Effects of ageing and exercise training on postural stability in relation to strength ratios of the lower limb muscles

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Bachelor of Human Movement Science (ExSci) (Hons)

This thesis is presented in fulfilment of the requirements for the degree of

Doctor of Philosophy at Southern Cross University

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I certify that the work presented in this thesis is, to the best of my knowledge and belief, original, except as acknowledged in the text, and that the material has not been submitted, either in whole or in part, for a degree at this or any other university.

I acknowledge that I have read and understood the University's rules, requirements, procedures and policy relating to my higher degree research award and to my thesis. **I certify that I have complied** with the rules, requirements, procedures and policy of the University (as they may be from time to time).

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Date: 30/10/2013
Abstract

The functioning of the lower limb muscles plays a critical role in the production of daily activities such as postural control. Postural control relies upon the integration of sensory inputs and appropriate motor outputs to the lower limb, trunk and upper limb muscle groups. A number of studies, however, have shown that with ageing both sensory inputs and motor outputs diminish leading to alterations in the strategies used in postural control. Some examples of reduced motor function with ageing include decreased muscular strength and an alteration in the coordination of agonist/antagonist muscle activation patterns. Considering the alteration in motor output with ageing it seems appropriate to investigate the possible practical role that lower limb strength ratios may play in functional task such as postural control. This line of investigation is especially important when considering the dynamic interaction between agonist/antagonist pairs during functional activities. Previous studies have highlighted the beneficial effects of exercise interventions on postural control and muscular strength. One example that has shown some potential in the improvement of muscular strength and postural control in older adults is Tai Chi. However, previously there has been very little investigation into the effect of ageing or Tai Chi exercise on lower limb agonist/antagonist strength ratios or coactivation behaviour.

Three studies were designed in this project with the aims of 1) to examine the effects of joint angle on maximal muscular strength and agonist/antagonist strength ratios at the knee and ankle joints in young adults; 2) to investigate the effects of ageing and gender on maximal muscular strength, strength ratios, agonist/antagonist coactivation and postural control under different sensory conditions; and 3) to investigate the efficacy of 12 weeks of Tai Chi practice on the lower limb muscular strength, strength ratios, agonist/antagonist coactivation and postural control in an older population, respectively.
Study 1 consisted of an observational analysis of the differences between torque measures at different knee and ankle joint angles and an evaluation of the correlations between the variables of interest. Twenty five participants (12 male and 13 female) recruited (age 24.4 ± 6.0 years; height 1.70 ± 0.08 metres; weight 67.08 ± 9.63 kg). Study 2 was a cross-sectional analysis of the changes in postural maintenance and strength ratios of the lower limb. This study involved 25 young (age 24.4 ± 6.0 years; height 1.70 ± 0.08 metres; weight 67.08 ± 9.63 kg) and 30 older (age 72.7 ± 4.4 years; height 1.67 ± 0.09 metres; weight 75.09 ± 14.64 kg) adult volunteer participants. Study 3 was a test-retest intervention analysis of the changes in postural maintenance and strength ratios of the lower limb due to Tai Chi exercise. Thirty nine older adult (age range 65 to 80 years) volunteer participants were recruited and allocated into either a Tai Chi training group (24 participants) (age 72.7 ± 4.4 years; height 1.67 ± 0.09 metres; weight 72.54 ± 15.55 kg) or a control group (15 participants) (age 73.9 ± 4.1 years; height 1.66 ± 0.07 metres; weight 74.64 ± 9.74 kg).

The results indicated that in all of the four muscle groups (knee extensors, knee flexors, ankle plantarflexors and ankle dorsiflexors) and at the three joint angles (knee joint at 90°, 60° and 30° and ankle joint at +20°, neutral and -20°) males were significantly stronger than females. However, there were no differences in muscle activation (as indicated by surface SEMG) between genders. There were few differences between males and females in either the hamstrings to quadriceps strength ratio (HQR) or dorsiflexor to plantar flexor strength ratio (DPR). There were however significant differences in HQR and DPR at different joint angles when genders were pooled. There were significant positive correlations between muscle strength and some postural control measures (Mean Vel and Diff Co st), but no significant correlations between strength ratios and postural control measures. The young group (YG) were generally stronger and had higher muscle activation levels than the older group (OG). The YG had a higher HQR but the OG had a higher DPR. However, there were no differences in HQR or DPR between male and female participants. The OG demonstrated significantly
poorer performance than the YG in some postural control measures and the males were found to have poorer performance when compared to females in some measured postural control variables. The 12 weeks of Tai Chi training resulted in a significant improvement of muscular strength in older adults. However, no significant differences were found in strength ratios, muscle activation and postural control measures of the participants, pre and post training.

In study one, joint angle changes had a greater effect on strength output of the knee extensors (KE) and ankle plantarflexors (AP) than that on the knee flexors (KF) and ankle dorsiflexors (AD). These effects had contributed to the increased HQR and DPR at knee joint angle of $30^0$ and ankle joint angle at $+20^0$, respectively. The positive correlations found between some postural measures and maximal voluntary contractions (MVC) suggest that in fact increased maximal strength has an adverse effect on quiet postural control in young adults. This is further supported by the fact that older males exhibited significantly poorer performance in postural control compared with older females yet males were significantly stronger in most muscle groups. In Study Three, it was found that Tai Chi exercise significantly improved muscular strength; however there was very little improvement in postural control, further supporting the fact that maximal strength might not be an important factor that affected performance in quiet stance.

The findings of this thesis showed that there were gender differences in maximal strength, coactivation levels and postural control. The gender differences seen when analysing coactivation levels is a novel finding and further research should be conducted to examine the possible mechanisms for these gender differences in coactivation. Not only did gender have an effect on neuromuscular and postural measures but age also influenced many of these variables. The ageing process not only led to a significant decline in postural control and maximal strength, but also had an effect on lower limb strength ratios. The changes in strength ratios were the result of different rates of decline in strength among the lower limb
muscle groups. Therefore future investigations may benefit from exploring the muscle specific declines in maximal strength and the functional relevance of lower limb strength ratios. Finally, 12 weeks of Tai Chi exercise was shown to significantly improve maximal strength of the lower limb muscle groups but did not improve postural control. The lack of improvement in postural control may have been due to the dynamic nature of Tai Chi compared with the static nature of the postural assessment. Future research should investigate the mechanisms of strength improvement due to Tai Chi exercise and the possible relationship with dynamic postural assessment techniques.
List of Publications Derived from this Project

Book Chapters


Journal Publications


Conference Publications

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<th>Description</th>
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<tbody>
<tr>
<td>A/D</td>
<td>Analogue to digital</td>
</tr>
<tr>
<td>AD</td>
<td>Ankle dorsiflexor</td>
</tr>
<tr>
<td>AnPo</td>
<td>Anterior – Posterior</td>
</tr>
<tr>
<td>AP</td>
<td>Ankle platarflexor</td>
</tr>
<tr>
<td>BF</td>
<td>Biceps femoris</td>
</tr>
<tr>
<td>BMI</td>
<td>Body mass index</td>
</tr>
<tr>
<td>CG</td>
<td>Control group</td>
</tr>
<tr>
<td>COG</td>
<td>Centre of gravity</td>
</tr>
<tr>
<td>COM</td>
<td>Centre of mass</td>
</tr>
<tr>
<td>COP</td>
<td>Centre of pressure</td>
</tr>
<tr>
<td>Crit Point</td>
<td>Critical point</td>
</tr>
<tr>
<td>Crit Point Coord</td>
<td>Critical point coordinates</td>
</tr>
<tr>
<td>df</td>
<td>Degrees of freedom</td>
</tr>
<tr>
<td>Diff Co lt</td>
<td>Diffusion coefficient long term</td>
</tr>
<tr>
<td>Diff Co st</td>
<td>Diffusion coefficient short term</td>
</tr>
<tr>
<td>DPR</td>
<td>Dorsiflexor to Plantarflexor Ratio</td>
</tr>
<tr>
<td>SEMG</td>
<td>Electromyography</td>
</tr>
<tr>
<td>EMS</td>
<td>Electromyostimulation</td>
</tr>
<tr>
<td>GL</td>
<td>Gastrocnemius lateral head</td>
</tr>
<tr>
<td>GLM</td>
<td>General linear model</td>
</tr>
<tr>
<td>HBE</td>
<td>Home based exercise</td>
</tr>
<tr>
<td>HQR</td>
<td>Hamstring to Quadriceps Ratio</td>
</tr>
<tr>
<td>KE</td>
<td>Knee extensor</td>
</tr>
<tr>
<td>KF</td>
<td>Knee flexor</td>
</tr>
<tr>
<td>LOG</td>
<td>Line of gravity</td>
</tr>
<tr>
<td>Mean Dist</td>
<td>Mean distance</td>
</tr>
<tr>
<td>Mean Vel</td>
<td>Mean velocity</td>
</tr>
<tr>
<td>MeLa</td>
<td>Medial – Lateral</td>
</tr>
<tr>
<td>MVC</td>
<td>Maximal voluntary contraction</td>
</tr>
<tr>
<td>Neut</td>
<td>Neutral</td>
</tr>
<tr>
<td>n</td>
<td>Number</td>
</tr>
<tr>
<td>OG</td>
<td>Old group</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>------------------------------------</td>
</tr>
<tr>
<td>PG</td>
<td>Pooled group</td>
</tr>
<tr>
<td>RFD</td>
<td>Rate of force development</td>
</tr>
<tr>
<td>RMS</td>
<td>Root mean square</td>
</tr>
<tr>
<td>Scal Ex lt</td>
<td>Scaling exponent long term</td>
</tr>
<tr>
<td>Scal Ex st</td>
<td>Scaling exponent short term</td>
</tr>
<tr>
<td>SEMG</td>
<td>Surface electromyography</td>
</tr>
<tr>
<td>Sig</td>
<td>Significance</td>
</tr>
<tr>
<td>SOT</td>
<td>Sensory organisation test</td>
</tr>
<tr>
<td>TA</td>
<td>Tibialis anterior</td>
</tr>
<tr>
<td>TC</td>
<td>Tai chi</td>
</tr>
<tr>
<td>TCG</td>
<td>Tai chi group</td>
</tr>
<tr>
<td>VL</td>
<td>Vastus lateralis</td>
</tr>
<tr>
<td>YG</td>
<td>Young group</td>
</tr>
<tr>
<td>95% CCA</td>
<td>95% confidence circle area</td>
</tr>
</tbody>
</table>
Units of Measurement

° Degrees

\text{cm} \quad \text{Centimetre}

\text{Hz} \quad \text{Hertz}

\text{Kg} \quad \text{Kilogram}

\text{Kg/m}^2 \quad \text{Kilogram per square metre}

\text{m} \quad \text{Metre}

\mu\text{V} \quad \text{Microvolt}

\text{mm} \quad \text{Millimetre}

\text{mm/s} \quad \text{Millimetre per second}

\text{mV} \quad \text{Millivolt}

\text{min} \quad \text{Minute}

\text{s} \quad \text{Seconds}

\text{mm}^2 \quad \text{Square millimetre}

\text{mm}^2/\text{s} \quad \text{Square millimetre per second}

\text{N.m} \quad \text{Newton metre}

\text{V} \quad \text{Volt}

\text{yrs} \quad \text{Years}
Chapter 1: Introduction
1.1 Background to the Study

In the past several decades the life expectancy of Australians has increased with the current average life expectancy of males and females being 78.5 and 83.3 years respectively (Australian Bureau of Statistics, 2006; Australian Government - Department of Health and Ageing, 2006). The ageing process is frequently accompanied by a decrease in physiological capacities which are fundamental to the maintenance of functional independence and quality of life. Therefore it is in the interest of both the scientific community and the government sector to carry out research programs and update policies with the aim of promoting healthy ageing, improving standards of living and decreasing the burden placed on the health care system. This can be accomplished through the investigation of appropriate and cost effective exercise modalities such as Tai Chi, that aid in the promotion of healthy ageing.

As humans age and physiological capabilities decline, it is often found that the incidence of falls increase. A fall can be defined as “unintentionally coming to the ground or some lower level and other than as a consequence of sustaining a violent blow, loss of consciousness, sudden onset of paralysis as in stroke or an epileptic seizure”. This definition was first coined by the Kellogg International Working Group on the Prevention of Falls in the Elderly in 1987 (Lord, Sherrington, & Menz, 2001). Falls are among the most common and serious health problems facing older adults and are associated with increased incidence of mortality, morbidity, reduced physical function and premature admission to nursing homes (American Geriatrics Society, British Geriatrics Society, & Prevention, 2001).

Postural control is the ability to maintain the body’s centre-of-gravity within the base of support during standing (King, Judge, & Wolfson, 1994; Laughton et al., 2003). This ability involves the integration of sensory information from the vestibular, visual and tactile-proprioceptive receptors which stimulate motor responses to maintain balance. These motor responses are delivered via several parts of the brain including the cerebellum, brainstem,
basal ganglia and sensory-motor cortex (King et al., 1994; Lord, Clark, & Webster, 1991c). In
the motor system, factors associated with decreased postural control include the decline in
muscle strength and power, the reduced capacity to respond appropriately to disturbances in
postural activity (Ryushi et al., 2000) and the efficacy of signal transmission to the motor
neurons (Burnett, Laidlaw, & Enoka, 2000; Christou & Carlton, 2001).

In relation to control of balance and posture, the hip and lower limb muscle groups (knee
extensors, knee flexors, ankle plantarflexors and ankle dorsiflexors) require close examination
due to their function in controlling body sway (Dean, Kuo, & Alexander, 2004; Grasso, Zago,
& Lacquaniti, 2000). These muscle groups act as agonist/antagonist pairs across the knee and
ankle joints respectively and postural control requires the dynamic interaction between
agonist and antagonist muscle groups to successfully maintain standing posture. Therefore, it
may be hypothesised that strength ratios of the lower limb [both the hamstrings to quadriceps
(HQR) and dorsiflexor to plantarflexor (DPR) ratios] may influence the ability of the postural
control system to maintain upright stance. The potential role of lower limb strength ratios in
postural control may also be more pronounced in older adults. This is due to the relatively
larger decline in maximal strength of the larger muscle groups, the quadriceps and
gastrocnemius, as compared with the hamstrings and tibialis anterior of the lower limbs
(Frontera et al., 2008; Simoneau, Martin, & Van Hoecke, 2007b). However, there has been
very little investigation on the effects of age, gender, or joint angle on either the HQR or DPR
and the relevance of these ratios to functional tasks such as postural control.

The lack of comprehensive investigation into the effects of joint angle on strength ratios
seems questionable as it has been shown that joint angle changes cause significant alterations
in single lower limb muscle groups maximal strength capacity (Alonso, McHugh, Mullaney,
& Tyler, 2009; Babault, Pousson, Michaut, & Van Hoecke, 2003; Becker & Awiszus, 2001;
Billot, Simoneau, Ballay, Van Hoecke, & Martin, 2011; Miyamoto & Oda, 2003; Savelberg
& Meijer, 2004; Simoneau et al., 2007b; Sosnoff, Voudrie, & Ebersole, 2010). In some past investigations it has been shown that the HQR does change according to the knee joint angle during dynamic contractions (Aagaard, Simonsen, Magnusson, Larsson, & Dyhre-Poulsen, 1998; Coombs & Garbutt, 2002; Rosene, Fogarty, & Mahaffey, 2001). Yet, to the author’s knowledge, there has been no report of the effect of joint angle change on HQR measured in isometric contractions. The DPR is a relatively new lower limb strength ratio measure that has gained little research attention until the recent past. Much like the HQR, joint angle changes have been shown to alter the DPR (Simoneau et al., 2007b). There is still a need to clarify at which ankle joint angle the DPR is greatest and what, if any, relation the DPR has with functional tasks such as postural control.

The HQR has been extensively examined in athletic populations in relation to performance of athletic functional tasks (Gerodimos et al., 2003; Gur, Akova, Punduk, & Kucukoglu, 1999; Olmo, Lopez-Illescas, Martin, Jato, & Rodriguez, 2006; Read & Bellamy, 1990; Rosene et al., 2001; Tourny-Chollet, Leroy, Delarue, & Beuret-Blanquart, 2003). Within the studies that have examined the HQR, it is a common conclusion that with a higher HQR there is an improvement in dynamic stability of the knee joint and anterior cruciate ligament laxity is decreased leading to a decreased incidence of injury (Ahmad et al., 2006). Although there have been numerous investigations into the role of the HQR in athletic populations, very little examination has focused on the ageing effects on the HQR. Previously it has been shown that at a knee joint of 90\(^0\) during isometric contractions there is a significant decline in HQR with age (Bezerra, Zhou, & Crowley, 2008).

As with the HQR, there have been only a handful of investigations into the effects of ageing on the DPR. Of these few studies it has been shown that with ageing there is a significant increase in the DPR which is mainly due to the relatively larger decline in maximal strength of the ankle plantarflexors (AP) with ageing (Simoneau, Martin, & Van Hoecke, 2005;
Simoneau et al., 2007b). However further research is required to determine if this age–related decline in HQR and increase in DPR are similar when assessing these strength ratios at different joint angles.

Interest in the concept of coactivation (also known as co-contraction) of agonist/antagonist pairs around the joints of the lower extremities has grown in the last decade (Benjuya, Melzer, & Kaplanski, 2004). This is due to the influence coactivation can have on the motor outputs and behaviours such as muscular strength or postural control strategy. Several influencing factors, including joint angle, age and resistance training, have been shown to potentially affect the level of coactivation (Hortobagyi & Devita, 2006; Melzer, Benjuya, & Kaplanski, 2004).

An interesting observation in relation to coactivation is that during the ageing process there seems to be a shift away from optimally scaling the activation of the prime movers and the concurrent activity of the antagonist muscles in young individuals to a disproportionately heightened coactivation of the antagonist muscles in older individuals (Hortobagyi & Devita, 2006). This age–related increase in coactivation has been shown in functional tasks such as postural control and stepping tasks, especially when older individuals have restricted sensory feedback such as reduced visual feedback (Benjuya et al., 2004; Hortobagyi & DeVita, 2000; Melzer, Benjuya, & Kaplanski, 2001). However this data is based on a limited number of studies and therefore it is prudent to investigate the effect of altered sensory conditions on postural coactivation. The heightened antagonist activity during functional tasks such as postural control is said to be an effort to stiffen the lower limb and reduce excessive joint movements (de Boer, Morse, Thom, de Haan, & Narici, 2007; Melzer et al., 2001). Therefore the relative strength of agonist/antagonist pairs of the lower limbs may have a direct impact on the movement strategy adopted in older adults especially when excessive coactivation is present. Consequently, there is a need to investigate not only the ageing effect on lower limb
strength ratios but also how this may influence coactivation levels and therefore force output and postural control, in older adults.

It is also known that males generally demonstrate significantly higher level of strength than females across the lifespan (Lindle et al., 1997; Maughan, Watson, & Weir, 1983a; Yasuda, Glover, Phillips, Isfort, & Tarnopolsky, 2005). Whether the differences in muscular strength between genders would affect the strength ratios and muscle activation/coactivation and play a significant role in postural control tasks are largely unknown. Considering that recently some investigations have found gender differences in muscle activation patterns during fatigue and unloading (Clark, Collier, Manini, & Ploutz-Snyder, 2005; Deschenes, McCoy, Holdren, & Eason, 2009), it seems pertinent to investigate the potential gender differences in these variables.

