

Ethnic Group

☐ Caucasian
☐ Aboriginal & Torres Strait Islanders
☐ Asian
☐ Others

What is your employment status?

☐ In full time paid work
☐ In part time or casual paid work
☐ Not in paid work/retired

Medical History

☐ Heart Disease
☐ Diabetes
☐ Liver Disease
☐ High Blood Pressure
☐ Ulcer or stomach disease
☐ Stroke/Neurological
☐ Anemia or other blood disease
☐ Kidney disease
☐ Depression
☐ Back pain
☐ Others (list)

_____

Please list the medication/s you are taking:

_____

Have you experienced any falls over the past 1 year? If yes, how many times and when was that?

_____

Physical Activity

1. Select the option that best describes the level of your physical activity in a typical week during the last 12months such as walking or bicycling to the store or gardening.

A= No everyday activity
B= Activity at some time during the week
C= Activity several times a week
D= Almost daily or daily activity

2. Select the option that best describes the level of exercise done in a typical week during the last 12months such as sport/open air activity

A= No activity
B= Very little activity
C= “Soft” activities such as walking at least once per week
D= “Hard” Activities such as jogging, swimming, or gymnastics at least once per week
E= “Hard” activities or competitions such as running or ball sports with regularity

Activities-Specific Balance Confidence (ABC) Scale

For each of the following, please indicate your level of confidence in doing the activity without losing your balance or becoming unsteady by choosing one of the percentage points on the scale from 0% to 100%. If you do not currently do the activity in question, try and imagine how confident you would be if you had to do the activity. If you normally use a walking aid to do the activity or you hold on to someone, rate your confidence as if you were using these supports. If you have any questions about answering any of these items, please ask the therapist.

_____

For each of the following activities, please indicate your level of self-confidence by choosing a corresponding number from the following scale:

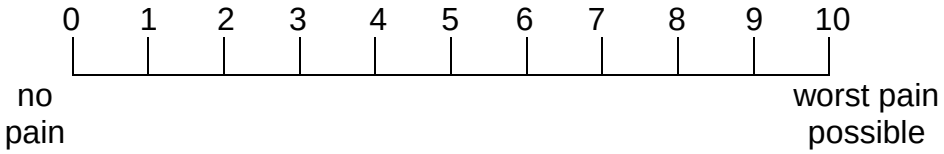
0%	10	20	30	40	50	60	70	80	90	100%
no confidence										completely confident

"How confident are you that you will not lose your balance or become unsteady when you…

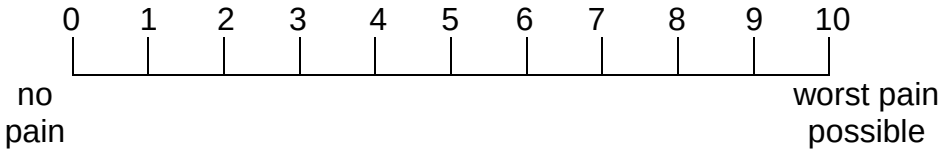
1. …walk around the house? _____%
2. …walk up or down stairs? _____%
3. …bend over and pick up a slipper from the front of a closet? _____%
4. …reach for a small can off a shelf at eye level? _____%
5. …stand on tip toes and reach for something above your head? _____%
6. …stand on a chair and reach for something? _____%
7. …sweep the floor? _____%
8. …walk outside the house to a car parked in the driveway? _____%
9. …get into or out of a car? _____%
10. …walk across a parking lot to a mall? _____%
11. …walk up or down a ramp? _____%
12. …walk in a crowded mall where people rapidly walk past you? _____%
13. …are bumped into by people as you walk through the mall? _____%
14. …step onto or off of an escalator while you are holding onto a railing? _____%
15. …step onto or off of an escalator while holding onto parcels such that you cannot hold onto the railing? _____%
16. …walk outside on icy sidewalks? _____%

Numeric Rating Scale
The following questions ask you to rate your neck pain on a scale from 0 (no pain) to 10 (worst possible pain). When answering these questions, think only of the pain you are experiencing in relation to your neck. If you are currently taking pain medications, please rate the pain according to how you think the neck will feel **WITHOUT** pain medications.