In relation to the effect of joint angle change on coactivation during strength tasks, conflicting results have been found depending on the lower limb joint investigated. It appears that at the knee joint the hamstrings muscle group exhibits greater levels of coactivity during dynamic contractions of the quadriceps muscle group when compared to the quadriceps coactivation level during hamstrings contraction (Baratta et al., 1988; Remaud, Cornu, & Guevel, 2007). At the ankle joint however, it has been found that there were no significant differences in coactivation level between joint angles of 20° dorsiflexed, neutral (0°) and 20° plantarflexed (Simoneau et al., 2007b). Further research is required to confirm such findings and to assess the coactivation response to different joint angles during isometric contractions at both the ankle and knee joints.

Many studies have found that the relative strength and power of the lower limb muscle groups have direct influences on the ability to control posture and that both strength and functional exercise training programs can increase muscle strength and improve postural control.
(Amiridis, Arabatzi, Violaris, Stavropoulos, & Hatzitaki, 2005; Barnett, Smith, Lord, Williams, & Baumand, 2003; Ryushi et al., 2000). One traditional mode of exercise that has repeatedly been shown to improve muscular strength and postural control in older adults is resistance training (Ferri et al., 2003; Hess & Woollacott, 2005). However postural control involves not only appropriate force production by the muscles to counteract gravitational forces but also the integration of sensory information (somatosensory, visual and vestibular inputs) to successfully maintain upright stance. Therefore recently there has been a push to employ more functional movement training that may be more beneficial in improving postural control. One such exercise mode is Tai Chi (TC) which involves soft coordinated body movements that utilize the individuals own weight as the resistance (Xu, Hong, & Li, 2008) and appears to have a greater beneficial effect on the proprioceptive capacity post training compared with bioenergetic activities such as resistance exercise or walking (Gauchard, Jeandel, Tessier, & Perrin, 1999). Tai Chi has been shown to improve dynamic stability, help to reduce the incidences of falls and improve muscular strength of the lower limbs in older adults (Howe, Rochester, Neil, Skelton, & Ballinger, 2011; Sherrington, Tiedemann, Fairhall, Close, & Lord, 2011; Tsang, Wong, Fu, & Hui-Chan, 2004; Voukelatos, Cumming, Lord, & Rissel, 2007; Wu, Zhao, Zhou, & Wei, 2002). However there has been no investigation into the effect of TC exercise on the HQR, DPR and agonist/antagonist coactivation and its potential to influence static postural control.

In summary, very little attention has been afforded the effects of ageing and TC on the HQR and DPR and the possible relation with functional tasks such as postural maintenance. This is surprising given that increases in coactivation of agonist/antagonist pairs are commonly found in older adults during functional tasks such as postural control (Benjuya et al., 2004; Hortobagyi & Devita, 2006). It is therefore prudent to investigate whether ageing and TC exercise influence the HQR, DPR and coactivation (during both strength and postural tasks) levels and whether and how these measures would influence postural control.
1.2 Aims of the Investigation

The purpose of the research presented in this thesis is to advance the understanding of factors that affect the ability to control posture in older adults with the following specific aims:

1. to determine the differences in agonist/antagonist strength ratios (HQR and DPR) and coactivation of the lower limb muscles at different joint angles and the relationship with postural control;
2. to determine the age–related changes and the role of agonist/antagonist strength ratios (HQR and DPR) of the lower limb and level of coactivation in postural control during sensory conflicting conditions; and
3. to investigate the effects of a specific exercise intervention, Tai Chi, on lower limb muscle strength ratios (HQR and DPR), coactivation and postural stability in older adults.

1.3 Research Hypotheses

The following null hypotheses have been developed:

1. Lower limb muscular strength, strength ratios (HQR and DPR) and strength task coactivation will not be altered by joint angle changes.
2. Lower limb muscular strength and strength ratios (HQR and DPR) are not related to the ability to control posture in young adults.
3. Ageing or gender does not affect the lower limb muscular strength, agonist/antagonist strength ratios, or strength task coactivation.
4. The level of coactivation during postural tasks is not affected by ageing or gender during postural tasks with altered sensory conditions.
5. Tai Chi, as an exercise intervention, does not cause changes in lower limb muscle strength, strength ratio (HQR and DPR), or strength task coactivation.

6. Tai Chi, as an exercise intervention, does not cause changes in postural control or postural control coactivation levels.

1.4 Research Design

The following three studies were designed and implemented to investigate the overall aims and null hypotheses of this thesis.

1.4.1 Study One

The effects of joint angle on strength ratio and coactivation of the agonists and antagonists at the knee and ankle joints and their correlations with postural control.

Study One was a descriptive evaluation of the correlations between the variables of interest and an analysis of the differences between torque measures at different knee and ankle joint angles. The following aims and null hypotheses were developed to investigate research hypotheses 1 and 2 which would help to address the first research aim.

Aims:

1. To determine whether the lower limb muscle strength, the agonist/antagonist strength ratio and strength task coactivation are affected by joint angle and gender.

2. To investigate the relationship between lower limb maximal strength and agonist/antagonist strength ratio with postural control measures.
Null Hypotheses:

1. Lower limb muscular strength, strength ratio (HQR and DPR) and strength task coactivation are not altered by joint angle changes.
2. Lower limb muscular strength, strength ratio (HQR and DPR) and strength task coactivation are not different between genders.
3. Lower limb muscular strength and strength ratio (HQR and DPR) are not related to the ability to control posture in young adults.

1.4.2 Study Two

An investigation of the effects of age and gender on lower limb strength ratio, strength task coactivation, postural control and postural task coactivation.

Study Two was a cross-sectional analysis of the changes in postural maintenance and strength ratios of the lower limb with age and gender. The following aims and null hypotheses were developed to investigate research hypotheses 3 and 4 which would help to address the second research aim.

Aims:

1. To determine whether the lower limb muscle strength and the agonist/antagonist strength ratio are affected by age and gender.
2. To determine whether the ability to control posture in altered sensory conditions is affected by age and gender.
3. To determine whether strength task coactivation and postural task coactivation in lower limb muscles are affected by age and gender.

**Null Hypotheses:**

1. Ageing does not affect the lower limb muscular strength, agonist/antagonist strength ratios, or strength task coactivation.
2. Gender does not affect the lower limb muscular strength, agonist/antagonist strength ratios, or strength task coactivation.
3. Ageing does not affect the ability to control posture in altered sensory conditions (firm or compliant surface and eyes open or closed).
4. Gender does not affect the ability to control posture in altered sensory conditions (firm or compliant surface and eyes open or closed).
5. The level of coactivation during postural tasks is not affected by ageing during postural tasks with altered sensory conditions.

**1.4.3 Study Three**

**Effects of Tai Chi training on postural control, coactivation and lower limb muscle strength ratio modulation.**

Study Three was a test – retest analysis of the changes in postural maintenance and strength ratios of the lower limb due to Tai Chi exercise intervention. The following aims and null hypotheses were developed to investigate research hypotheses 5 and 6 which would help to address the third research aim.
Aims:

1. To investigate the effect of 12 weeks of Tai Chi exercise on lower limb muscle strength, agonist/antagonist strength ratio and strength task coactivation.
2. To investigate the effect of 12 weeks of Tai Chi exercise on postural control and postural task coactivation.

Null Hypotheses:

1. Tai Chi, as an exercise intervention, does not cause changes in lower limb muscle strength, strength ratio (HQR and DPR), or strength task coactivation.
2. Tai Chi, as an exercise intervention, does not cause changes in postural control or postural control coactivation level.

1.5 Significance of the Investigation

Many studies have investigated age-related changes in muscular strength and their relationship with postural control. However, very few have explored age-related changes in strength ratios of the agonist/antagonist muscle groups of the lower limbs and coactivation of these muscle groups and their possible roles in the maintenance of upright posture. With the previous findings that both the quadriceps and hamstrings strength (especially when adopting the “hip-strategy”) (Runge, Shupert, Horak, & Zajac, 1999) and dorsiflexor and plantarflexor strength (especially when adopting the “ankle-strategy”) (Nashner & McCollum, 1985) are important in postural control, it is important to understand if the relative strength of these agonist/antagonist pairs and the level of coactivation has an effect on the ability to maintain stance during postural tasks.
This study will provide new evidence that may result in a better understanding of the factors and mechanisms that determine the ability to control posture and help develop improved assessment tools and exercise programs for postural control in older adults.

1.6 Limitations and Delimitations

The predicted minimum number of subjects that were required to detect differences between mean values was determined by the data presented in the literature. However, due to slight difference in experimental settings, the results obtained within this thesis may be different to the results of the literature. This may limit the statistical power in the present study.

All subjects were volunteers, therefore it was not a random sample of the population being investigated. Also within Study Three the allocation of participants was based on the availability to participate in three sessions of TC per week for 12 weeks. Both of these factors may have had a potential influence of selection bias and therefore the results may not be a reflection the population.

The use of laboratory test did not reflect exactly the daily activities of the volunteers; thus the interpretation of the results is limited to the task performed.

The testing was performed under specific conditions. Therefore the results may reflect the function of the selected muscle groups and population. The data extrapolation directly to other muscle groups and/or outside this sample population must be done with caution.

The inclusion and exclusion criteria were based on the self-reported medical screen questionnaire (Appendix D). The self-reported nature of this questionnaire may have led to inaccurate current health status reports and physical activity level reports and hence inclusion when exclusion may have been warranted.
The postural EMG and coactivation calculations were assessed over a 0.5 sec period in the middle of the 30 sec recording time. This calculation did not take into consideration the COP position or motion which is likely to have an influence on the resulting EMG measures.

Postural control involves not only muscle groups from the lower limb but also muscles of the hip. The primary focus of this thesis was the lower limb and therefore there was no investigation of hip muscle influence on postural control in the current investigations. The lack of hip musculature investigation may limit the inferential use of the outcomes of this thesis.

Cointervention, intention to treat analysis and selection bias within Study Three were not actively monitored/undertaken for either the control or TC group. This may have led to the introduction of confounding variables which could erode the validity of the results of the trial and hence be perceived as a limitation of Study Three.
Chapter 2: Literature Review
This chapter is a review of the literature relating to the effects of ageing and exercise on muscular strength, strength ratios of the lower limbs, postural control and agonist/antagonist coactivation during strength and postural tasks.

2.1 Biomechanics of Stance

The ability to maintain a standing position is of fundamental importance to daily life. Upright stance is a naturally unstable position that requires continuous adjustments of muscle contractions to maintain joint positions from the neck to the ankle (Maurer & Peterka, 2005). It requires maintenance of the body’s centre of gravity (COG) within the supporting base, i.e., between the feet (King et al., 1994; Laughton et al., 2003; Ryushi et al., 2000). The COG is usually located within the body at approximately the level of the second sacral segment. Despite this relatively large distance from the base of support (BOS), the body is able to provide responses to the changes in the location of the COG. The movement of the COG during unconstrained standing can be measured by the trajectory of the Centre of Pressure (COP) when an individual stands on a force platform. The movements of COP are derived from the location of the vertical ground reaction forces on the surface of a force platform under the feet (Prieto, Myklebust, Hoffmann, Lovett, & Myklebust, 1996; Santos, Delisle, Lariviere, Plamondon, & Imbeau, 2008; Winter, 1995). These COP trajectories have, for many years, been used to infer biomechanical mechanisms of postural control (Lord & Sturnieks, 2005; Melzer et al., 2004; Prieto et al., 1996) and some of the commonly used COP assessment methods are described in Section 2 of this chapter.

In the static erect posture the vertical projection of the COG is often termed the line of gravity (LOG) and this line has important implications in the maintenance of posture. Any shift in the location of the COG, e.g. anterior translation, will cause movement of the LOG in the same
direction, i.e. anteriorly. However, during static erect posture the LOG must fall within the border of the supporting feet to maintain equilibrium (Nashner, 1990).

When the LOG passes directly through the axis of rotation of a joint, no net gravitational torque is produced. However, during quiet upright bipedal stance this optimal alignment of joints or “optimal posture” does not exist. Often when maintaining postural control the LOG passes either anteriorly or posteriorly to the axis of rotation of all joints involved which will cause gravitational torque around the joints. This torque will cause rotation around the joint which will consequently require a counterbalancing torque, through muscular contractions, to maintain the upright posture. Also, the magnitude of the gravitational moment increases as the distance between the LOG and joint axis increases (Levangie & Norkin, 2001).

When analysing stance in the sagittal plane it can be seen that the LOG falls either anteriorly or posteriorly to the ankle, knee and hip joint axes. For the ankle joint, the LOG usually passes anteriorly to the lateral malleolus which is the ankle axis of rotation (Danis, Krebs, Gill-Body, & Sahrmann, 1998). This anterior LOG positioning causes a gravitational dorsiflexion moment. To counteract this dorsiflexion moment there is a need to activate posterior muscles such as the soleus and gastrocnemius (Izquierdo, Aguado, Gonzalez, Lopez, & Hakkinen, 1999). The activation of posterior lower limb muscles has been established on several occasions (Borg, Finell, Hakala, & Herrala, 2007; Runge et al., 1999) with some authors stating that the ankle muscle’s strength is the main modulator for ankle movement during postural control (Horak, Earhart, & Dietz, 2001).

Like the ankle joint, during standing the LOG does not pass through the joint axes of the knee and hip joints. The knee joint is usually close to full extension during quiet posture, however the LOG passes just anterior to the knee joint axis which creates a gravitational moment causing extension at the knee joint (Danis et al., 1998). Posterior knee joint capsule tension
and associated ligaments are usually sufficient to counterbalance the gravitational moment at the knee and therefore little muscle activity is needed. A small amount of activity, however, has been identified in that a small amount of activation occurs in posterior thigh muscles (Levangie & Norkin, 2001) which would help to counteract the extension moment due to gravity. It has also been hypothesised that activity of the soleus may augment the gravitational extension moment at the knee through its posterior pull on the tibia as it acts at the ankle joint (Levangie & Norkin, 2001). The LOG acting at the hip passes through the greater trochanter, which is slightly posterior to the axis of rotation. This posteriorly located gravitational line creates an extension moment at the hip which causes posterior rotation of the pelvis on the femoral head (Kagaya, Sharma, Kobetic, & Marsolais, 1998). This is supported by research that has shown activity within the hip flexors during standing (Basmajian, 1978).

While all the above examples were discussed in relation to a near optimal posture, in reality there is always movement of the body segments to counter the destabilization torque due to gravity. The LOG will often pass on the opposite side of the joint axis and would therefore require activation of the opposing muscles, compared to what was explained above. For example, if an individual adopted a flexed knee posture or the movement of the COG was posterior then the LOG would pass posterior to the knee joint and create a flexion moment. To stabilise the knee and maintain erect posture, activation of the quadriceps muscles would then be required (Levangie & Norkin, 2001).

### 2.2 Assessments of Posture Control

Static posturography is a method in which the performance of the postural control system in a static position and environment is characterised. When an individual attempts to stand still, the COP under their feet moves relative to a global coordinate system. A plot of the time-varying coordinates of the COP is known as a stabilogram (Collins, De Luca, Burrows, &
Lipsitz, 1995). Many researchers have measured the anterior-posterior (AnPo) and medial-lateral (MeLa) displacements of the COP in an attempt to evaluate and interpret the behaviour of the postural control system. The measurement of postural control is often conducted using either traditional posturography or stabilogram diffusion analysis, which are methods of computing the COP behaviours. Traditional postural control variables are most often characterised with measures based on the displacement of the COP measured with a force platform (also known as summary statistics) (Prieto et al., 1996). The stabilogram diffusion analysis generates a stabilogram diffusion function that summarizes the mean square COP displacement as a function of the time interval between COP comparisons and is based on the assumption that erect posture is, in part, a stochastic process (Collins & De Luca, 1993).

2.2.1 Stabilogram Traditional Parameters

The COP is the location of the vertical reaction vector on the surface of the force platform on which the subject stands. The COP reflects the orientation of the body segments (joint angles), as well as the movements of the body to keep the COP within the base of support. The anterior-posterior, medial-lateral displacement of the COP can be measured with the force platform. The COP parameters can be measured in 1) Time-Domain “distance” measures, 2) Time-Domain “area” measures, and 3) Time-Domain “hybrid” measures (Prieto et al., 1996). Several authors have used combinations of these COP measurements to characterise the behaviour of the postural control system (Doyle, Hsiao-Wecksler, Ragan, & Rosengren, 2008; Raymakers, Samson, & Verhaar, 2005; Santos et al., 2008; Vieira, de Oliveira, & Nadal, 2009) with a large majority of these parameters being drawn from the work of Prieto et al. (1996).

The COP coordinate time series, AnPo and MeLa, are commonly used to compute measures of postural steadiness and characterize the static performance of the postural control system. These two time series also define the COP path relative to the origin of the force plate. The
resultant distance (RD) time series is the vector distance from the mean COP to each pair of points in the AnPo and MeLa time series (Prieto et al., 1996). The following procedures are for the composite measures computed using both the AnPo and ML time series and those based on the AnPo time series. Every measurement defined for the AnPo time series is similarly defined for the MeLa time series (Prieto et al., 1996).

The time-domain distance measures estimate a parameter associated with either the displacement of the COP from the central point of the stabilogram, or the velocity of the COP. The mean distance (Mdist) is the mean of the RD time series and represents the average distance from the mean COP, while the mean distance- AnPo is the mean absolute value of the AP time series and represents the average AnPo distance from the mean COP (Prieto et al., 1996). This method of calculating the mean COP distance essentially normalizes each participants COP movement distance against their average COP location. The root-mean-squared (RMS) distance from the mean COP is the RMS value of the RD time series and can also be calculated for just the RMS distance- AnPo and MeLa time series (Prieto et al., 1996).

The total excursion (TotEx) is the total length of the COP path and is approximated by the sum of the distances between consecutive points on the COP path. The total excursion in the AnPo direction is the total length of the COP path in the AnPo direction and is approximated by the sum of the distances between consecutive points in the AnPo time series (Prieto et al., 1996). Although this measure of mean COP distance travelled does indicate the summed distance the COP has travelled, these measures can sometimes be inadvertently inflated due to quantification noise. The mean velocity (Mvel) is the average velocity of the COP and is also calculated for all three time series (RD, AnPo and MeLa). In effect, this normalizes the total excursions to the analysis interval. The COP time series are filtered to the frequency range of interest to minimize the quantization noise that may inadvertently inflate measures such as mean velocity and total excursions (Prieto et al., 1996). The last time-domain measure is the
range which is the maximum distance between any two points on the COP path and can be calculated for the RD time series or the AnPo and MeLa directions (Prieto et al., 1996).

The time-domain area measures and time-domain hybrid measures have also been used in the past but generally not to the same degree. These measures are methods that are statistically based estimates of the area enclosed by the stabilogram or are measures that model the stabilogram with a combination of distance measures respectively. Examples of the time-domain area measures include the 95% confidence circle area (Area-CC) (Santos et al., 2008) and the 95% confidence ellipse area (Area-CE) (Doyle et al., 2008), while the sway-area (Area-SW) (Raymakers et al., 2005) and mean frequency (MFreq) (Prieto et al., 1996) are examples of time-domain hybrid measures. Although this is not an exhaustive list of the parameters used in traditional stabilogram analysis, there still is a need for future investigations to elucidate which measures best represent changes in the postural control system, e.g. due to ageing.

### 2.2.2 Stabilogram Diffusion Parameters

The statistical-biomechanic method of assessing the COP trajectories, named stabilogram-diffusion analysis (SDA), was developed by Collins and De Luca (1993). This analysis is based on the assumption that the movement of the COP represents the combined output of co-existing deterministic and stochastic mechanisms. The COP displacement analysis is calculated by computing the square of the displacements between all pairs of points separated by a specific time interval and averaged over the number of time intervals making up a COP time series. These analyses reveal that over short-term intervals of time during undisturbed stance the COP behaves as a positively–correlated random walk whereby the COP tends to drift away from a relative equilibrium point. This is interpreted as an indication that the postural control system uses open-loop control mechanisms which operate without sensory feedback (descending commands which set the steady-state activity levels of the postural
muscles) (Laughton et al., 2003). In long-term intervals of time, it resembles a negatively–correlated random walk whereby the COP tends to return to a relative equilibrium point, indicating that the postural control system now uses closed-loop control mechanisms. It is inferred that this period is one in which the postural control system operates with sensory feedback (from visual, vestibular and somatosensory systems) (Collins & De Luca, 1993; Collins et al., 1995; Laughton et al., 2003). This perspective has the advantage that it leads to the extraction of repeatable COP parameters which can be directly related to the steady-state behaviour and functional interaction of the neuromuscular mechanisms underlying the maintenance of upright stance (Collins et al., 1995).

The stabilogram-diffusion analysis involves the extraction of three sets of posturographic parameters: diffusion coefficients, scaling exponents and critical point coordinates (Collins et al., 1995). The diffusion coefficient is an average measure of the stochastic activity of a random walker, i.e., it is directly related to its jump frequency and/or amplitude and can be thought of as an indicator of the relative stability of the system (Doyle et al., 2008). The short-term and long-term COP diffusion coefficients characterize the stochastic activity of the open-loop and closed-loop postural control mechanisms, respectively (Collins et al., 1995). Diffusion coefficients are calculated from the slopes of the resultant linear-linear plots of mean square COP displacement versus the change in time (Collins et al., 1995). The long-term and MeLa diffusion coefficients are usually lower than the respective short-term and AnPo diffusion coefficients which reflect the increased level of stochastic activity over the short-term time series and AnPo direction comparatively to long-term time series and MeLa direction, respectively (Collins & De Luca, 1993).

Quantification of the correlation between the step increments that make up an experimental time series is the second posturographic parameter used in SDA and is termed “scaling exponents” (Collins et al., 1995). Scaling exponents are calculated from the slopes of the
resultant log-log plots of mean square COP displacement versus the change in time. This measure can be thought of as providing an indication whether the motion of the COP is more or less likely to continue moving in the same direction that it is currently moving (Doyle et al., 2008). Scaling exponents may assume a value in the range of 0 to 1. If the scaling exponents are equal to 0.5, then the increments in COP displacements are statistically independent. If the scaling exponent value is greater than 0.5, then past and future increments are positively correlated, i.e., future displacement increments tend to move in the same direction as the current displacement value (persistent behaviour). If scaling exponents are less than 0.5, then the stochastic activity is negatively correlated, i.e., increasing/decreasing trends in the past imply decreasing/increasing trends in the future (anti-persistent behaviour) (Collins et al., 1995; Peterka, 2000). From a physiological standpoint, SDA scaling exponents quantify the correlated behaviour of the respective postural control mechanisms, i.e., short-term scaling exponents characterize the drift-like dynamics of the open-loop postural control mechanisms, whereas the long-term scaling exponents characterize the antidrift-like dynamics of the closed-loop postural control mechanisms (Collins et al., 1995).

The critical point coordinates approximate the transition region that separates the short-term and long-term regions. The estimation of the critical point coordinates is determined by the intersection point of the straight lines fitted to the two regions of the linear-linear version of the resultant stabilogram-diffusion plot. The transition points occur at relatively small time intervals (0.33 to 1.67 s) and small mean square displacement (1.10 mm$^2$ to 29.37 mm$^2$) (Collins & De Luca, 1993; Collins, et al., 1995). These coordinates approximate the temporal and spatial characteristics of the region over which the physiological postural control system switches from open-loop control to closed-loop control.

Many studies have utilised the SDA technique since the work of Collins & De Luca was first published with some authors using the technique to examine age-related changes in postural
control (Baratto, Morasso, Re, & Spada, 2002; Collins et al., 1995; Dozza et al., 2005; Laughton et al., 2003). The SDA approach has the advantage that it can be directly related to the steady-state behaviour and functional interaction of the neuromuscular mechanisms underlying the maintenance of upright position. Thus, this statistical-biomechanics approach seems be useful to formulate and test hypotheses concerning the relative contribution of different sensorimotor subsystems (visual, vestibular and proprioceptive) and strategies to control posture (Collins & De Luca, 1993, 1995a; Collins et al., 1995; Doyle et al., 2008; Newell, Slobounov, Slobounova, & Molenaar, 1997; Peterka, 2000).

2.3  Physiology of Postural Control

Any detected angular deviation from upright stance applies neural strategies, at supraspinal and spinal levels, involving the interaction between the sensory and motor system to create continuous corrective torque to compensate for disturbances. Postural control involves integration of sensory information from the vestibular, visual and tactile-proprioceptive receptors which stimulate motor responses to maintain balance via several parts of the brain including the cerebellum, brainstem, basal ganglia and sensory-motor cortex (Lord, Clark, & Webster, 1991b; Lord, Ward, Williams, & Anstey, 1994). Once the postural system has integrated all sensory information the CNS sends out appropriate motor responses to effector muscles in an effort to maintain the posture. These corrective movements imply the ability to choose appropriate motor responses based on past experience, to modify these responses on the basis of the continuous sensory input and to produce the needed muscular contraction to stabilize posture (Era et al., 1996).

Proprioception, vision and vestibular inputs are the main sources of sensory information to guide and control posture and movement. This information is provided via kinaesthetic receptors located in the muscles, tendons, joints, skin, the eyes and vestibular receptors and
provide essential feedback for the maintenance of postural control (Lord et al., 1991c). The peripheral receptors located in two main sensory organs, the muscle spindle and Golgi tendon organ, appear to provide the most important sensory input in the maintenance of postural control (Era et al., 1996; Melzer et al., 2004). The vestibular and visual systems seem to contribute to the postural control system more when there is reduced sensory feedback from proprioceptive inputs, especially in some pathological conditions and ageing (Era et al., 1996).

Muscle spindles are distributed throughout the belly of muscles and report the absolute amount of stretch and the rate of change of stretch in a particular muscle (Mynark & Koceja, 2001). The response to muscle length change, known as stretch reflex, plays an important role in counteracting the pull of gravity in upright posture (Barr & Kiernan, 1993). The tendon receptors, known as Golgi tendon organs, are sensitive to the amount of tension developed on a tendon and send the impulses to the spinal cord. This proprioceptive information is important in maintaining balance and adjusting posture during standing and has an increased role when both visual and vestibular information are poor or reduced (Winter, Allen, & Proske, 2005). The vestibular apparatus is centrally involved in body balance and has close reflex connections with the visual system (Horak et al., 2001; Horak, Shupert, Dietz, & Horstmann, 1994). A diminutive vestibular reflex has an impact on the maintenance of posture when both proprioceptive and visual information are unavailable or ambiguous (Bacsi & Colebatch, 2005; Horak et al., 2001; Horak, Nashner, & Diener, 1990; Nashner, Black, & Wall, 1982).

In the motor system, the main factors associated with decreased postural control include the decline in muscle strength and power, and the reduced capacity to respond appropriately to disturbances in postural activity (Dean et al., 2004; Grasso et al., 2000). The hip and lower limb muscle groups (knee extensors, knee flexors, ankle plantarflexors and ankle dorsiflexors)
should be examined closely because of their influence in controlling posture (Laughton et al., 2003). Although these muscles predominantly control AnPo postural movements they have also been shown to play an important role in joint stability and hence the overall behaviour of the postural control system (including MeLa movements). It has also been shown that the hamstrings and dorsiflexors play a significant role in MeLa movements during quiet stance (Amiridis et al., 2005). The dynamic interaction between the agonists and antagonists in maintaining posture has received limited attention with some of this limited attention being focused on the concept of coactivation. It has been suggested that an increase in strength of lower limb muscle groups may be a factor that could improve not only postural control but the stability of muscle contractions and coactivation behaviour of opposing muscle groups (Benjuya et al., 2004; Hortobagyi & Devita, 2006; Melzer et al., 2004). This could be especially important due to the contraction of hamstrings acting as a quadriceps’ antagonist muscle and vice-versa in the thigh, while in the lower leg the same principle applies to the plantarflexors (e.g. gastrocnemius) and dorsiflexors (e.g. tibialis anterior) during postural control. Several studies have demonstrated that reduced quadriceps and ankle dorsiflexion strength greatly increases body sway in a situation of reduced sensation and visual input (Daubney & Culham, 1999; Lord, Clark, & Webster, 1991a; Lord et al., 1991b), highlighting the importance of loss of lower limb strength as a limiting factor in the control of upright stance.

### 2.3.1 Effects of Ageing on Postural Control

Ageing is a natural process that brings with it many biological, physiological and psychological changes. These changes often affect the individual’s quality of living; nevertheless the fact remains that the ageing body can accomplish most, if not all, of the functions of its youth. These functions are, however, often diminished with ageing with the main differences being that movements are less precise, take significantly longer time to
produce, and require much more motivation (Porth & Matfin, 2009; Woollacott, 1993). But as in youth, physiological function can be maintained to a degree through continued use and exercise (Carter, Kannus, & Khan, 2001).

In chronological terms, the older adult population is defined as individuals 65 years and older. Still there is considerable heterogeneity among this age group and as a result older adults are often sub-grouped into young-old (65 – 74 years), middle-old (75 – 84 years) and old-old (85+ years) categories. This further grouping of older individuals reflects more accurately the changes in physiological function (Porth & Matfin, 2009).

Physiological changes often seen with ageing reflect a general decline in body system functions. These declines result in a diminution of various systems such as the muscular and neurologic systems resulting in a reduction of physical capabilities. The ageing muscular system experiences a decrease in muscular strength which is directly related to both a reduction in the size of existing muscle fibres (muscular atrophy) as well as a loss of muscle fibres. Accompanying this strength loss is a decline in reaction time which is often associated with type II muscle fibre loss while type I fibres are said to remain relatively stable throughout life (Timiras, 2003c). The progressive ageing-related decline in muscle strength cannot be stopped entirely; however, it is said that it can be slowed with the introduction of appropriate exercise interventions (Carter et al., 2001; Sherrington et al., 2011). Neurological structural changes that may affect day-to-day routines also occur with the ageing process and include a loss of neurons in both the brain and spinal cord. Another change in the nervous system with ageing is neuronal dendrite atrophy which results in impaired synaptic connections and diminished electrochemical reactions leading to the slowing of many neuronal processes (Timiras, 2003a). Sensorimotor changes with ageing include a decline in muscle strength, slowed reaction time, diminished reflexes (especially in the ankles) and proprioceptive changes (Timiras, 2003a). These changes have functional consequences such
as compromised balance and postural control, and slowed and more deliberate movements (Porth & Matfin, 2009; Timiras, 2003b).

Morphological and physiological alterations associated with ageing often cause degradation in the ability to maintain upright posture (Abrahamová & Hlavačka, 2008; Horak, Shupert, & Mirka, 1989; Woollacott, 1993). It is often found that with ageing there is a decline in the capacity to control posture with an associated increase in the incidence of falls and a decrease in mobility (Woollacott, 1993). This ageing process often results in a decrease in stability of the open-loop postural control mechanisms (Laughton et al., 2003) and also a greater delay in the closed-loop postural control (Amiridis, Hatzitaki, & Arabatzi, 2003; Prieto et al., 1996). Both the delay in the onset of the closed-loop postural control and the larger instability of the open-loop postural control cause an increase in short-term postural sway through endorsing a higher level of stochastic activity (Amiridis et al., 2003; Kuo & Zajac, 1993b). It is possible that these age-related changes in the open-loop postural control mechanisms are due to a postural control strategy adopted by older individuals whereby they increase the level of muscle activity across their lower-limb joints (Laughton et al., 2003). Moreover, compared with healthy young adults, older adults exhibit significantly increased levels of antagonist muscle co-activation in response to postural perturbations (Amiridis et al., 2003; Benjuya et al., 2004). This co-activation of antagonistic muscles has been said to improve joint impedance and more specifically joint stiffness, which in turn contributes to the overall stability of the system (van Soest, Haenen, & Rozendaal, 2003).

It is also common to find in the postural control literature that, when using measures of COP traditional summary statistics, older adults exhibit greater COP velocities, distances and amplitude and/or frequencies. For example, Abrahamová & Hlavačka (2008) found that under four sensory organisation test (SOT) conditions (combination of eyes open and closed on either hard or foam surface), the older group (60-82 years) exhibited significantly greater
AnPo COP amplitude, velocity and root mean square values when compared to a young group (20-40 years). In another study, Du Pasquier et al. (2003) found that velocity measures were best at reflecting postural stability impairment with ageing. They also found that closure of the eyes increased sway but to a much greater degree in the older individuals compared to the younger group. All of the above authors attributed the decreased functionality of the postural control system to physiological changes in sensory and motor systems that are often seen with ageing.

### 2.3.2 Sensory Inputs and Ageing

Effective maintenance of postural control not only relies on appropriate application of muscle forces to maintain body position but also requires sensory inputs. These sensory inputs allow the nervous system to decide on the when and how of the restorative forces in an effort to maintain stance (Woollacott, 1993). When sensory inputs are altered or absent, as is often experienced with natural ageing, the control system must interpret and respond to incomplete data. This partial reduction of sensory feedback with ageing often has a concomitant effect on a person’s stability and postural control (Du Pasquier et al., 2003; Fransson, Kristinsdottir, Hafstrom, Magnusson, & Johansson, 2004; Low Choy, Brauer, & Nitz, 2007). These variations in sensory feedback can either be environmental, as in weightlessness, or physiological such as visual, vestibular, or proprioceptive abnormalities. All of these three physiological factors have been proven to diminish with ageing and have been implicated in alterations in postural control (Balo, Ying, & Jacobson, 2003; Du Pasquier et al., 2003; Lord & Menz, 2000).

#### 2.3.2.1 Vision

Visual inputs provide important information to the CNS regarding the motion and position of the head in relation to the surrounding environment. Visual inputs not only provide the
postural system with motion information but also provide a reference for verticality and further information such as colour, form and depth which all contribute to sensory feedback and orientation with reference to the external environment. This visual information can have significant effects on the maintenance of upright posture. For example, Hafström et al. (2002) found that sway increased when visual motion feedback was deprived or visual field was restricted. In other studies, similar results have been found in that visual environmental motion induces postural adjustments (Guerraz, Gianna, Burchill, Gresty, & Bronstein, 2001; Mergner, Schweigart, Maurer, & Blümle, 2005) as well as illusions of self-motion (Guerraz & Bronstein, 2008).

Collins & De Luca (1995a) investigated the effects of eyes-open and eyes-closed on both open-loop and closed-loop postural control mechanisms in a group of healthy young adults. The authors interpreted the results as an indication that the visual system is integrated into the postural control system in one of two ways. Either visual input causes a decrease in the mediolateral and anteroposterior stochastic activity of the open-loop control mechanism, or it causes an increase in the stochastic activity and uncorrelated behaviour of the closed-loop control mechanism in the anteroposterior direction. The authors hypothesised that in both schemes visual input serves to decrease the stiffness of the musculoskeletal system. However these alterations in postural control strategies in relation to visual inputs can differ when comparing young to older adults.

With ageing, there are multiple structural changes in the eye which cause functional constraints affecting the ability to maintain adequate postural control. There is typically a loss of visual field, a reduction in light transmission to the retina (causing an increase in visual threshold), a decline in visual acuity (caused by an increase in lens’ stiffness, colour opacity, increased incidents of cataracts and macular degeneration) and reduction in visual contrast sensitivity (which causes problems in contour and depth perception) (Harwood, 2001; Lord et
al., 1991c; Lord & Menz, 2000). Many previous studies have demonstrated that age-related changes in visual information have undesirable effects on functional skills including postural control (Lord & Menz, 2000; Matheson, Darlington, & Smith, 1999; Teasdale, Stelmach, & Breunig, 1991; Teasdale, Stelmach, Breunig, & Meeuwsen, 1991). For example, Anand et al. (2003a) investigated postural stability changes in older adults while they were influenced by cataract simulation and refractive blur. They found that cataract simulation and refractive blur caused significant increases in COP-root mean square and concluded that changes in contrast sensitivity rather than resolution changes are responsible for increasing postural instability.

As humans age, the resulting reduction or alteration in the amount and quality of visual sensory information available to the motor cortex (Prieto et al., 1996) is often associated with deterioration in postural control (Kristinsdottir, Fransson, & Magnusson, 2001; Peterka, 2000). It is a common finding that older adults exhibit significantly faster centre-of-pressure (COP) velocities, COP distances and COP excursions in comparison with younger adults, with the trend being exacerbated when eyes are closed (Kuo & Zajac, 1993a). A study by Lord & Ward (1994) found that under challenging conditions (standing on foam with eyes open or closed), vision, along with strength and reaction time, played a significant role in postural maintenance. It was concluded that up until age 65, balance control was significantly influenced by vision and that increasing sway areas in the oldest age groups (over 65 years) were, in part, attributable to visual deficits.

2.3.2.2 Vestibular Apparatus

Although we are not conscious of the vestibular sensation, as we are with other senses, vestibular inputs are important for the coordination of many motor functions. The vestibular organs are located in the inner ear and have connections to the CNS. They contribute to the reflex activity necessary for effective posture and movement and provide information about the position and movement of the head with respect to gravity and inertial forces (Horak,
In humans, our sense of equilibrium is facilitated by hair cells that line the vestibular apparatus of the inner ear. These hair cells are tonically active and synapse, via primary sensory neurons, to the vestibular nerve, in the vestibular nuclei of the medulla, or run without synapsing to the cerebellum, which is the primary site of equilibrium processing (Silverthorn, 2010). This vestibular sensory information has been shown on several occasions to be integral in the maintenance of upright posture. For example, in a study by Bacsi & Colebatch (2005), it was confirmed that vestibulospinal reflexes were acutely facilitated as body sway increased and vestibular reflexes appeared to have a specific role in the maintenance of upright stance, especially under conditions where postural information was absent or attenuated. It should also be noted that the integration of visual and vestibular sensory information has an important role in the coordination of motor skills such as postural control. This integration is termed the vestibule-ocular reflex and has the role of rotating the eyes in the opposite direction to the movement of the head, allowing for gaze to remain steady during head movements (Bear, Connors, & Paradiso, 2007; Shumway-Cook & Woollacott, 2007).