Select the number that best describes the worst neck (or neck related) pain you felt over the last 24hrs



Select the number that best describes the least neck (or neck related) pain you felt over the last 24hrs



NDI: To be completed by patient
This questionnaire has been designed to give your therapist information as to how your neck pain has affected your ability to manage in everyday life. Please answer every question by placing a mark on the line that best describes your condition today. We realize you may feel that two of the statements may describe your condition, but **please mark only the line which most closely describes your current condition**.

Pain Intensity
_____I have no pain at the moment.
_____The pain is very mild at the moment.
_____The pain is moderate at the moment.
_____The pain is fairly severe at the moment.
_____The pain is very severe at the moment.
_____The pain is the worst imaginable at the moment.

Personal Care (Washing, Dressing, etc.)
_____I do not have to change the way I wash and dress myself to avoid pain.
_____I do not normally change the way I wash or dress myself even though it causes some pain.
_____Washing and dressing increases my pain, but I can do it without changing my way of doing it.
_____Washing and dressing increases my pain, and I find it necessary to change the way I do it.
_____Because of my pain I am partially unable to wash and dress without help.
_____Because of my pain I am completely unable to wash or dress without help.

Lifting
_____I can lift heavy weights without increased pain.
_____I can lift heavy weights but it causes increased pain
_____Pain prevents me from lifting heavy weights off of the floor, but I can manage if they are conveniently positioned (ex. on a table, etc.).
_____Pain prevents me from lifting heavy weights off of the floor, but I can manage light to medium weights if they are conveniently positioned.
_____I can lift only very light weights.
_____I can not lift or carry anything at all.

Reading
_____I can read as much as I want to with no pain in my neck.
_____I can read as much as I want to with slight pain in my neck.
_____I can read as much as I want with moderate pain in my neck.
_____I can't read as much as I want because of moderate pain in my neck.
_____I can hardly read at all because of severe pain in my neck.
_____I cannot read at all.

Headache
_____I have no headache at all.
_____I have slight headaches which come infrequently.
_____I have moderate headaches which come infrequently.
_____I have moderate headaches which come frequently.
_____I have severe headaches which come frequently.
_____I have headaches almost all the time.

Concentration
_____I can concentrate fully when I want to with no difficulty.
_____I can concentrate fully when I want to with slight difficulty.
_____I have a fair degree of difficulty in concentrating when I want to.
_____I have a lot of difficulty in concentrating when I want to.
_____I have a great deal of difficulty in concentrating when I want to.
_____I cannot concentrate at all.

Work
_____I can do as much as I want to.
_____I can only do my usual work but no more.
_____I can do most of my usual work, but no more.
_____I cannot do my usual work.
_____I can hardly do any work at all.
_____I can't do any work at all.

Driving
_____I can drive my car without any neck pain.
_____I can drive my car as long as I want with slight pain in my neck.
_____I can drive my car as long as I want with moderate pain in my neck.
_____I can't drive my car as long as I want because of moderate pain in my neck.
_____I can hardly drive at all because of severe pain in my neck.
_____I can't drive my car at all.

Sleeping
_____I have no trouble sleeping.
_____My sleep is slightly disturbed (less than 1 hour sleep loss).
_____My sleep is mildly disturbed (1-2 hour sleep loss).
_____My sleep is moderately disturbed (2-3 hours sleep loss).
_____My sleep is greatly disturbed (3-5 hours sleep loss).
_____My sleep is completely disturbed (5-7 hours sleep loss).

Recreation
_____I am able to engage in all my recreational activities with no neck pain at all.
_____I am able to engage in all my recreational activities with some pain in my neck.
_____I am able to engage in most but not all of my usual recreational activities because of pain in my neck.
_____I am able to engage in a few of my usual recreational activities because of pain in my neck
_____I can hardly do any recreational activities because of pain in my neck.
_____I can't do any recreational activities at all.