Acute unilateral or bilateral loss of vestibular function has been shown to have devastating effects on postural control. This is particularly evident with ageing where there is a loss of 40% of the vestibular hair and nerve cells by 70 years of age (Rosenhall & Rubin, 1975) which often leads to deteriorations in vestibular function (Ray & Monahan, 2002). The extent of this disturbance, however, is often dependant on the ability of the nervous system to compensate for the loss of this important sensory input (Horak, 2010). This is due to the vestibular system functioning as a reference system for other sensory modalities (vision and somatosensory). For example, Horak et al. (1990) found that sensory deficits resulted in postural response alterations. Vestibular loss gave rise to a normal ankle strategy and a lack of hip strategy, even when required for the task of maintaining posture on a shortened surface.
Although about one third of older adults suffer from disturbed vestibular reflexes, many studies have not found any effects on postural control (Lord et al., 1991b; Lord & Ward, 1994; Lord et al., 1994). The proposed reason for this lack of effect on postural control is that older people with adequate peripheral sensation and/or vision can compensate for reduced vestibular function (Lord & Sturnieks, 2005). However, individuals with vestibular dysfunction may experience conditions such as vertigo and nystagmus, suggesting that vestibular disorders influence postural control and that further research is required to better understand the vestibular contributions to the control of balance (Lord & Sturnieks, 2005).

2.3.2.3 Somatosensation

Somatosensation is a complex sensory system that involves input from not only musculotendinous and articular receptors, for example muscle spindles and Golgi tendon organs (i.e. proprioceptive receptors), but also cutaneous skin receptors (McKeon & Hertel, 2007). All of these sensory modalities contribute to the control of many motor functions in everyday life and have been shown to be essential in the successful maintenance of upright stance (Lord & Sturnieks, 2005; Low Choy et al., 2007; McKeon & Hertel, 2007; Yi & Park, 2009).

Proprioception is the afferent information that contributes to conscious sensation (muscle sense) and segmental posture (joint stability/joint position). The sensory organs that are most commonly referred to as proprioceptors include muscle spindles, Golgi tendon organs and joint receptors (Shumway-Cook & Woollacott, 2007; Silverthorn, 2010). Muscle spindles relay information about the muscle’s length and rate of stretch and are distributed throughout the belly of the muscle, while Golgi tendon organs are found in muscle tendons and transmit information regarding muscle tension or force. Muscle spindles provide sensory information by means of primary endings connected to the spinal cord via type Ia afferent fibres and secondary endings connected to the central nervous system via type II afferent fibres. The
Golgi tendon organs send their impulses to the spinal cord via the Ib afferents fibres. Joint receptors are the third type of proprioceptor and are found in the capsules and ligaments around joints of the body. These receptors are stimulated by mechanical distortion that is experienced when the relative position of bones linked by flexible joints is changed (Porth & Matfin, 2009; Silverthorn, 2010).

Proprioceptors provide the CNS with position and motion information which provides the body with a reference to the supporting surface and is arguably the most important contributor to postural stability (Lord & Sturnieks, 2005). Proprioceptive information from the ankle regarding joint position in normal healthy individuals, has been said to be of principal importance in controlling standing balance (Fitzpatrick & McCloskey, 1994). Other studies of young individuals have found that lateral ligament anaesthesia of the ankle (McKeon, Booi, Branam, Johnson, & Mattacola, 2010) and changes in support surface conditions (Fransson, Gomez, Patel, & Johansson, 2007; Isableu & Vuillerme, 2006) have significant effects on postural control. It has also been proposed that plantar cutaneous receptors contribute considerably to the maintenance of posture (McKeon & Hertel, 2007).

Previous studies have reported that with ageing, there are proprioceptive deficits including decreases in both cutaneous vibratory and joint sensation (Low Choy et al., 2007). These and other proprioceptive losses increase the threshold to movement detection and decrease postural stability (Hay, Bard, Fleury, & Teasdale, 1996; Kristinsdottir et al., 2001; Low Choy, Brauer, & Nitz, 2008; Speers, Kuo, & Horak, 2002). Age differences have been demonstrated when proprioceptive information was perturbed by means of tendon vibration of tibialis anterior and soleus muscles and were even greater when proprioceptive input needed to be reintegrated after the perturbation was removed (Teasdale & Simoneau, 2001). Doumas and Krampe (2010) investigated adaptations and reintegration of proprioceptive information in young and older adults when undertaking postural tasks. Their results indicated that when
inaccurate proprioception was introduced, AP sway path length increased. These increases were, however, comparable in both the young and older groups. What was different between the two age groups was the reintegration phase on restoration of a stable platform. In this stage, there was a sizable increase in AP path length which was greater in magnitude and duration for older adults. In another study, Kristinsdottir et al. (2001) found that vibration sensation was the major determinant for postural control, with those older adults who lacked intact vibration sensation exhibiting an increased high frequency sway compared with younger adults and those older adults with intact sensation. They concluded that the status of sensory receptors of the lower limbs were of the utmost importance for postural control in older people.

2.3.3 Motor Outputs and Ageing

The maintenance of upright postural control is not only reliant on effective sensory input but also the application of appropriate motor outputs. Both strength and power of lower limbs have been indicated as important factors in the control of balance, gait and preventions of falls and have traditionally been the focus of many papers in the ageing and postural control literature (Barrett & Lichtwark, 2008; Izquierdo, Aguado, et al., 1999; Perry, Carville, Smith, Rutherford, & Newham, 2007). More recently however, there has been growing interest in the possible role that steady muscular contractions (usually termed steadiness) (Kouzaki & Shinohara, 2010) and fatigue (Egerton, Brauer, & Cresswell, 2009; Helbostad et al., 2010) have on the control of posture.

2.3.3.1 Muscular Strength

Muscular strength, or the amount of force a muscle produces, is a major contributor to the maintenance of posture. With ageing there is a decline in the strength of nearly all muscles of the body. However, in relation to lower limbs, strength declines at steady rates of
approximately 1–2% per year (Vandervoort, 2002) and it has been found that 20% to 40% of muscular strength is lost from the third to the eighth decade (Doherty, 2003). However, it is often seen that the major decrease in strength occurs after the fifth decade (Doherty, Vandervoort, & Brown, 1993; Izquierdo, Ibanez, et al., 1999; Petrella, Kim, Tuggle, Hall, & Bamman, 2005) which often results in modifications in functional tasks such as the control of posture, transfers, or climbing stairs (Hasegawa et al., 2008).

It seems that muscle strength, as a musculoskeletal characteristic of postural control, is important in generating basic acceleration vectors to control posture. In both cross-sectional and longitudinal studies, lower extremity muscle weakness has been identified as a risk factor contributing to falls in the older populations (Lord et al., 1991a; Perry et al., 2007). This has been shown to be especially true when considering muscles on the posterior side of the lower limbs. Kou & Zajac (1993a) conducted a biomechanical analysis of muscle strength based on a musculoskeletal model of the lower limb and reported that a 1% increase in KF strength may result in approximately 0.9% increase in the maximum acceleration vector, while a similar increase in other muscles such as gluteus may have no such effect. It was also concluded that KF muscle strength is thought to have an increased contribution in both hip and ankle strategies to control posture. However, research has not examined whether the loss in KF force has any impact on balance.

In a study by Lord et al. (1991b) it was shown that poor performance in two clinical measures of postural stability was associated with reduced quadriceps and ankle dorsiflexion strength. This was especially apparent when postural tests were conducted with compliant surfaces which suggest that in situations where there is a reduction in ankle proprioceptive inputs, older subjects are more reliant on motor outputs such as muscular strength. In a similar study Daubney & Culham (1999) found that the difference between fallers and non-fallers was muscular strength of the knee extensors and ankle dorsiflexors, which provides further
evidence that the force generating capacity of lower limb muscles is important in the maintenance of postural control.

2.3.3.2 Power

Muscular power can be defined as the amount of force that is produced by a muscle per unit of time and has been linked by many authors to the ability to control posture (Izquierdo, Aguado, et al., 1999; Katayama et al., 2004; Perry et al., 2007; Robinovitch, Heller, Lui, & Cortez, 2002). Generally, it has been shown that muscle power declines, with age, at a faster rate of approximately 3.5% per annum compared with decline in isometric muscle strength of approximately 1.5% per annum (Thomas, Tomlinson, Hong, & Hui, 2006). It has also been shown that power output can decrease by 50% or more from the third to the eighth decade (Izquierdo, Ibanez, et al., 1999; Kostka, 2005; Runge, Rittweger, Russo, Schiessl, & Felsenberg, 2004).

Izquierdo et al. (1999) examined the maximal and explosive force production capacity and balance performance in men of different ages. Thirty two males were divided into three groups according to age: 12 young (21 ± 1 years), 10 middle aged (40 ± 2 years) and 10 older (71 ± 5 years) with all subjects being healthy and habitually physically active. They found that the rate of force development was lower in older men compared with middle aged men and was as much as 64% lower than in young men. In both middle age and older groups the rate of force development (RFD) was found to be significantly correlated with individual balance measures. It was concluded that ageing may lead to impaired postural control with a decrease in the speed of postural adjustments and that the decreased ability to develop force rapidly in older people seems to be associated with a lower capacity for neuromuscular responses in controlling posture.
Power output has also been implicated in the postural differences between fallers and non-fallers. Perry et al. (2007) examined the difference between young (29.3 ± 0.6 years) and older fallers (76.4 ± 0.8 years) and non-fallers (75.9 ± 0.6 years) to assess if the history of falling is associated with strength and power output. Younger individuals were much stronger and more powerful compared to older people while there were significant differences between fallers and non-fallers. The fallers exhibited only 85% of the strength and 79% of the power of similar aged non-fallers. It was concluded by the authors that power output appears to be the most relevant measure of fall risk and its importance to postural control should be further studied.

Finally, Bezerra et al. (2009) assessed RFD of the knee extensors and flexors in static knee extension and flexion and analysed the relationship with traditional COP and stabilogram parameters during static posture. Three groups of healthy volunteers, aged 18-30 (YG), 40-50 (MG) and 60-77 (OG) years, with 10 males and 10 females in each group, participated in the study. Results showed significantly lower RFD in OG compared with YG and MG in knee extensors and flexors. Both the MG and YG exhibited significantly lower COP mean distance measures in the AP direction and mean velocity measures in the AP and ML directions compared to the OG. Moderate and negative correlations were found between COP mean velocity in ML and the strength of the knee extensors and flexors in all posture-testing conditions. It was concluded that higher RFD in the thigh musculature may contribute to better static postural control performance. It was suggested that RFD be further examined for its validity as an indicator in postural control, particularly in the knee flexors.

2.3.3.3 Steadiness of Force Production

The ability to control force, termed steadiness (ST), can be understood as the magnitude of fluctuation in force when performing either isometric or anisometric (concentric and eccentric) steady contractions (Enoka, 1997). ST has been examined in many different muscle
groups and it has been reported that the upper limbs demonstrate a better control of force than do the muscle groups of the lower limbs (Christou, Zelent, & Carlton, 2003; Tracy & Enoka, 2002). These findings have led to suggestions by some authors that individuals who experience an increased ST within lower limb muscle groups may also have difficulties in the performance of daily activities (Kouzaki & Shinohara, 2010).

Available research has reported that muscle steadiness is better maintained in young adults than older adults (Burnett et al., 2000; Christou & Carlton, 2001; Enoka, Burnett, Graves, Kornatz, & Laidlaw, 1999; Laidlaw, Bilodeau, & Enoka, 2000) and both isometric and anisometric muscle steadiness may be limiting factors for older adults in performing daily tasks (Seynnes et al., 2005) such as repeated rising from a chair (Manini, Cook, Ordway, Ploutz-Snyder, & Ploutz-Snyder, 2005) or postural control (Kouzaki & Shinohara, 2010). This line of thoughts seems logical because the maintenance of upright bipedal stance is another motor task requiring the capacity to control forces of the lower limb because of the continuous need to neutralize destabilizing forces (Wolfson, Whipple, Derby, Amerman, & Nashner, 1994). Despite this assumption, the potential association between the performance of daily activities and force fluctuations during isolated voluntary steady contractions has not been clearly shown.

From the limited research reported in the literature there have been some promising results. Kouzaki & Shinohara (2010) investigated the functional significance of force fluctuations during voluntary contractions of the plantar flexors and postural sway during quiet stance. When the young and older groups were pooled it was found that a significant positive correlation between the coefficient of variation (CV) of COP measures and CV of force during plantar flexion existed. This correlation was only seen at contraction intensities of 2.5% ($r = 0.620, P < 0.01$) and 5% ($r = 0.455, P < 0.01$) maximal voluntary contraction, which corresponds to commonly seen muscle activity levels during quiet stance. In another study in
our laboratory (Bezerra, Zhou, Crowley, & Baglin, 2010) it was found that in older adults, moderate correlations ($r > 0.5$) existed between COP mean distance and root means square in anterior-posterior direction and steadiness at low contraction intensities of the plantar flexors, dorsiflexors and knee extensors. Therefore, further research should be conducted to verify whether ST of all four muscle groups of the lower limbs is important in postural control.

2.3.3.4 **Strength Ratio between Agonists and Antagonists**

It has been emphasized in the literature that the Hamstring to Quadriceps Ratio (HQR) is of integral importance in the maintenance of knee joint stability and the prevention of knee injuries such as ACL ruptures or hamstring muscle tears (Gabbe, Finch, Bennell, & Wajswelner, 2005; Mjolsnes, Arnason, Osthagen, Raastad, & Bahr, 2004; Verrall, Slavotinek, Barnes, Fon, & Spriggins, 2001). Previously it has been found that the HQR appears not to be affected by age in young individuals (12 to 17 years) (Highgenboten, Jackson, & Meske, 1988; Rosene et al., 2001) and no differences in HQR have been reported across sport, gender or side of the body (Bahr & Holme, 2003; Gabbe et al., 2005; Verrall et al., 2001). However, in adult athletes age does have an influence on the HQR and hence injury (Baratta et al., 1988; Mesfar & Shirazi-Adl, 2006). However, few investigations have been conducted on the age-related changes of the HQR in older populations and the possible complications that may cause in the everyday functioning of these individuals.

Just as the HQR has been proven to provide stability to the knee joint, the DPR also has a potential functional role. It is common in the literature to highlight that strength on the lower limb musculature is a limiting factor in the maintenance of postural control especially when considering the muscles acting at the ankle joint (Daubney & Culham, 1999; Kuo & Zajac, 1993a; Lord et al., 1991a, 1991b). Considering that there is a dynamic interaction between the ankle plantarflexors and dorsiflexors during functional tasks such as postural control, it is
surprising that there has not been more in-depth examination of the influence of these strength ratios in relation to posture and falls.

From the above information, it seems plausible that the balance between agonist/antagonist muscle strength may play a key role in knee and ankle stability and therefore functional tasks such as postural control. These roles seem to increase when the ankle joint is in the neutral position and when the knee joint angle approaches those angles commonly used in daily tasks such as posture. Therefore, the age-related decline in KF and PF strength may contribute to a lack of knee and ankle stability respectively and eventually may compromise posture in older adults. To date, little research has investigated the HQR or DPR and their age-related changes in relation to postural stability. Whether the HQR and DPR are correlated with the ability to control posture and whether and how this relationship is affected by ageing and/or training, has not been extensively examined.

However, of the few studies that have investigated the role of strength ratios of lower limb agonist/antagonist muscle pairs in postural control, there have been some interesting findings. In our laboratory, it was found that there are significant age-related declines in quadriceps’ and hamstrings’ maximal voluntary contraction strength and HQR (due to a greater decline in the hamstrings in older adults compared with the quadriceps) (Bezerra et al., 2008). An additional finding was that the HQR exhibited significant negative correlations with most stabilogram parameters. The authors concluded that a higher HQR may be associated with better postural control performance and suggested that the HQR should be further examined for its validity as a meaningful indicator in postural control, particularly in relation to ageing (Bezerra et al., 2008).
2.3.4 Postural Strategies and Ageing

When standing in an upright position the COG is said to be continuously repositioned via a flexible inverted pendulum about the ankles (Amiridis et al., 2003) and is dependent on the effective control of the torques at the ankle, knee and hip joints (Edwards, 2007). This COG fluctuation causes a COP drift away from the relative equilibrium point during the maintenance of stance (Collins et al., 1995). Such slow movements of the body are detected by the sensory system and integrated by the CNS and reflex pathways. These signals generate the commands necessary to drive the muscles involved around the lower limb joint, so that these muscles restore body balance (Fujisawa et al., 2005; Morasso & Schieppati, 1999). These postural control movements are often categorized into three discrete control strategies: either the “ankle strategy”, “hip strategy”, or the “stepping strategy” (Fujisawa et al., 2005; Liu, Kim, Long, Pohl, & Duncan, 2003). However, other strategies have been hypothesised that highlight the role of knee joint dynamics and also the use of muscle coactivation around the joints of the lower limb (Benjuya et al., 2004). The strategy selected by individuals is based on sensory information, area of support, musculoskeletal characteristics, degree of freedom, task constraints and particularly the age of the individual.

2.3.4.1 Ankle Strategy

The ankle strategy was defined first by Nashner and McCollum (1985) who characterised the human postural control system as a single-segment inverted pendulum. This strategy was said to occur when there was early activation of ankle joint muscles and then activation radiated in sequence to the thigh and then trunk muscles. Therefore, it is thought that the nervous system controls postural movement through activation of the ankle joint muscle groups, while keeping the knee and hip joints in a fixed position (Fujisawa et al., 2005; Kuo & Zajac, 1993b). Keeping the knee fixed is not equivalent to keeping the knee muscles inactivated as torque is still needed from both the agonists and antagonists to maintain the constraint (Kuo &
Under this strategy, the aim is to keep the trunk parallel to the legs without changing the angle of the hip and knee joints, while at the same time the hip moment is regulated approximately proportional to the ankle moment (Fujisawa et al., 2005). This strategy is mainly used in situations in which the perturbations to equilibrium are small, when the inclination angle is small, the area of support is large and the support surface is firm (Fujisawa et al., 2005; Kuo & Zajac, 1993b). The ankle strategy is also most commonly seen in young adults in comparison with older adults, who generally adopt a postural strategy termed hip strategy (Xu, Hong, Li, & Chan, 2004).

### 2.3.4.2 Hip Strategy

The hip strategy has been categorised as the early activation of ventral trunk and thigh muscles, i.e. top down activation, and is related with the motion of the body as a double-segment inverted pendulum with counterphase motions at the hip and ankle joints (Colobert, Crétual, Allard, & Delamarche, 2006; Runge et al., 1999). This strategy is more complex than the ankle strategy because the moments around the two joints are not simply proportional and require at least two independent sensory inputs. When a large disturbing force is applied to body segments, or the area of support is not wide enough to receive a sufficient amount of the ankle moment, the inclination angles of the body become so large that the ankle strategy may not be able to restore body balance. Therefore, near the body limits of stability, the nervous system regulates the joint moments using the hip strategy (Fujisawa et al., 2005; Kuo & Zajac, 1993b; Runge et al., 1999; Saffer, Kiemel, & Jeka, 2008). This strategy has been reported to be highly effective in the maintenance of postural control and an efficient means of stabilizing body posture especially in older individuals (Amiridis et al., 2003).

As noted above, the hip strategy is most often associated with older adults in comparison with young adults who utilize the ankle strategy more regularly (Xu et al., 2004). This over-reliance on hip strategy in older adults has been linked to degeneration in neural, muscular...
and skeletal mechanisms leading to increased susceptibility to falls (Amiridis et al., 2003; Tsang & Hui-Chan, 2003). Possible explanations for the greater hip strategy dependence seen in older people include inadequate torque production by ankle muscles (Amiridis et al., 2003; Widmaier, Raff, & Strang, 2004) and insufficient proprioceptive contribution from the distal lower limb and foot as a result of peripheral neuropathies (Anand et al., 2003a; Anand, Buckley, Scally, & Elliott, 2003b).