Dizziness Handicap Inventry

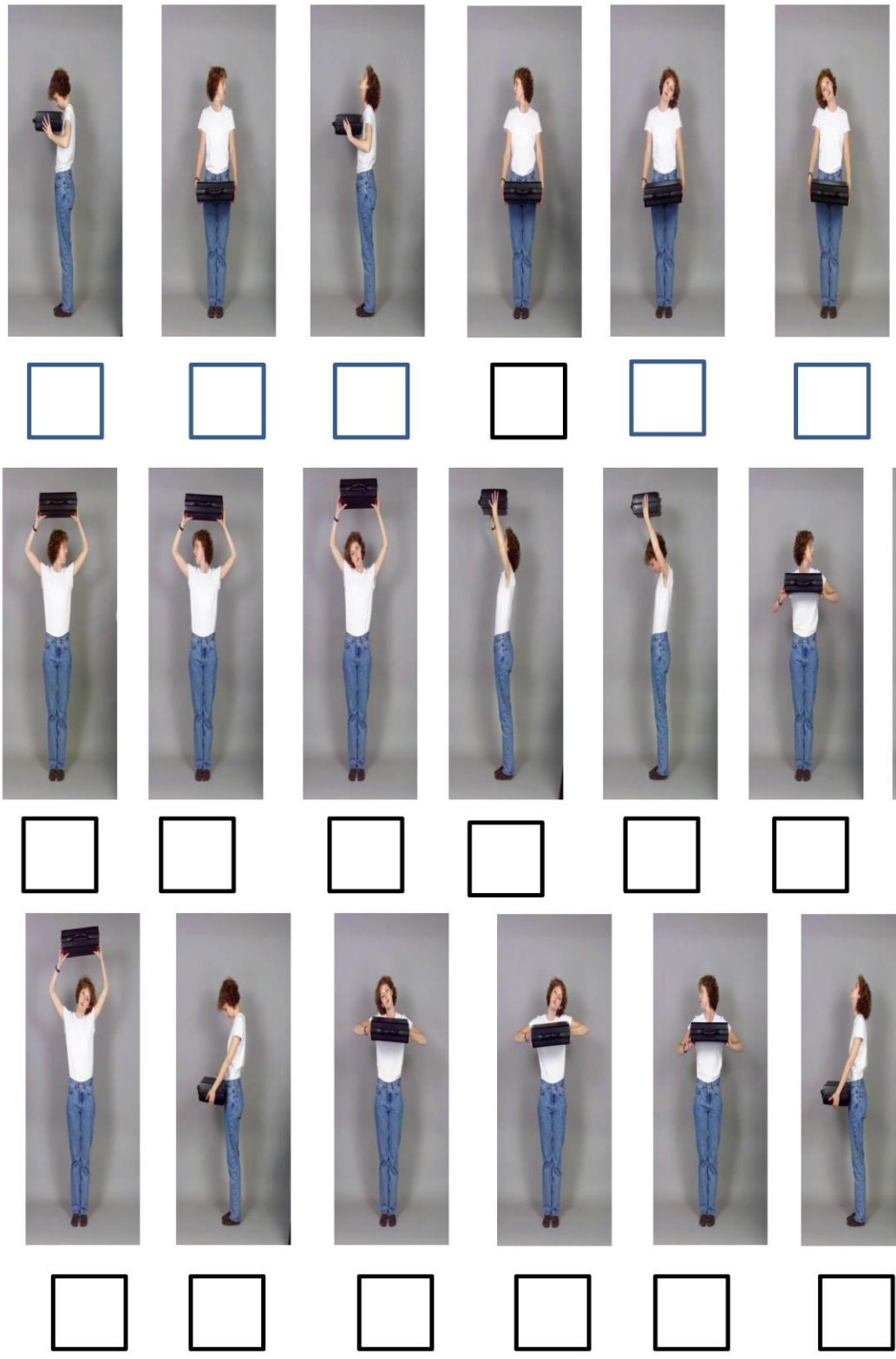
Instructions: The purpose of this scale is to identify difficulties that you may be experiencing because of your dizziness. Please check “always”, or “no” or “sometimes” to each question.