2.3.4.3 Stepping Strategy

The production of coordinated postural control involves dynamic movements such as stepping. This is especially true when in-place strategies such as hip and ankle strategies are not sufficient to control or maintain upright stance (Maki & McIlroy, 1997). The stepping strategy has traditionally been described as the strategy utilised when there is a requirement to increase the individual’s base of support, usually after a large perturbation (Liu et al., 2003). However change-in-support strategies, such as the stepping strategy, have more recently been shown to be the strategy used in response to much smaller perturbations that may not require an increased base of support (Liu et al., 2003; Maki & McIlroy, 1997).

2.3.4.4 Agonist/Antagonist Coactivation

The concept of coactivation (also known as co-contraction) of agonist/antagonist pairs around the joint of the lower extremity has only recently gained much attention (Benjuya et al., 2004). It has been found in past investigations that coactivation level is dependent on several factors. These factors include age, joint angle and the muscle groups being investigated, all of which may have an influence on the postural control strategy adopted (Hortobagyi & Devita, 2006; Melzer et al., 2004).

Ageing may also have an influence on the coactivation level. Healthy young individuals produce the net torque at a joint by optimally scaling the activation of the prime movers and
the concurrent activity of the antagonist muscles. In contrast, older adults generate the desired
torque with a different neural strategy that involves a near-complete activation of the agonist
combined with a disproportionately heightened coactivation of the antagonist muscles.
Changes in spinal reflex circuitry are the traditionally accepted mechanism that influences
coactivation. However, recent imaging, EEG, microstimulation and magnetic brain
stimulation studies make the hypothesis tenable that, in conjunction with modulations of
spinal circuits, cortical and possibly subcortical mechanisms are also responsible for the age-
associated changes in coactivation (Hortobagyi & Devita, 2006). It has been shown that
during postural tasks and tasks that involve stepping, the level of coactivation at the ankle
joint is significantly increased in older people (Benjuya et al., 2004; Hortobagyi & DeVita,
2000; Melzer et al., 2001). This association is further enhanced when older people have
restricted visual feedback, narrow base of support, or are required to undertake dual cognitive
tasks while maintaining posture (Benjuya et al., 2004; Melzer et al., 2001). It has previously
been speculated that older people adopt this coactivation strategy in an effort to stiffen the
ankle joint which helps to reduce excessive movements thus decreasing postural sway
(Melzer et al., 2001). Due to this adopted strategy it may be hypothesised that the relative
strength ratios of these agonist/antagonist muscles may play a role in the degree of
coactivation during postural tasks.

2.4 Effects of Exercise Intervention on Postural Control

The regression of the physiological process and functional performance with ageing has
evident impacts on the quality of life of older individuals. Loss of strength, decreasing aerobic
capacity and increased risk of falls are well-known consequences associated with the ageing
process (Lord et al., 1991c; Lord & Ward, 1994). As the aged population continues to grow,
the development and implementation of cost-efficient and effective exercise interventions for
the improvement of postural control and prevention of falls is of utmost importance. Research
concerning exercise habits and lifestyle choices in older adults has produced strong evidence that exercise and other forms of physical activity can produce health benefits (American College of Sports Medicine, 2006). Also, training studies involving resistance exercises (Bird, Hill, Ball, & Williams, 2009; Ferri et al., 2003; Hess & Woollacott, 2005), Tai Chi (Choi, Moon, & Song, 2005), electromyostimulation (Amiridis et al., 2005), balance exercises (Nagy et al., 2007) and walking exercises (Melzer, Benjuya, & Kaplanski, 2003) have shown that older adults respond positively to exercise and often produce enhancements in functional abilities and health variables.

2.4.1 Resistance Exercise

A decline in muscular strength occurs with ageing and is often associated with an observable decline in functional performance. This lack of capacity by the muscle effectors to respond appropriately is frequently linked to disturbances in postural control (Lord et al., 1994). It has been shown that systematic strength training can lead to considerable increases in lower limb performance. For example, appropriate strength training may have a positive influence on maximal strength (Ferri et al., 2003; Hakkinen & Hakkinen, 1995), muscle size (Hakkinen, Newton, et al., 1998; Kryger & Andersen, 2007), muscle architecture (Blazevich, Cannavan, Coleman, & Horne, 2007) and the control of muscular contraction force (Manini, Clark, Tracy, Burke, & Ploutz-Snyder, 2005; Tracy, Byrnes, & Enoka, 2004).

Another function that is often observed to improve with resistance training is postural stability (Hess & Woollacott, 2005; Ryushi et al., 2000). Ryushi et al. (2000) conducted a 10 week resistance training schedule that was focused on strength development of the quadriceps muscle group. It was found that the quadriceps strength and the limits-of-stability to the rear were increased and the percentage change in the path length was decreased significantly with strength training. The authors concluded that strength gains in the quadriceps is thought to possibly enable accurate movement of the COG farther towards the rear, suggesting that
strength gains have a positive influence on a person’s perception of their postural control. Similar findings were shown by Hess & Woollacott (2005) when they also conducted 10 weeks of high intensity strength training of the quadriceps, hamstrings, tibialis anterior and triceps surae. After training, there were significant improvements in strength, Berg Balance Scale, Timed Up and Go and the Activities-Specific Balance Confidence Scale in the experimental group. In another study by Bird et al. (2011), it was shown that a multi-component exercise program consisting of resistance and flexibility exercises over 12 months resulted in significant improvements in sit–to–stand, timed up and go and postural sway. These findings showed that strength training can effectively strengthen lower extremity muscles in balance–impaired older individuals which, in turn, results in significant improvements in functional balance ability and decreased risk of falls.

2.4.2 Tai Chi Exercise

Postural equilibrium requires proprioceptive acuity. Proprioception is the afferent information that contributes to conscious sensation (muscle sense), total posture (postural equilibrium) and segmental posture (joint stability). It is well established that proprioception is impaired with age (Fong & Ng, 2006; Tsang & Hui-Chan, 2003; Xu et al., 2004) and it has previously been postulated that this decrement in proprioceptive acuity makes it difficult for older individuals to detect changes in body position (Gauchard et al., 1999). Indeed, some studies have shown that diminished proprioception is a major contributing factor to falls in older populations (Li, Xu, & Hong, 2008; Wong & Lan, 2008; Wu, 2002). Exercise has been shown to have beneficial effects on improving a number of sensorimotor systems that contribute to stability (Lord et al., 1994). Of the exercise modes available, it appears that proprioceptive exercises such as Tai Chi (TC) have a more beneficial effect on the proprioceptive capacity post training compared with bioenergetic activities such as resistance exercise or walking.
Tai Chi is a traditional Chinese exercise and has been used for centuries. It was originally developed as a form of martial arts, however it has now become popular among many older populations as a form of exercise to improve health and physical wellbeing. The basic exercise involved in TC is a series of individual movements that are linked together in a continuous manner and that flow smoothly from one movement to another. These elements incorporate postural muscle strengthening, balance, shifts of weight distribution and postural alignment (Wolf et al., 1997). The simple, soft and fluid movements of TC are ideal for older people regardless of previous exercise experience. Tai Chi is performed in a semi-squat posture that can place a large load on the muscles of the lower extremities. The movements demand guided motions of the hip, knee and ankle joints in various directions, requiring concentric, eccentric and isometric contractions of the hip, knee and ankle muscles (Xu et al., 2008). Tai Chi has been demonstrated to cause significant improvements in the neuromuscular and somatosensory systems which have particular importance in the performance of postural control and hence it has become important in the areas of falls prevention and healthy ageing (Li, Hong, & Chan, 2001; Liu & Frank, 2010; Wong & Lan, 2008; Wu, 2002).

A multitude of studies have examined the effects of TC interventions on balance control and the prevention of falls. In one such study, Voukelatos et al. (2007) examined the effectiveness of a 16 week TC program with the aim of improving balance and reducing falls in a group of adults aged 60 years and older. It was concluded in that study that participation in TC for one hour per week over 16 weeks can prevent falls and improve balance in relatively healthy community-dwelling older populations. In other studies, significant improvements have been shown in postural control and falls risk reduction when undertaking shorter TC interventions.
such as four, eight (Tsang & Hui-Chan, 2004a) or 12 weeks (Choi et al., 2005). The positive effect of TC on postural control and falls prevention has also been studied for older people who have practiced TC for one or more years. In a majority of these studies, positive health outcomes directly or indirectly related to improved posture and falls prevention have been demonstrated. For example, long term TC practice (minimum of 1.5 hours per week for at least three years) was found to improve knee muscle strength, body sway in perturbed one-legged stance and balance confidence (Tsang & Hui-Chan, 2005). In other studies that investigated the long term effects of TC practice in an older adult population, it was found that TC improves standing balance under reduced or conflicting sensory conditions (Tsang et al., 2004), improves isokinetic knee extensor strength and reduces postural sway (Wu et al., 2002) and improves balance control, flexibility and cardiovascular fitness (Hong, Li, & Robinson, 2000).

Another aspect of TC, as a form of exercise intervention, that should be discussed is the stylistic differences in TC. This is important as different styles of TC have vastly different physiological intensities (Liu & Frank, 2010). Historically there are five different styles of TC (Chen, Yang, Wu, Sun and Wu/Hao styles), however the most common form that has been utilised by older populations in the West is Yang style due to its characteristics which are slow, large and graceful movements with a high stance position (Sheng, Gu, & Fu, 2006). Chen style on the other hand is somewhat more challenging and requires a lower stance position which is interspersed with quick, explosive movements (Liu & Frank, 2010; Sheng et al., 2006). These stylistic differences between TC forms may lead to significant differences in exercise intensity. However to the authors’ knowledge there has been no investigation of the difference between TC styles and the relative exercise intensity, or whether these differences have a significant effect on physiological adaptations post intervention.
2.4.3 Other Types of Exercise and Interventions

Several other exercise modes have been examined in the past in relation to their effect on postural control in older populations. Of these exercise modes, most are easily implemented, cost effective and simple enough to be conducted at home.

2.4.3.1 Electromyostimulation Exercise

Electromyostimulation (EMS) is a mode of training that induces a muscular contraction by the application of an external electrical stimulus on the muscle. The artificial stimulus evokes an action potential independent and different from normal voluntary contractions. Research has suggested that EMS recruits muscular fibres in a reverse order relative to normal voluntary contractions (Feiereisen, Duchateau, & Hainaut, 1997; Heyters, Carpentier, Duchateau, & Hainaut, 1994; Knaflitz, Merletti, & De Luca, 1990).

Electromyostimulation has been considered an important tool in physiotherapy and rehabilitation for many years (Kramer, Lindsay, Magee, Mendryk, & Wall, 1984; Trimble & Enoka, 1991) and is increasingly used in post-injury and post-operation rehabilitation (Bax, Staes, & Verhagen, 2005). However, EMS has only recently been considered as a training methodology to improve strength and postural control in older adults (Amiridis et al., 2005; Bezerra, Zhou, Crowley, Brooks, & Hooper, 2009; Paillard et al., 2010). Little is known about whether EMS training is effective in improving postural control. Of the limited research that has been conducted, Amiridis et al. (2005) tested older adults (training group \[n = 10, \text{age} = 72.4 \pm 3.5 \text{years}\] and control group \[n = 11, \text{age} = 71.9 \pm 7.1 \text{years}\] and found that after four weeks of EMS training of the ankle dorsiflexors (40 minutes per session, four sessions per week) there was a decrease in postural sway, greater ankle muscle SEMG activity, greater stability of the ankle joint and significant changes in the mean position of all three joints of
the lower limb. Therefore further research should be conducted to clarify whether lower limb EMS training has a beneficial impact on postural control in older adults.

2.4.3.2 Balance Training

Balance training is another coordinative exercise that has previously been utilised as a possible exercise intervention for the improvement of postural control. The inclusion of balance training in exercise programs appears to be important for older age groups and tailored balance training has been shown to improve postural stability and functional performance (Howe et al., 2011; Judge, 2003; Judge, Whiple, & Wolfson, 1994). These exercise programmes, including low intensity strength and balance training, improved the balance and reduced the fall rates of the study group compared with the controls (Beling & Roller, 2009; Islam et al., 2004; Sihvonen, Sipilä, Taskinen, & Era, 2004; Vrantsidis et al., 2009; Weerdesteyn et al., 2006). These finding are similar to that of Nagy et al. (2007) who found that eight weeks of balance training produced a significant improvement in postural control.

In a systematic review and meta-analysis of effective exercise for the prevention of falls in older people (Sherrington et al., 2011), it was found that exercise could prevent falls and improve balance in older individuals and that greater relative effects were seen in programs that included exercises that challenged balance. The effect of exercise on postural control has been further highlighted in the publication, Frailty and Injuries: Co-operative Studies of Intervention Techniques (Province et al., 1995) which, on prospective meta-analysis of individual participant data from eight trials, found a pooled estimate of a 17% lower falls risk from exercise programs that included balance training.
2.4.3.3 Home-Based Exercise

Home-based exercise (HBE) and community-based group exercise were first prescribed in the late 1980s to the early 1990s (King et al., 1992). One potential advantage of HBE is the ability to incorporate the exercise sessions into the participant’s own lifestyle, leading to higher amounts of incidental exercise and increased feeling of control over the exercise program (Ball, Crawford, & Owen, 2000; Daly et al., 2005). Furthermore, HBE may foster long-term adherence through greater convenience and flexibility (King et al., 1992), reducing the cost of transport and avoidance of the high cost of membership to fitness training providers (Daly et al., 2005; Jette et al., 1996). Most of the HBE training programs use body weight as the resistance and elastic bands as equipment, since the elastic-bands have been considered a valid alternative to machine-based resistance training (Yamauchi et al., 2005). However other studies have adopted the use of ankle weights, walking plans, functional balance tasks, or a combination of the above (Campbell et al., 1997; Robertson, Campbell, Gardner, & Devlin, 2002).

In one study by Campbell et al. (1997), the authors examined the effect of a home based strength and balance retraining exercises in reducing falls and injuries in older women (80 years and older). One hundred and sixteen women were separated into either an exercise group or control group respectively. The intervention consisted of a multifaceted home exercise program involving lower limb strengthening exercises with ankle cuff weights, balance tasks such as standing with one foot directly in front of the other and a multitude of walking based exercises such as stair climbing and walking backwards. After one year of training it was reported that there was a significant reduction in the number of falls incidents and a significant improvement in balance. Some year’s later Robertson et al. (2002) completed a similarly designed study involving a similar home based exercise programme. Within this study, 1016 community dwelling women and men aged 65 to 97 were allocated
into either a control group (n = 404) or an exercise group (n = 612). The exercise intervention was very similar to that of Campbell et al. (1997) with the program consisting of muscle strengthening and balance retraining exercises design specifically to prevent falls. The outcome of the intervention was a significant reduction in the number of falls and the number of fall related injuries by 35%. These two studies show that the implementations of appropriate home based exercise programs can have a significant positive effect on older individuals living in the community.

2.5 Assessment of Muscular Strength

It is stated that a close relationship exists between muscle strength, functional ability and independence in old age (Thom, Morse, Birch, & Narici, 2005). With this in mind, it remains very important that measurements of MVC are accurate and reliable over time (Todd, Gorman, & Gandevia, 2004). Many factors can affect strength assessment, such as the type of muscular contraction and the joint angle. Having a good understanding of the effects of these factors is imperative to obtaining appropriate and meaningful data for answering research questions and hypotheses.

Muscular strength can be assessed by the use of one of three contraction types which are isometric (Alway, MacDougall, Sale, Sutton, & McComas, 1988; Thom et al., 2005; Todd et al., 2004); isotonic (Izquierdo, Ibanez, et al., 1999) or isokinetic contractions (Babault, Pousson, Ballay, & Van Hoecke, 2001; Ferri et al., 2003). In isometric strength testing, the muscle acts against immovable resistance at a specific joint angle with the muscle undergoing no net change in length and no changes in joint angle, which is similar to that during the maintenance of upright posture. Both isotonic and isokinetic contractions require dynamic movements of body segments and limbs. The speed of contraction and the range of motion in these movements have a direct influence on the force-producing capacity of the muscle.
group/s in contraction. During an isotonic contraction the muscle contracts to move a given object against gravity throughout a certain range of motion (ROM), although maximal muscle demand occurs only during a small portion of the movement. During an isokinetic contraction the muscle contracts at a given angular velocity and against maximal load throughout the ROM.

Various joint angles have been utilized when assessing muscle strength, depending on the muscle group being investigated. In isometric strength assessment of the knee extensors and flexors, a knee joint angle of $90^0$ from full extension is commonly used because testing at this angle has an advantage of eliminating limb weight as a factor in the production of force (Izquierdo, Aguado, et al., 1999; Izquierdo, Ibanez, et al., 1999; Todd et al., 2004). However, other knee joint angles between $10^0$ and $85^0$ from full extension have also been used in strength tests (Babault et al., 2003; de Ruiter, Kooistra, Paalman, & de Haan, 2004; Savelberg & Meijer, 2004). The assessment of ankle plantarflexion and dorsiflexion isometric strength is usually conducted with the ankle joint flexed at $90^0$ (Alway et al., 1988; Ferri et al., 2003; Simoneau et al., 2005; Todd et al., 2004) which has been seen as desirable as this is the joint angle at which the ankle exists when conducting activities of daily living such as standing posture. However, some authors have utilized ankle joint angles of $20^0$ dorsiflexed or plantarflexed to investigate strength and activation changes of these muscle groups due to ankle joint angle changes (Simoneau et al., 2007b; Thom et al., 2005).

### 2.5.1 Lower Limb Strength Ratios

It is common to use the HQR as an indicator to describe the knee joint muscle strength properties and for assessing knee joint functionality. There have been reports on the HQR at different contraction modes such as isometric, concentric and eccentric. The HQR has been calculated using various analysis techniques (Aagaard et al., 1998; Coombs & Garbutt, 2002; Gerodimos et al., 2003).
Generally when assessing the HQR, despite that maximum effort is required in muscle contraction, the isokinetic strength tests normally produce significantly greater HQR values than the isometric and isotonic tests (Aagaard et al., 1998). However, it is still debatable as to which contraction mode is most applicable when assessing the functional relevance of the HQR.

There are two main methods of calculating the HQR in the literature which include the conventional and functional HQR. The first method, referred to as the conventional HQR, involves dividing the participant’s maximal KF torque by the maximal KE torque under the same contraction mode (Aagaard et al., 1998; Coombs & Garbutt, 2002). The second method, referred to as the functional HQR, involves dividing the maximal concentric contraction of KF by the maximal eccentric contraction of KE (or the other way around) at defined target knee joint position. This method can only be assessed during isokinetic or isotonic contractions (Aagaard et al., 1998; Coombs & Garbutt, 2002; Rosene et al., 2001). Aagaard et al. (1998) were the first to coin the term functional HQR as it was proposed to be a more functionally relevant method when assessing the ratio of strength. This logic was based on the fact that during functional tasks such as walking, the agonist/antagonist muscle pairs are never functioning in a concentric or eccentric fashion at the same time. When the quadriceps is concentrically contracting, such as in the swing phase of walking, the hamstrings are contracting eccentrically to help control and slow the angular velocity around the knee joint and hence protect the joint from injury (Aagaard et al., 1998).

The DPR is a relatively new concept which has received very little attention in the literature especially when compared to the HQR. From the limited studies that have analysed the DPR, it is common to use similar calculation and contraction modes to that of the HQR (Simoneau et al., 2005, 2007b).
2.6 Ageing and the Physiology of Muscular Strength

An adequate level of muscular strength is extremely important for the production of functional movements and has repeatedly been linked to the ability to maintain functional independence. Muscular strength has repeatedly been found to significantly decrease as people age. This age–related reduction in maximal strength has been well established with a multitude of cross–sectional and longitudinal studies being conducted on many of the lower limb muscle groups (Frontera et al., 2000; Frontera et al., 2008; Izquierdo, Ibanez, et al., 1999; Lanza, Towse, Caldwell, Wigmore, & Kent-Braun, 2003; McNeil, Doherty, Stashuk, & Rice, 2005; Roos, Rice, Connelly, & Vandervoort, 1999; Simoneau et al., 2005, 2007b). However, the degree to which a specific lower limb muscle group’s maximal strength is affected due to ageing varies. It appears that the quadriceps and gastrocnemius muscle groups experience more consistent declines in strength with age whereas within the hamstrings and tibialis anterior muscles contradictory results have been found in different studies (Frontera et al., 2008; Simoneau et al., 2007b).

A longitudinal study by Frontera et al. (2000) analysed isokinetic maximal strength of the KE and KF muscle groups at both slow (60°/s) and fast (240°/s) contraction velocities 12 years apart. It was found that both the KE and KF maximal strength had declined by between 23.7 to 29.8% and 28.5 to 29.4% respectively. However, a later longitudinal study by Frontera et al. (2008) under the same contraction conditions found that over an 8.9 year period KE isokinetic muscle strength significantly declined by 22.4 to 37.1% while there was no significant change in KF maximal strength. A cross–sectional study by Izquierdo et al. (1999) investigated the maximal isometric strength of the KE and KF. Analysis between the middle aged group (42 ± 2.9 years) and older group (65 ± 4.1 years) found that in both muscle groups, the older group was significantly weaker. Finally, Macaluso et al. (2002) conducted a cross–sectional comparison of KE and KF strength between young (22.8 ± 5.7 years) and
older (69.5 ± 2.4 years) females. Young women were found to exhibit 43% stronger KE and 47% stronger KF strength when compared to the older group.

Within the AP and AD muscle groups it has also been found that maximal muscle strength declines with age. Thom et al. (2005) examined two groups, one young (26.5 ± 4.1 years) and one older (73.9 ± 3.8 years), who completed maximal isometric muscle contractions of the Triceps Surae muscle group. The authors found that during isometric contractions there was a 62.6% reduction in maximal strength from the young group to the older group. This finding was similar to the work of Simoneau et al. (2005) and (2007b) who found that with age there was a significant decrease in maximal plantarflexion strength. However, when investigating the AD maximal strength there appears to be inconsistent findings in relation to the age. For example, Simoneau et al. (2005) and (2007b) found the AD of older individuals (77.1 ± 1.8 and 77.5 ± 3.2 years, respectively) was similar in maximal strength to that of younger adults (23.9 ± 1.7 and 23.7 ± 1.7 years, respectively). This is in contrast to the findings of other authors who have found age–related declines in AD maximal strength. Lanza et al. (2003) found that, on average, older individuals (72.2 ± 6.4 years) produced 21% less isometric torque in the AD compared with the young group (26.3 ± 4.8 years). This is similar to the results of Connelly et al. (1999) who found that mean AD MVC torque was 26% lower for a group of older individuals (82.0 ± 1.7 years) compared with young (20.8 ± 0.8 years). However, it appears that the strength decline in AD is possibly not pronounced until after the 80th decade. This is evidenced in that the average age of older participants in the Simoneau et al.’s studies was ~77 years while in the study by Connelly et al., it was ~82 years which is considerably older than those of Simoneau et al. This line of thought may be explained in the study conducted by M’Neil et al. (2005) who found that in spite of similar height and weight, very old men (82 ± 4 years) produced significantly less (31% deficit) maximal isometric dorsiflexion torque than either the young (27 ± 3 years) or young–old (66 ± 3 years) men, with no difference between these last two groups. Therefore, there is a need to clarify,
especially when considering the KF and AD, at what age there is a significant reduction in strength.

The production of muscular strength is a complex process that requires the coordination and integration of many anatomical structures and physiological processes. The ageing process causes a vast array of changes to the neuromuscular unit and has been associated with the age-related decline in muscle strength. Some of the neural factors that are considered partially responsible for the age-related decrease in maximal strength include a decrease in the number of motor units (MU) recruited, a decrease in the firing frequency of each MU, a decrease in the coordination of agonist/antagonist activation and an increase in inhibitory reflexes (Arihara & Sakamoto, 1999; Burnett et al., 2000; Doherty et al., 1993; Enoka, 1997; Sale, 1987; Zhou, 2003).

2.6.1 Motor Unit Number and Type Distribution

Normally, in a voluntary contraction the spinal motor neurons send a train of action potentials to the muscle fibres being activated (Marieb & Mallatt, 2003). Therefore, muscle contractions that occur during normal body movements are tetanus contractions. In the body, the activation of motor units does not occur simultaneously. Instead, various motor units are stimulated to contract at different times. Thus, some motor units are contracting while others are relaxing. The overlap of tetanic contractions results in a smooth contraction and aids in sustaining a coordinated muscle contraction (Powers & Howley, 2004). This not only has direct implications on the ability to produce maximal force but also in reducing fluctuations in force production (Burnett et al., 2000). However, with ageing there is often a remodelling of the neuromuscular system which involves the gradual loss of motor unit numbers and hence a change in motor unit type distribution within muscles (Dalton, McNeil, Doherty, & Rice, 2008; McNeil et al., 2005).
Ageing is characterised by a gradual loss of spinal motor neurons due to such processes as apoptosis and reduced insulin-like growth factor I. The age-related loss of spinal motor neurons leads to a decline in muscle fibre number and size (sarcopenia). When motor neurons are lost it has the effect of leaving behind denervated muscle fibres. Collateral sprouting of nearby surviving motor axons reinnervate some, but not all, denervated muscle fibres, which results in the formation of very large but much less motor units (Aagaard, Suëtta, Caserotti, Magnusson, & Kjaer, 2010; Roos, Rice, & Vandervoort, 1997). This reorganisation has repeatedly been found to be a contributor to the age–related reduction in maximal muscle strength. For example, McNeil et al. (2005) observed a 39% reduction in the number of MUs in the tibialis anterior muscle of old (average 66 years) compared with young (average 27 years) subjects, along with an even greater reduction (61%) in very old subjects (average 82 years). This was accompanied with a significant reduction in isometric maximal strength in the very old participants but not for the old. However, in another study (Dalton et al., 2008) a comparison between young (average 27 years) and older (average 75 years) adults found that there were no differences in motor unit number estimations between the groups but there was however a significant decrease (39%) in maximal isometric plantarflexion torque.

2.6.2 Motor Unit Firing Frequency

The force of muscle contractions can be graded not only by recruitment of varying numbers of motor units but also by varying the force output of individual motor units. This is achieved by activating the muscle fibres of a motor unit at different frequencies, that is, by varying the firing rate of motor units (Kamen, 2004; Sale, 1987). The firing rates of motor units can also be adjusted to achieve different rates of force development and the firing pattern of a motor unit can affect its muscle fibres’ response to subsequent stimulation (Sale, 1987). A motor unit’s minimum firing rate is the lowest that can be maintained when the motor unit is recruited at its threshold. The maximum rate is that attained during an MVC (Sale, 1987). The
large range in minimum and maximum firing rates is due in part to variation among muscles and among motor units within a muscle (Kamen, 2004). Small distal muscles tend to have motor units with higher maximum rates than large proximal limb muscles (Kamen, 2004; Sale, 1987). In some muscles, most motor units have similar minimum firing rates with no significant difference between units of different thresholds. In other muscles, higher threshold motor units have higher minimum and maximum firing rates. Within open biopsies of the quadriceps, units recorded from fields of predominantly type I fibres had low thresholds and low minimum and maximum firing rates, whereas units from fields of type II fibres had high thresholds and fired in bursts (Sale, 1987).

The ageing process also seems to be a factor affecting motor unit discharge rates, particularly at higher force levels. Several studies have examined the relative difference between discharge rates in young adults and elderly (Connelly et al., 1999; Kamen, Sison, Du, & Patten, 1995; Patten & Kamen, 2000) with the young exhibiting as much as 40% higher discharge rates during maximum contraction than the elderly (Kamen et al., 1995). In a study conducted by Connelly et al. (1999) the results from approximately 950 motor unit trains of the tibialis anterior during a series of repeated brief steady-state contractions at 10, 25, 50, 75 and 100% of MVC, indicated that at all relative torque levels mean firing rates were 30-35% lower in the older (82.0 ± 1.7 years) compared to younger (20.8 ± 0.8 years) subjects. The lower motor unit firing rates of the tibialis anterior muscle in older adults may simply be due to larger motor units in older people, innervated primarily by slow motorneurons. However, a study by Roos et al. (1999) found that at all isometric force levels of the quadriceps muscle group (10%, 25%, 50%, 75% and 100% MVC), there were no differences in mean motor unit firing rates between young and older subjects. It should be understood however that there is limited research on the direct comparison of muscle groups and their motor unit firing rates during functional task.
2.6.3 Motor Unit Synchronization

Descending, spinal, and peripheral excitatory inputs to spinal motor neurons diverge extensively to make synaptic connections across a large segment of a motor neuron population (Yao, Fuglevand, & Enoka, 2000). Such branching of pre-synaptic fibres will provoke near simultaneous excitatory potentials in motor neurons and thereby slightly increasing the probability that some motor neurons will be brought to action potential threshold almost simultaneously (Yao et al., 2000). The magnitude of this synchronized discharge among motor units is variable and is influenced by factors such as the task undertaken, the motor units and muscles involved, the type of habitual physical activity performed by the individual and the pattern of shared synaptic input onto the motor neurons, either directly or through last order interneurons (Semmler, Steege, Kornatz, & Enoka, 2000; Yao et al., 2000). Muscular force is modulated by the combined activity of groups of motor units that produce individual twitch contractions in numerous synergistic and antagonistic muscles. Joint motor unit interactions involving synchrony are observed among coactivated muscles and is frequently greater in pathological conditions such as tremor and various central nervous system lesions (Kamen & Roy, 2000).

Advancing age is accompanied not only by alteration in the muscular characteristic but changes in the neuromuscular system. One such motor neuron characteristic is the so-called motor unit synchronization. At lower force levels, motor unit synchronization might be detrimental in older individuals due to exaggeration of already intensified tremor observed with ageing. However, at higher levels of muscular force, motor unit synchronization might be an alternative mechanism invoked by older individuals to compensate for declines in maximal force capacity (Kamen & Roy, 2000). Kamen and Roy (2000) found that during a 50% MVC isometric contraction over 16 seconds, measures of synchronization amplitudes were virtually identical between the young (27.7 ± 4.13 years) and older (74.9 ± 7.12 years).
participants. These findings may indicate that synchronized discharge between motor units may not have a significant effect on strength output. However, there is a need for further investigation into motor unit synchronization comparisons between muscle groups, especially in the lower limbs.

2.6.4 Agonist/Antagonist Coactivation

Antagonist muscle coactivation is referred to as the simultaneous activity of the agonist and antagonist muscle groups occurring during both voluntary static and dynamic contractions (Remaud et al., 2007). This phenomenon is particularly present when the agonist contraction is strong and rapid, when the task requires precision, or when subjects are untrained in the task (Sale, 1987; Sale, Martin, & Moroz, 1992). Antagonistic muscle coactivation reduces the external net torque produced at the joint level by generating an opposing moment produced by the agonist muscles. Coactivation of the antagonist muscles may provide stabilization of the joint by increasing joint stiffness during rapid, precise agonist contractions, thus preventing the musculoskeletal system from joint injury (Aagaard et al., 2000; Miller, Croce, & Hutchins, 2000). However, contraction of the antagonist also impairs, by reciprocal inhibition, the ability to fully activate the agonist. It has been suggested that the inhibition is a protective mechanism in activities involving very strong cocontractions. Thus, when subjects are introduced to a new and relatively complicated strength task, excessive cocontractions of the antagonists may limit full motor unit activation and therefore strength of the agonists (Sale, 1987). Several factors have been shown to influence antagonist muscle coactivation such as the contraction type (Kellis & Unnithan, 1999; Remaud et al., 2007), the joint angle (Baratta et al., 1988; Remaud et al., 2007; Simoneau et al., 2007b), the investigated muscle (Aagaard et al., 2000; Kellis & Unnithan, 1999; Miller et al., 2000; Remaud et al., 2007) and the age of the participants (Macaluso et al., 2002; Simoneau et al., 2005, 2007b).
2.6.4.1 Effect of Contraction Type

Kellis et al. (1999) investigated the coactivation of the vastus lateralis and biceps femoris muscles in pubertal children and adults and found that the averaged SEMG of the hamstrings, when acting as an antagonist, was significantly higher during concentric compared with eccentric knee extensor efforts. This finding indicates that the effect of the antagonist activity on the resultant knee extensor moment would be greater during concentric tests compared with the corresponding eccentric tests. In another study that looked at the effects of different contraction modes on coactivation levels was conducted by Remaud et al. (2007), the results indicated that both muscle activity and antagonist coactivation levels were significantly greater during isotonic contractions compared to isokinetic ones. It has been proposed that antagonist muscle coactivation may result from a “common drive” generated at the supra-spinal level which would control the recruitment of both agonist and antagonist motor neuron pools. The greater variations in instantaneous movement velocity occurring during isotonic movement, compared to the constant velocity during isokinetic movement, has also been hypothesized as partly accountable for the higher hamstring coactivation during isotonic modes (Remaud et al., 2007). The coactivation level during isometric contractions is yet to be compared to other contraction modes and needs further investigation along with the age related differences between young and older adults.

2.6.4.2 Effect of Muscle Group

The level of muscle coactivation between agonist/antagonist pairs also depends on the muscles being investigated. Aagaard et al. (2000) investigated antagonist muscle coactivation during isokinetic knee extension and found that the antagonist coactivation was always greater in the lateral hamstrings (biceps femoris) compared to the medial hamstrings (semitendinosus). These values corresponded to approximately 30% for the biceps femoris and 10% for the semitendinosus of the SEMG obtained during maximal agonist contractions.
A later study by Remaud et al. (2007) is in line with those of Aagaard et al. in that, after pooling data from both contraction types, they found that the biceps femoris muscle exhibited a 44% greater coactivation than the semitendinosus. Due to its lateral insertion on the tibia, the biceps femoris muscle is capable of creating external tibial rotation. The pronounced biceps femoris coactivation observed thus may represent a protective mechanism against the internal tibial rotation induced by the contraction of the quadriceps (Remaud et al., 2007). Evidence seems to suggest that the cerebellum plays an important role in switching from reciprocal activation to coactivation which may be the means by which the neuromuscular system prevents injury to the knee joint (Aagaard et al., 2000). Moreover, in certain types of joint movement a common drive mechanism seems to exist by which the CNS may control the separate agonist/antagonist motor neuron pools as if they were one pool performing the same task. This common drive appears to be present during either of two states: when uncertainty exists in the required task or during anticipation of compensatory muscle forces (Aagaard et al., 2000). There also seems to exist a difference in the behaviour of the quadriceps muscles compared to the hamstrings when acting as antagonists. Miller et al. (2000) examined reciprocal coactivation patterns of the medial and lateral quadriceps and hamstrings. Not only was there a significant increase in coactivation level of the biceps femoris compared to the semitendinosus, but there were also significantly higher levels of coactivation of the hamstrings muscle group compared with the quadriceps when working as the antagonist. The results of this study also suggest that during isokinetic testing, both the vastus medialis and biceps femoris have significantly greater coactivation levels when compared to the vastus lateralis and semitendinosus, respectively.

2.6.4.3 Effect of Joint Angle

In relation to the effects of joint angle on coactivation, contradictory findings have been shown. Baratta et al. (1988) found that the plots of normalized antagonist SEMG versus joint
angle for each muscle group were inversely related to their moment arm variations over the joint range of motion during an isokinetic (150/sec) knee extension task. Remaud et al. (2007) found that for both isotonic and isokinetic contractions, hamstrings coactivation was on average 15.2% higher at 85° compared to that observed at 45°. These authors hypothesized that hamstrings coactivation would increase as hamstring muscles’ moment arm decreased. This would compensate moment arm variations during the movement and would allow hamstring muscles to develop a constant opposing torque around the joint. However, at the ankle joint during isometric plantarflexion and dorsiflexion, Simoneau et al. (2007b) found that there were no significant differences in coactivation level between joint angles of 20° dorsiflexed, neutral (0°) and 20° plantarflexed. Further research is required to confirm such findings and to assess the coactivation response during isometric contractions at the knee joint at different joint angles.

2.6.4.4 Effect of Ageing

Ageing is also said to have an influence on the coactivation level. Healthy young individuals produce the net torque at a joint by optimally scaling the activation of the prime movers and the concurrent activity of the antagonist muscles (Hortobagyi & Devita, 2006). In contrast, old adults generate the desired torque with a different neural strategy that involves a near complete activation of the agonist combined with a disproportionately heightened coactivation of the antagonist muscles (Hortobagyi & Devita, 2006). Spinal reflex circuitry changes are the traditionally accepted mechanism that influences coactivation. However, recent imaging, EEG, microstimulation, and magnetic brain stimulation studies make the hypothesis tenable that in conjunction with modulations of spinal circuits, cortical and possibly subcortical mechanisms are also responsible for the age associated changes in coactivation (Hortobagyi & Devita, 2006).
The primary spinal coordinator of agonist/antagonist muscle activity is the disynaptic reciprocal inhibition through the Ia inhibitory interneuron. One hypothesis is that a decline in reciprocal inhibition with advancing age is associated with the increased antagonistic muscle activity observed with ageing (Hortobagyi & Devita, 2006). In a study conducted by Kido et al. (2004), it was found that in both the soleus and tibialis anterior muscles there was an inverse relationship between the magnitude of inhibition and age so that reciprocal inhibition decreased with increasing age. This reduction was present during quiet standing and walking, suggesting little modulation of or compensation for this inhibition occurs during dynamic activities compared with static standing.

The inhibitory interneuron involved in the disynaptic reciprocal inhibition receives inputs from a variety of spinal and supraspinal structures (Chalmers & Knutzen, 2004). Renshaw cells contribute to motor neuron excitability and hence the net torque generated. These cells also inhibit agonist motorneurons and disinhibit, by synapsing on the Ia inhibitory interneurons, the antagonist muscle. The net effect of this interaction between recurrent inhibition and reciprocal inhibition is to minimize the difference in force output between the agonist and antagonist muscles (Chalmers & Knutzen, 2004). Presynaptic inhibition can also modify reciprocal inhibition. At the onset of voluntary contraction, presynaptic inhibition normally decreases at the primary afferent terminals in the agonist muscles, whereas presynaptic inhibition increases at the afferent terminals in the antagonistic muscle. Presynaptic inhibition, at least on the homonymous Ia terminals, seems to decrease with ageing (Earles, Vardaxis, & Koceja, 2001). In addition to a lower level of presynaptic inhibition in older adults at rest, in a recent study there was no modulation of presynaptic inhibition in older individuals at 10-20% of maximal strength (Earles et al., 2001). The relatively high levels of presynaptic inhibition in young individuals at rest make the access to the motoneuron pool easier for the central drive, and the reduction in this inhibition during contraction would preserve the reflex gain in the target muscle. In contrast, the low level of
presynaptic inhibition at rest and its lack of modulation with contraction in older adults may indicate a shift to cortical mechanisms for movement control (Hortobagyi & Devita, 2006).