Answer each question only as it pertains to your dizziness problem.

	Questions	Always	Sometimes	No
P1	Does looking up increase your problem?	☐	☐	☐
E2	Because of your problem, do you feel frustrated?	☐	☐	☐
F3	Because of your problem, do you restrict your travel for business or pleasure?	☐	☐	☐
P4	Does walking down the aisle of a supermarket increase your problem?	☐	☐	☐
F5	Because of your problem, do you have difficulty getting into or out of bed?	☐	☐	☐
F6	Does your problem significantly restrict your participation in social activities, such as going out to dinner, going to movies, dancing or to parties?	☐	☐	☐
F7	Because of your problem, do you have difficulty reading?	☐	☐	☐
F8	Does performing more ambitious activities like sports, dancing, and household chores, such as sweeping or putting dishes away; increase your problem?	☐	☐	☐
E9	Because of your problem, are you afraid to leave your home without having someone accompany you?	☐	☐	☐
E10	Because of your problem, have you been embarrassed in front of others?	☐	☐	☐
P11	Do quick movements of your head increase your problem?	☐	☐	☐
F12	Because of your problem, do you avoid heights?	☐	☐	☐
P13	Does turning over in bed increase your problem?	☐	☐	☐
F14	Because of your problem, is it difficult for you to do strenuous housework or yard work?	☐	☐	☐
E15	Because of your problem, are you afraid people may think that you are intoxicated?	☐	☐	☐
F16	Because of your problem, is it difficult for you to go for a walk by yourself?	☐	☐	☐
P17	Does walking down a sidewalk increase your problem?	☐	☐	☐
E18	Because of your problem, is it difficult for you to concentrate?	☐	☐	☐
F19	Because of your problem, is it difficult for you to walk around your house in the dark?	☐	☐	☐
E20	Because of your problem, are you afraid to stay home alone?	☐	☐	☐
E21	Because of your problem, do you feel handicapped?	☐	☐	☐
E22	Has your problem placed stress on your relationship with members of your family or friends?	☐	☐	☐
E23	Because of your problem, are you depressed?	☐	☐	☐
F24	Does your problem interfere with your job or household responsibilities?	☐	☐	☐
P25	Does bending over increase your problem?	☐	☐	☐

PFACTS

For each of the following activities please rate out of 10 - how fearful you are of performing the activity where 0 = no fear at all and 10 = most fearful. Write your answer in the box underneath the photo.