2.6.5 Lower Limb Strength Ratios

Much of the research that has been conducted in relation to the HQR has aimed at young athletic populations and the role that the HQR plays in knee joint stability and sports–specific functional performance. Very little research has been conducted on the age–related changes in the HQR and DPR or the possible importance of these ratios on activities of daily living. Another area that has received little attention in the literature is the effects of joint angle changes on isometric HQR and DPR values. This seems surprising given that muscle length changes can have significant effects on the force–producing capacity of a muscle/muscle group.

The most frequently reported strength ratio until recently has been based on the concentric strength of the two opposing muscle groups in question. Under this contraction mode HQR values are said to range from 0.40 to 0.90, although this is dependent on angular velocity, test position and population group (Coombs & Garbutt, 2002). There also seems to be little consensus of a normative value for the concentric HQR, although 0.6 appears to have gained some support (Aagaard et al., 1998). During strength measurement, coactivation of opposing muscle groups has been repeatedly shown to take place. Therefore, during knee extension the KE will contract concentrically while the KF, at the same time, are contracting eccentrically. This led to the development of a new method for the assessment of the HQR termed the functional HQR. In this method the HQR is calculated by dividing the maximal eccentric KF force by the maximal concentric KE force (Aagaard et al., 1998). When utilising the functional HQR it has been found that the ratio can reach as high as 1.4 and is much higher than the conventional ratio at most joint angles and contraction velocities. Aagaard et al. (1998) found that the functional HQR was always 1.0 or greater during fast knee extension.
which is approximately double that of the conventional HQR. It was also found that the functional HQR increased as the knee extended.

DPR’s are often a lot smaller than those of the HQR due to the disproportionately stronger plantarflexors in the young (Simoneau et al., 2007b). However, with ageing, because of the larger age–related losses in plantarflexor strength relative to the dorsiflexors, the DPR begin to exhibit similar ratios as that of the knee joint (Simoneau et al., 2007b). It is not known what level of DPR is the best due to the lack of understanding of the functional importance of this strength ratio.

To the author’s knowledge there has been very little examination of the HQR and DPR during isometric contraction. Therefore much research is needed to examine the effects of age, gender and joint angle on the isometric strength ratios of the lower limb.

2.7 Effects of Gender on Muscle Strength and Activation

Many previous investigations have explored the gender differences in maximal torque productions of skeletal muscle with a large majority showing that males produce significantly greater torques in most large muscle groups of the body compared to females (Lindle et al., 1997; Maughan et al., 1983a; Yasuda et al., 2005). It has traditionally been hypothesised that the majority of maximal strength differences between genders is due to anatomical features such as muscle cross–sectional areas and fibre type distribution (Staron et al., 2000; Yasuda et al., 2005). For example it has been shown that males have a greater percentage of type II fibre area in the vastus lateralis compared with females, while females have a higher percentage of type I fibre area compared with males (Yasuda et al., 2005). It has been suggested the higher percentage of type II fibres in males may explain the greater maximal strength observed in knee extension in males due to the higher force–generating capacity of type II fibres (Yasuda et al., 2005).
This line of thought however, has been supplemented in recent years with the idea that there exists a gender difference in physiological processes that may influence maximal torque production (Deschenes et al., 2009). Two areas of physiological investigation that have shown gender differences in muscle function are during muscular fatigue (Clark et al., 2005) and muscular unloading (Deschenes et al., 2009). An investigation on muscle fatigue patterns (as measured by SEMG activity) found that fatigability is more pronounced in men which was suggested to be possibly the result of gender-related differences in central activation, neuromuscular junction transmission and membrane excitability (Clark et al., 2005). In another investigation it was found that after one week of muscle unloading females showed greater unloading-induced decrements in muscle performance (as assessed by SEMG) (Deschenes et al., 2009). It was also shown that the loss of peak torque was significantly correlated with the decline in SEMG consequent to unloading. The decrease in SEMG activity post unloading could be attributed to either a decrease in the rate of firing of motor neurons and/or a diminished ability to achieve full recruitment of all motor units (Kamen et al., 1995). Therefore further research is required to investigate the potential differences in muscle activation strategies between males and females during strength tasks.

2.8 Effects of Exercise on Muscular Strength

Muscular strength is fundamental to the successful and efficient performance of functional tasks such as walking, raising from a chair, or postural control. With ageing however, there is a reduction in the force production capacity of most muscle groups which leads to a decrement in activities of daily living (Carroll, Riek, & Carson, 2001). Therefore, there is an increased necessity to investigate the most efficient and effective training modes that slow or even reverse the functional performance deficits associated with ageing.
There are many types of training that have been explored and found to significantly improve muscular strength and functional performance. One of the more traditional modes of exercise investigated has been resistance training which has been repeatedly found to be an effective countermeasure to the age–related decline in strength (Gabriel, Kamen, & Frost, 2006; Latham, Bennett, Stretton, & Anderson, 2004; Liu & Latham, 2011; Liu & Latham, 2009). A training mode that has gained interest in the past two decades is TC. Originally thought of as a coordinative exercise that has a beneficial effect on functional tasks such as postural control, TC has also been found to improve muscular strength of the lower limb muscle groups (Xu et al., 2008).

2.8.1 Resistance Exercise

Since the late 1980’s, when Frontera and colleagues (1988) found that heavy resistance training with older adults resulted in significant strength improvements of the quadriceps, there has been a growing number of studies that have documented the beneficial effects of resistance training. Many studies have now shown that resistance training involving the lower limb muscle groups can have an advantageous effect on not only muscular strength but functional performance (Hess & Woollacott, 2005; Liu & Latham, 2011; Liu & Latham, 2009; Morse, Thom, Mian, et al., 2005; Ryushi et al., 2000; Schlicht, Camaione, & Owen, 2001; Simoneau, Martin, & Van Hoecke, 2007a; Symons, Vandervoort, Rice, Overend, & Marsh, 2005). Some studies have examined long term resistance training programs (up to 1 year) (Brochu et al., 2002; Buchner et al., 1997; Chin A Paw, van Poppel, Twisk, & van Mechelen, 2006) while others have investigated the effects of much shorter programs (6 to 12 weeks) (Boshuizen, Stemmerik, Westhoff, & Hopman-Rock, 2005; Foley, Halbert, Hewitt, & Crotty, 2003; Latham et al., 2003; Seynnes et al., 2004). In both cases considerably large improvements in muscular strength have been found. Many of these progressive resistance exercise programs have however focused mainly on the strength adaptations of the much
larger KE and AP muscle groups with noticeably less attention being afforded to the KF and AD.

Many studies have looked into strength programs and found that within relatively short training periods of 6-12 week, older adults can experience substantial improvements in strength. In a study by Symons et al. (2005) the effects of 12 weeks (3 times per week) of knee extension training using a Biodex System 3 dynamometer was investigated. Participants were randomly allocated into one of three training groups which consisted of concentric (n = 10, age 71.8 ± 3.1 years), isometric (n = 11, age 74.8 ± 7.6 years), or eccentric contractions (n = 9, age 70.5 ± 5.2 years). It was found that there were significant improvements, from 10 to 26% depending on contraction type, in maximal strength across all groups. This improvement in strength was coupled with improvements in step time, peak concentric work and concentric power. Another study by Ryushi et al. (2000), the researchers allocated 21 participants into an exercise group (age 53.7 ± 7.2 years) and 7 into a control group (53.6 ± 9.4 years). The resistance exercise that was utilised was a dynamic resistance training program over a 10 week period at 70% of participant’s one-repetition maximum until volitional fatigue of the KE was experienced. During the 10 weeks, knee extension maximal strength of the exercise group improved on average 18.5% at week 5 and 22.7% at week 10. In addition there was a significant increase in the limits-of-stability and a decrease in sway path length during postural tasks. Lastly, Ferri et al. (2003) conducted a study that had a group of 16 older men (67.9 ± 0.9 years) train three times per week at an intensity of 80% of their one repetition maximum. The resistance exercises consisted of both calf raises and leg presses over a 16 week period. For the KE and AP, respectively, training resulted in a 19.4 and 12.4% increase in maximal isometric torque. However, a limitation of the study was that there was a lack of a control group and due to this fact there was no random allocation into the training group along with no intention to treat analysis undertaken.
With long term resistance programs there have also been many studies that have shown significant strength improvements. For instance, Simoneau et al. (2006) analysed the effects of a 6 month resistance training program on the age related deficit in plantarflexion MVC. Within this study 20 participants were randomly allocated into either a resistance training group (five men and six women, age, 78.1 ± 3.1 years; height, 1.60 ± 0.06 m; mass, 65.6 ± 13.7 kg) or a control group (five men and four women; age, 75.9 ± 3.4 years; height, 1.61 ± 0.07 m; mass, 64.5 ± 11.0 kg). The exercise consisted of 2 supervised resistance training sessions per week (consisting of a calf raise type exercise) plus one home-based session involving Therabands. The program resulted in improved strength of the AP (24.5% increase) and AD (7.6% increase). In another study that utilised the same training methodology (Simoneau et al., 2007a) participants were randomly assigned to either a training group (n = 12, five males and seven females, age 78.5 ± 2.9 year; height 1.60 ± 0.06 m; mass 65.5 ± 13.7 kg) or a control group (n = 11, six males and five females, age 76.2 ± 4.3 year; height 1.63 ± 0.09 m; mass 66.3 ± 11.4 kg). It was found that within the training group there were significant improvements in AP and AD strength. After 6 months there was a 16.0% increase in maximal torque compared to baseline in the AP which was followed by another 13.8% increase after 12 months. This was accompanied by a 6.5% improvement in the AD maximal torque after 6 months but no change from 6 to 12 months. In 2007, de Boer et al. completed a study in which they assigned 14 older women (age 74.2 ± 3.1 years, height 1.6 ± 0.6 m, weight 69.7 ±18.6 kg) to a mixed training program and 12 to a nontraining control group (age 73.6 ± 4.3 years, height 1.6 ±0.4 m, weight 61.4 ± 9.4 kg) (de Boer et al., 2007). The training sessions involve 12 months of combined aerobic, weight-lifting exercises mainly of the KE and AP, stretching and TC exercises performed three times per week. Training resulted in a significant increase in AP MVC, with a mean increase over all joint angles of 11.7% and an 18.4% increase at the optimal angle of 20° dorsiflexed. Within the AD there was however a significant decrease in maximal strength with a mean decrease of 5.7% over all angles.
analysed. The decreased AD strength was attributed to the effect of a relatively higher coactivation of the plantarflexors during dorsiflexion maximal strength testing.

Limitations of the above described studies however include the fact that many of these researchers focused on healthy older populations and did not investigate the influence of dosage (i.e. frequency and intensity). For example, a study by Chin A Paw et al. (2006) investigated the effects of either a strength training program, functional skills training program, or a combined training program in a population of frail residential care individuals. Participants were randomly allocated into one of the three training groups or a control group. Interestingly it was shown that twice weekly functional skills or combined exercise was successful in improving several fitness and performance measures, however less than twice weekly training was not enough for functional improvement. This highlights the importance of careful consideration of both population and dosage when undertaking interventions such as resistance training.

2.8.2 Tai Chi Exercise

Tai Chi is an exercise that is performed in a semi-squat posture which can place very large loads on the lower extremity muscle groups. Many of the movements of TC require guided and coordinated movements of the knee and ankle joints. These movements can be similar to common body weight resistance exercises such as lunges and squats (Jacobson, Chen, Cashel, & Guerrero, 1997). This has led to an increase in interest into the possible benefits of TC on muscular strength and the performance of functional tasks. However to date, assessments of TC exercise on muscle strength have mainly focused on the KE and KF with little attention being afforded to the AP and AD.

Lan et al. (1998) completed a study that had older adults complete 12 months of TC exercise. This resulted in muscle strength enhancement in both the KE (20.3% improvement) and KF
(15.9% improvement). In a study by Li et al. (2009), 25 older adults participated in 16 weeks of TC training and a further 25 were randomly allocated into the control group. Maximal strength of the KE, KF, AP and AD was assessed both pre- and post-exercise intervention and found that TC resulted in significant improvements in both the KF and AP. However, there were no changes in maximal strength of either the KE or AD. In an earlier study (Tsang & Hui-Chan, 2005) a cross-sectional design was implemented to examine whether older TC practitioners had better knee musculature strength compared with healthy older adults. Maximal concentric and eccentric strength, at an angular velocity of 30°/s, was assessed for both the KE and KF. It was found that TC practitioners were significantly stronger in the KE and KF for both contraction modes. These findings however cannot be considered conclusive as there were several lifestyle characteristics that were not controlled for within the study. For example, long term TC practitioners may have a better lifestyle across other domains such as nutrition. Another aspect of the Tsang study that should be noted is that TC was practiced at very slow movement speeds. This may have resulted in “velocity specificity” adaptations of muscle strength. Therefore, the much slower isokinetic testing speeds used in the Tsang’s study may explain the significantly higher maximal strength in the TC practitioners. This potential velocity specific adaptation is highlighted by the findings of Wu et al. (2002) who found no difference in isokinetic strength of the knee flexors at higher isokinetic testing velocities.

Although these papers highlight the potential beneficial effects that TC training can have on muscular strength many of these studies have methodological weaknesses and/or major differences. For example, some studies have utilised a cross-sectional design (Tsang & Hui-Chan, 2005) while others have used a randomised, controlled trial (Li et al., 2009). There also appears to be major differences in both the type of muscular contraction and the muscles investigated. Therefore, more comprehensive randomised, controlled studies need to be
conducted to examine the effects of TC exercise on muscle strength of all four muscle groups of the lower extremity.

2.9 Summary

The human body’s ability to maintain upright posture is of the utmost importance and is essential to the everyday functioning of most people. In an effort to remain in this upright position the human body has to integrate several sensory modalities and produce appropriate motor responses to counteract internal and external perturbations and maintain posture. With ageing, however, there are many degenerative processes in the physiological systems that take place which often reduce the effective control of posture. This diminished ability to maintain posture is a risk factor for falls. In an effort to reduce the incidents of falls and identify those most at risk of postural control abnormalities, it is important to continue to develop appropriate postural control assessment techniques and the best practice for exercise prescription. Of the current information available it appears that appropriate exercise has a beneficial effect on the postural control system. Amongst the training modalities that have been examined it appears that exercises that involve coordinative balance tasks, such as balance training and Tai Chi, are the most effective in delaying the age-related decline in postural control.
Chapter 3: Methodology
3.1 Study One

The effects of joint angle and gender on strength ratio and coactivation of the agonists and antagonists at the knee and ankle joints and their correlations with postural control.

Aims:

1. To determine whether the lower limb muscle strength, the agonist/antagonist strength ratio and strength task coactivation are affected by joint angle and gender.
2. To investigate the relationship between lower limb maximal strength and agonist/antagonist strength ratio with postural control measures.

Null Hypotheses:

1. Lower limb muscular strength, strength ratio (HQR and DPR) and strength task coactivation are not altered by joint angle changes.
2. Lower limb muscular strength, strength ratio (HQR and DPR) and strength task coactivation are not different between genders.
3. Lower limb muscular strength and strength ratio (HQR and DPR) are not related to the ability to control posture in young adults.

3.1.1 Participants

Twelve male and 13 female volunteer participants (age range between 18 and 50 years) were recruited from the local and surrounding areas of Lismore, New South Wales (descriptive statistics of groups and genders presented in Table 3-1).
Table 3-1. Descriptive statistics of male and female and total participants’ age, height, weight and BMI.

<table>
<thead>
<tr>
<th></th>
<th>Male (n=12)</th>
<th>Female (n=13)</th>
<th>Total Sample (n=25)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>24.1 (4.9)</td>
<td>24.7 (7.0)</td>
<td>24.4 (6.0)</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.77 (0.05)</td>
<td>1.64 (0.05)</td>
<td>1.70 (0.08)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>72.97 (7.86)</td>
<td>61.65 (8.00)</td>
<td>67.08 (9.63)</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>23.37 (2.55)</td>
<td>23.02 (2.76)</td>
<td>23.19 (2.61)</td>
</tr>
</tbody>
</table>

Values in the table are Mean (SD)

Inclusion criteria applied were: 1) currently healthy (i.e. not suffering from any acute or chronic illnesses) as screened by the “Health Status Assessment Prior to Exercise Testing” questionnaire commonly used in our laboratory; and 2) had not participated in any systematic strength training in the last six months. The exclusion criteria were: 1) lack of independent ambulation (walking with an assistive device); 2) recent lower limb injuries (including any strains or sprains in the last month); 3) diagnosed neurologic or lower-extremity orthopaedic conditions (including spinal or lower back injuries); 4) corrected visual acuity worse than 20/100 or presence of a field defect; 5) true vertigo, 6) acute illness (e.g. the common cold) and; 7) use of medication known to affect balance, e.g. medication for psychiatric disorders, depression, or anxiety (Frank, Zhou, Bezerra, & Crowley, 2009). The implementation of the exclusion criteria was based on the self-reported responses to the “Health Status Assessment Prior to Exercise Testing” questionnaire. Participants who had no contraindications to participation were asked to sign the Informed Consent form, went through a familiarisation session and participated in one experimental session.

The sample size was estimated using G*power 3 (version 3.1.2) (Faul, Erdfelder, Lang, & Buchner, 2007). A priori estimation was used and it was found that to perform a 2 gender × 3 joint angles General Linear Model (GLM) with repeated measures, with an effect size of 0.25 and power of 0.80, the predicted minimum number of participants in each group would be nine. The study was approved by the Human Research Ethics Committee of Southern Cross
University (approval number ECN 10-037) and was performed in accordance with the Declaration of Helsinki.

### 3.1.2 Experimental Design

This study consisted of an observational evaluation of the differences between torque measures at different knee and ankle joint angles, and between genders and an analysis of the correlations between the variables of interest. Each participant was required to visit the laboratory once. The visit consisted of the following actions:

1) explanation of experimental procedures by the researcher and provision of informed consent,
2) completion of the health status assessment questionnaire,
3) familiarization of all experimental procedures including practice of all testing conditions,
4) formal postural control assessment trials, and
5) formal MVC assessment trials.

All testing sessions were carried out at the laboratories of the School of Health and Human Sciences, located in P Block of Lismore campus, Southern Cross University.

### 3.1.3 Materials

A Biodex Dynamometer (System 3, Biodex Medical Systems, Shirley, NY, USA) was used for the assessment of maximal torque of the knee extensors (KE), knee flexors (KF), ankle plantarflexors (AP) and ankle dorsiflexors (AD) muscle groups. Torque data were recorded at an analogue to digital conversion rate of 2000 Hz. Real time torque production was monitored by both the participant and researcher (computer screen directly in front of the participant’s eyes at approximately 1.5 to 2 metres).
During all strength testing sessions, two Velcro seat belts were placed over the participants’ shoulders and one was placed over the hips and they were consistently fastened to minimise pelvis and trunk motions.