Appendix 10 Wavelet analysis details

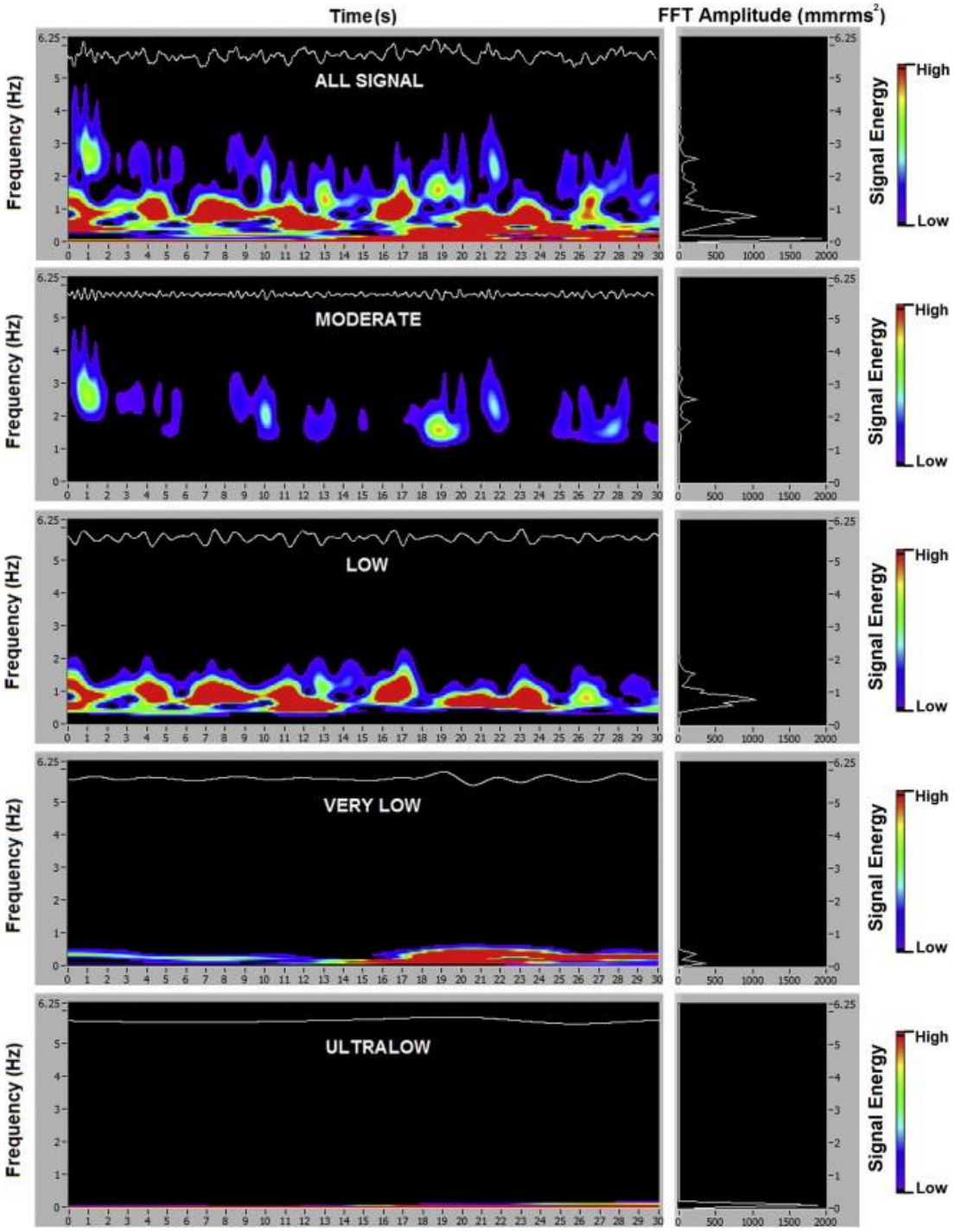
In studies 4, 5 and 6, we used discrete wavelet transforms. This section details the technicalities of this method of processing the CoP data and addresses the advantages and disadvantages of using this method. Essentially, a Symlet-8 discrete wavelet transform was used to process the CoP data. Specifically, this study focused on the anteroposterior axis. The CoP signal was separated into four frequency bands as per previous protocol (Liang et al., 2014): (i) moderate (1.56-6.25 Hz), (ii) low (0.39–1.56 Hz), (iii) very-low (0.10–0.39 Hz), and (iv) ultralow (<0.10 Hz) frequencies. This method is in contrast with previous studies (Adkin et al., 2002; Mancini et al., 2012) which separated the data using "stationary" filtering methods such as infinite impulse response filters (eg. Butterworth). The reasoning for employing wavelet transforms is manifold, and includes:

1. It provides a true separation of the signal in each bandwidth, in that it can be perfectly reconstructed from the different signal bands.
2. The discrete wavelet transform does not require a stationary signal for analysis, unlike methods such as Butterworth passband filtering. While this often only leads to trivial errors, it does overcome the known issues such as edge effects that the infinite impulse response filters have on non-stationary data.
3. The shape of many of the wavelet filters was designed to specifically mimic physiological signals, unlike the often overly curved patterns of Butterworth filter which is well suited to artificial signals.

However, a limitation of the discrete wavelet transform is that it uses cascading filter banks, with each band essentially halved (i.e. if the top passband is from 25 to 50 Hz, the next passband is from 12.5 to 25Hz). The advantage of this method is that by adding multiple passbands together, we are able to closely, but not perfectly, replicate the passbands reported in the prior studies. It must also be noted that the passbands reported in the prior studies are not perfect, as basic filtering theory shows that even though a designated low pass filter of 1Hz may be applied it will still have issues such as a slow roll off response (i.e. the signal will still contain a large amount of input from above 1Hz) or a large amount of passband ripple (i.e. the signal will be artificially inflated around the cut-off frequency). These factors cannot be overcome easily, particularly with neighbouring passbands being analysed separately, and therefore a wavelet method was chosen.

Previously members of the research team did examine different wavelet based methods of analysis and found this technique to effectively discriminate between healthy control and populations with lower limb pathology (Clark et al., 2014). To further elaborate on discrete wavelet transform, the figure below from Liang et al (2014) outlines how the

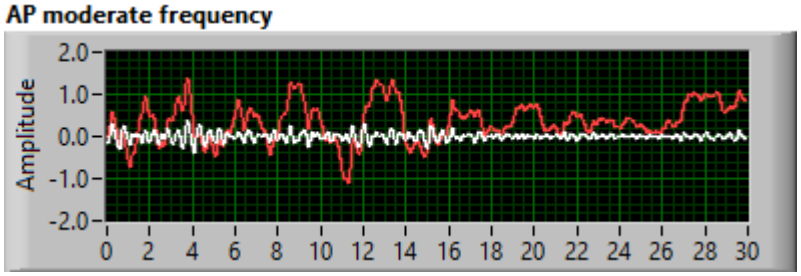
wavelet method is utilized in this thesis that separates the data into the distinct frequency bands.



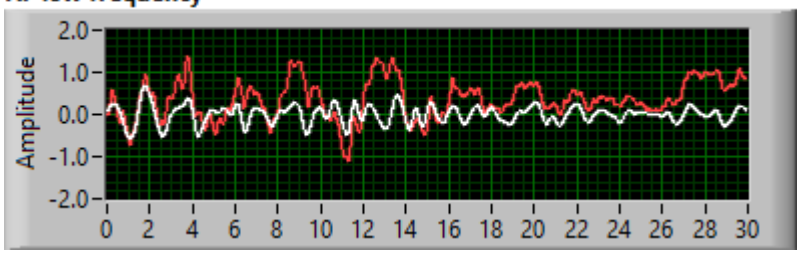
As can be seen from the FFT traces on the side of each scalogram/spectrogram the wavelet bands were able to separate the signal into distinct bands of data. While these do not perfectly attenuate the signal at the exact frequency thresholds set (no filter does without major compromises being made in factors such as passband ripple that have major impacts on the results), they are very capable of separating the signal in a way that approximates these bands, and importantly when reconstructed recreate the exact signal that was present

before deconstruction. This is seen more clearly in the following graphs where the white lines represents the deconstructed CoP signal of the specific frequency band, and the red lines represent the signal when reconstructed (all 4 white lines combined=red line).

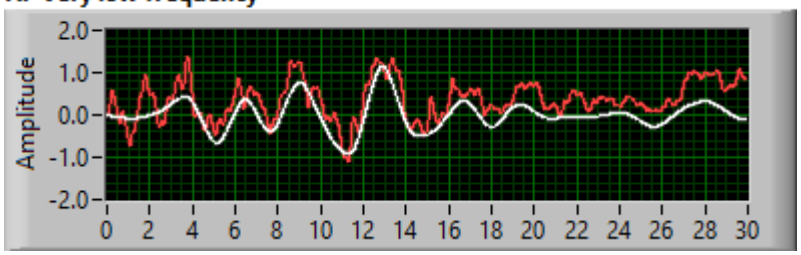
AP moderate frequency



AP low frequency



AP very low frequency



AP ultra low frequency