During knee joint investigation participants were seated with a hip joint angle of approximately $85^0$. The right leg (dominant leg) was fitted into the attachment for knee extension and flexion with the leg strap being approximately 2 cm above the medial malleolus of the ankle. The rotational axis of the knee joint was aligned with the rotational axis of the dynamometer for all testing conditions.

During the tests at different ankle joint angles the participant was in a semi-supine position with the hip and knee joint angles of approximately $45^0$ and $140^0$, respectively. The right leg was fitted into the ankle attachment for plantarflexion and dorsiflexion strength tests. The right foot was secured into the attachment with Velcro straps which stabilised the foot into the heel-cup. The right leg was supported by a support arm under the knee and was adjusted to have a knee joint angle of $140^0$ ($180^0$ as full extension), which was verified manually with a goniometer. The left foot was resting on the foot-rest attachment during all ankle tests. The transverse axis of the ankle joint was aligned with the rotational axis of the dynamometer for all testing conditions (Chen et al., 2010).

The postural tests were performed on a force plate (Kistler, type 9287, Winterthur, Switzerland) which provided a continuous record of the position of the participant’s centre-of-pressure (COP) at a sampling rate of 100 Hz. The postural COP data were captured and recorded via a custom written LabView program (version 8.2 LabView, National Instruments, Austin, Texas) and transferred to Excel spreadsheets (Microsoft Excel 2003) for later data analysis.
Surface electromyography (SEMG) signals of the vastus lateralis (VL), biceps femoris (BF), gastrocnemius lateralis (GL) and tibialis anterior (TA) were recorded using a Bagnoli-8 SEMG system (Delsys, Boston, MA, USA) with double differentiated surface electrodes (DE 3.1, Delsys, Boston, MA). The electrode housing was internally shielded and contained a pre-amplifier. The electrode sensors were three parallel silver bars (99.9% pure silver) of 1 mm in diameter, 10 mm in length and spaced 10 mm apart. A self-adhesive conductive disk electrode (50 mm in diameter, Dermatrode, Delsys, Boston, MA) was placed over the medial condyle of the femur bone of the tested leg during strength testing, as a reference electrode. All electrode placements were in accordance with the guidelines suggested by SENIAM (Hermens et al., 1999). The electrode placement on the VL muscle was at 2/3 the distance from the anterior superior iliac spine to the lateral side of the patella and was applied in the direction of the muscle fibres. The electrode on the BF muscle was at the middle point of the line between the ischial tuberosity and the lateral epicondyle of the tibia and was applied longitudinally over the belly of the muscle (Hermens, Freriks, Disselhorst-Klug, & Rau, 2000; Macaluso et al., 2002). The TA electrode placement was at 1/3 the distance from the head of the fibula to the medial malleolus and ~2 cm lateral to the tibial crest. The GL electrode placement was at 1/3 the line between the head of the fibula and the heel (Chen et al., 2010; Hermens et al., 2000). The locations on the skin for recording electrodes were thoroughly cleaned by firstly shaving, then wiping the area with alcoholic wipes. Surgical adhesive tape was used along with double–sided adhesive electrode-skin interface, to secure the electrode position on the skin. Electrically conductive gel was used to seal excellent conduction between skin and the surface electrodes.

The SEMG signal was filtered with a band-pass at a range from 15 to 450 Hz, amplified with a gain of 1000 times and sampled at an analogue to digital conversion rate of 2000 Hz. A 16-bit A/D converter was used with the input range of ±5 V and resolution of 0.153 µV (Bagnoli-8, Delsys, Boston, MA). The SEMG signals were captured and recorded via a custom written
LabView program (version 8.2 LabView, National Instruments, Austin Texas). This program was used to synchronise the collection of kinematic (from the Biodex dynamometer) and electromyographic (from the Bagnoli-8 SEMG) data simultaneously.

### 3.1.4 Experimental Procedures

The experimental procedures were carried out in the following order:

1) performing self-administered static stretches for the four muscle groups to be tested (each stretch held for 15-20 seconds);
2) preparing the skin and attaching SEMG sensors;
3) preparing the computer program and testing equipment for experimental procedures; and
4) carrying out the experimental testing.

The following experimental testing trials were carried out in a randomized order:

- isometric MVC of KE and KF muscle groups;
- isometric MVC of AP and AD muscle groups; and
- postural sensory organisation tests.

Maximal isometric strength was determined at three separate joint angles for both knee and ankle strength assessments. The three knee joint angles utilized were $90^0$, $60^0$ and $30^0$ from full knee extension. The three angles utilized for the ankle joint were neutral position ($90^0$), $20^0$ plantarflexion ($+20^0$) and $20^0$ dorsiflexion ($-20^0$). These joint angles were chosen as they are commonly used joint angles tested in similar laboratory tests (Alonso et al., 2009; Billot et al., 2011; Simoneau et al., 2007b; Sosnoff et al., 2010). Each contraction was started and stopped upon the researcher’s voice signal and had a duration of approximately 2 to 3 seconds. Participants were asked to maximally exert force (in a randomised order) in 1)
isometric knee extension, 2) isometric knee flexion, 3) isometric ankle dorsiflexion, or 4) isometric ankle plantarflexion, while receiving verbal encouragement, and to relax the muscle as quickly as possible when receiving the “STOP” signal. Real time visual feedback of force production was provided. The trial was considered successful if there was no notable negative slope in the strength–increasing phase (as assessed in real time via visual inspection of the force trace on the computer screen) or the participant did not manifest any dissatisfaction with the performance (Gandevia, 2001). This procedure was repeated three times for each muscle group at each joint angle, with a rest period of one minute between trials. The highest torque in the three attempts was deemed the participant’s maximal voluntary contraction (MVC) torque that was later used in statistical analysis (Chen et al., 2010).

Postural control was assessed by the static stabilometry tests (Collins et al., 1995; Prieto et al., 1996). Participants removed their shoes and stood on the force plate with the heels 10 cm apart and the toes positioned according to participants’ comfort. Participants were asked to stand upright, place their arms at the sides of the body in a relaxed manner, and to look straight ahead at a fixed target point 2 metres away at eye level, for the duration (30 seconds) of each test trial (Prieto et al., 1996). The procedure was repeated three times and the COP displacement was recorded in the anterior-posterior (AnPo) and medial-lateral (MeLa) directions. The testing condition of eyes open on a firm surface was used as it is a commonly chosen postural test which is often used as a comparator to more difficult postural tests such as eyes closed and compliant surfaces.

3.1.5 Data Analysis

During strength measurements the maximal contraction torque, HQR and DPR, level of activation (as indicated by SEMG) and level of coactivation were evaluated from the contraction that demonstrated the highest torque. The HQR was calculated by dividing the maximal strength of the hamstrings by the maximal strength of the quadriceps muscle groups.
The DPR was calculated by dividing the maximal strength of the dorsiflexors by the maximal strength of the plantarflexors. For assessment of voluntary activation, the root-mean-square (RMS) of SEMG activity of the VL, BF, GL and TA muscles was calculated. During isometric activity, the RMS was calculated over a time period of 0.5 s, from 250 ms before to 250 ms after the identified peak torque point (Simoneau et al., 2007b).

To evaluate the level of coactivation, the most commonly applied method was used: the RMS data recorded from the TA muscle during the plantarflexion action was divided by the corresponding RMS recorded during the dorsiflexion MVC and expressed as a percentage. This method was applied to the KE and KF in the same way (Macaluso et al., 2002; Simoneau et al., 2007b).

The performance of postural control was assessed by traditional parameters including mean distance (Mean Dist), mean velocity (Mean Vel), sway area and 95% confidence circle area (95% CCA). Along with these traditional parameters stabilogram diffusion coefficient parameters were also analysed which included diffusion coefficient short term (Diff Co st), diffusion coefficient long term (Diff Co lt), scaling exponent short term (Scal Ex st), scaling exponent long term (Scal Ex lt), critical point (Crit Point) and critical point coordinates (Crit Point Coord). For traditional measures the best COP score in three attempts was used in statistical analysis (as defined by the lowest mean distance of the three trials). Stabilogram-diffusion plots were computed for each subject trial with three such curves being averaged to obtain a resultant stabilogram-diffusion plot for a particular participant. A detailed description for the calculation of both the traditional and stabilogram parameters, according to Prieto et al. (1996) and Collins et al. (1995) respectively, are presented in Appendix F.

The SEMG RMS data was calculated over a time period of 0.5 s period in the middle of the 30 s recording time and was normalised as a percentage of the amplitude displayed during
maximum voluntary contractions. The normalised SEMG ratios for TA/GL and BF/VL were calculated in order to determine the coactivation levels in each joint during postural maintenance (Benjuya et al., 2004). This process was repeated for each joint angle assessed.

3.1.6 Statistical Analysis

Descriptive statistical analyses, including means and standard deviations, were performed for MVC, HQR, DPR, SEMG coactivation level and postural parameters by gender. Data was expressed as mean ± standard deviation.

Maximal torque, SEMG RMS, strength task coactivation and strength ratio (HQR and DPR) data were submitted to a two factor [gender (2) × joint angle (3)] repeated measures General Linear Model (GLM) with gender as the between-subject factor and joint angle as the within-subject factor. If a significant main effect or interaction was found, a post-hoc analysis with Bonferroni adjustment was conducted to identify the significant difference between the mean values. Bivariate two-tailed Pearson’s correlation coefficient was used to examine the relationship between MVC, HQR and DPR with postural control parameters. For all data analyses (repeated measures GLM and bivariate two-tailed Pearson’s correlation coefficient) assumption for the use of that particular statistical test were examined and met beforehand. The α level was set at $p \leq 0.05$. All statistical methods were performed using SPSS software version 19.0 for Windows (SPSS Inc, Chicago, IL, 2010).
3.2 Study Two

An investigation of the effects of age and gender on lower limb strength ratios, strength task coactivation, postural control and postural task coactivation.

Aims:

1. To determine whether the lower limb muscle strength and the agonist/antagonist strength ratio are affected by age and gender.
2. To determine whether the ability to control posture in altered sensory conditions is affected by age and gender.
3. To determine whether the strength task coactivation and postural task coactivation in lower limb muscles are affected by age and gender.

Null Hypotheses:

1. Ageing does not affect the lower limb muscular strength, agonist/antagonist strength ratios or strength task coactivation.
2. Gender does not affect the lower limb muscular strength, agonist/antagonist strength ratios or strength task coactivation.
3. Ageing does not affect the ability to control posture in altered sensory conditions (firm or compliant surface and eyes open or closed).
4. Gender does not affect the ability to control posture in altered sensory conditions (firm or compliant surface and eyes open or closed).
5. The level of coactivation during postural tasks is not affected by ageing during postural tasks with altered sensory conditions.
3.2.1 Participants

Twenty five young (age range between 18 and 40 years) and 30 older (age range between 65 and 80 years) adult volunteer participants were recruited from the local and surrounding areas of Lismore, New South Wales (descriptive statistics of groups and genders presented in Table 3-2). Inclusion and exclusion criteria were the same as stated above in section 3.1.1 of this chapter.

Table 3-2. Descriptive statistics of young and older participants’ age, height, weight and BMI when separated by gender or with pooled.

<table>
<thead>
<tr>
<th></th>
<th>Male</th>
<th>Female</th>
<th>Pooled</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Young (n=12) Older (n=15)</td>
<td>Young (n=13) Older (n=15)</td>
<td>Young (n=25) Older (n=30)</td>
</tr>
<tr>
<td>Age (yrs)</td>
<td>24.1 (4.9) 73.5 (4.8)</td>
<td>24.7 (7.0) 71.9 (3.9)</td>
<td>24.4 (6.0) 72.7 (4.4)</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.77 (0.05) 1.74 (0.08)</td>
<td>1.64 (0.05) 1.61 (0.04)</td>
<td>1.70 (0.08) 1.67 (0.09)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>72.97 (7.86) 85.57 (11.72)</td>
<td>61.65 (8.00) 64.60 (8.41)</td>
<td>67.08 (9.63) 75.09 (14.64)</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>23.37 (2.55) 28.46 (3.95)</td>
<td>23.02 (2.76) 24.84 (3.15)</td>
<td>23.19 (2.61) 26.65 (3.97)</td>
</tr>
</tbody>
</table>

Values in the table are Mean (SD)

The sample size was estimated using G*power 3 (version 3.1.2) (Faul et al., 2007). A priori estimation was used and it was found that to perform a 2 age groups × 2 gender GLM with repeated measures, with an effect size of 0.25, power of 0.80, the predicted minimum number of participants in each group would be 12.

3.2.2 Experimental Design

This study was a cross-sectional analysis of the changes in postural maintenance and strength ratios of the lower limb. Each participant was required to visit the laboratory once; the visit consisted of the following actions:

1) explanation of experimental procedures by the researcher and provision of informed consent;
2) completion of the health status assessment questionnaire;
3) familiarization of all experimental procedures including practice of all testing conditions;
4) formal postural control assessment trials; and
5) formal MVC assessment trials.

All testing sessions were carried out at the laboratories of the School of Health and Human Sciences, located in P Block of Lismore campus, Southern Cross University.

3.2.3 Materials

Materials for Study Two were as per Study One and have been explained in detail in section 3.1.3 of this chapter.

3.2.4 Experimental Procedures

The experimental procedures were carried out in the following order:

1) performing self-administered static stretches for the four muscle groups to be tested (each stretch held for 15-20 seconds);
2) preparing the skin and attaching SEMG sensors;
3) preparing the computer program and testing equipment for experimental procedures; and
4) carrying out the experimental testing.

The following experimental testing trials were carried out in a randomized order:

- isometric MVC of KE and KF muscle groups;
- isometric MVC of AP and AD muscle groups; and
postural sensory organisation tests.

Maximal isometric strength was determined at one joint angle for both knee and ankle strength assessment. The MVC of knee extension and flexion were assessed at knee joint angle of 30° from full knee extension and that of the ankle dorsi- and plantar-flexion were assessed at ankle joint angle of 90° (neutral). The experimental procedure for maximal strength recording was the same as for Study One and is explained in detail in section 3.1.4 of this chapter.

Performance in postural control was assessed by the static stabilometry tests (Collins et al., 1995; Prieto et al., 1996). Participants removed their shoes and stood on the force plate with the heels 10 cm apart and the toes positioned according to participants’ comfort. Participants were asked to place their arms at their sides in a relaxed manner and to look straight ahead at a fixed target point 2 metres away at eye level, for the duration (30 seconds) of each test (Collins et al., 1995; Prieto et al., 1996). Four sensory organization test (SOT) conditions were conducted. These included eyes open on a firm surface (SOT 1), eyes closed on a firm surface (SOT 2), eyes open on a compliant surface (SOT 3) and eyes closed on a compliant surface (SOT 4). The compliant surface consisted of a 24 mm thick foam rubber mat with density 44.1 kg/m³. Each condition was repeated three times and the COP displacement was recorded in the anterior-posterior (AnPo) and medial-lateral (MeLa) directions. During all postural testing, if a participant overbalanced or stepped (or opened their eyes during eyes closed testing) then that trial was disregarded.

3.2.5 Data Analysis

Data analysis procedures were conducted in accordance with section 3.1.5 of Study One of this chapter.
3.2.6 Statistical Analysis

Descriptive statistical analyses, including means and standard deviations, were calculated for MVC, HQR, DPR, coactivation level and postural parameters by gender and group.

Maximal torque, SEMG RMS, strength task coactivation and strength ratio (HQR and DPR) data were submitted to a two factor [age group (2) × gender (2)] univariate General Linear Model (GLM) with group and gender as the between-subject factors. Data for postural parameters and coactivation (SEMG) levels during postural tasks (SOT1 through SOT4) were submitted to a two factor [age group (2) × gender (2)] multivariate General Linear Model (GLM) with age group and gender as the between-subject factors. If a significant main effect or interaction was found, a post-hoc analysis with Bonferroni adjustment was conducted to identify the significant difference between the mean values. For all data analyses (univariate GLM) assumption for the use of that particular statistical test were examined and met beforehand. The α level was set at $p \leq 0.05$. All statistical methods were performed using SPSS software version 19.0 for Windows (SPSS Inc, Chicago, IL, 2010).
3.3 Study Three

Effects of Tai Chi training on postural control, coactivation and lower limb muscle strength ratio modulation.

Aims:

1. To investigate the effect of 12 weeks of Tai Chi exercise on lower limb muscle strength, agonist/antagonist strength ratio and strength task coactivation.
2. To investigate the effect of 12 weeks of Tai Chi exercise on postural control and postural task coactivation.

Null Hypotheses:

1. Tai Chi, as an exercise intervention, does not cause changes in lower limb muscle strength, strength ratio (HQR and DPR) or strength task coactivation.
2. Tai Chi, as an exercise intervention, does not cause changes in postural control or postural control coactivation level.

3.3.1 Participants

Thirty nine (39) older adult (age range: 65 to 80 years) volunteer participants were recruited from the local and surrounding areas of Lismore, New South Wales. The recruitment process involved handing out flyers (Appendix A: Call for Volunteers) to local aged groups and through radio broadcasting. The participants were allocated into either a Tai Chi training group (24 participants with 11 males and 13 females) or a control group (15 participants with 8 males and 7 females) (descriptive statistics of groups presented in Table 3-3). The allocation of groups was based on the ability of the participant to commit to attending TC classes three
times per week over the 12 week training period. Inclusion and exclusion criteria are as above in section 3.1.1 of this chapter.

Table 3-3. Descriptive statistics of the Tai Chi Group and Control Group participants age, height, weight and BMI.

<table>
<thead>
<tr>
<th></th>
<th>Tai Chi Group Mean (SD)</th>
<th>Control Group Mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>72.0 (4.2)</td>
<td>73.9 (4.1)</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.67 (0.09)</td>
<td>1.66 (0.07)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>72.54 (15.55)</td>
<td>74.64 (9.74)</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>25.81 (4.33)</td>
<td>27.11 (2.60)</td>
</tr>
</tbody>
</table>

Values in the table are Mean (SD)

The sample size was estimated using G*power 3 (version 3.1.2) (Faul et al., 2007). A priori estimation was used and it was found that to perform a 2 group × 2 trials GLM with repeated measures, with an effect size of 0.25, power of 0.80, the predicted minimum number of participants in each group would be 14.

3.3.2 Experimental Design

This study was a non-randomised, controlled trial with a test-retest design that aimed to analyse the changes in postural maintenance and strength ratios of the lower limb due to Tai Chi exercise intervention. Each participant was required to visit the laboratory twice (pre- and post-exercise intervention); the visits consisted of the following actions:

1) explanation of experimental procedures by the researcher and provision of informed consent;
2) completion of the health status assessment questionnaire;
3) familiarization of all experimental procedures including practice of all testing conditions;
4) formal postural control assessment trials; and
5) formal MVC assessment trials.

All testing sessions were carried out at the laboratories of the School of Health and Human Sciences, located in P Block of Lismore campus, Southern Cross University.

3.3.3 Materials

Materials for Study Three were as per Study One and are explained in detail in section 3.1.3 of this chapter. It has been shown previously that the isometric maximal strength assessment of the lower limb muscles in older adults has a high reliability (ICC between 0.95 and 0.98) level between testing sessions (Chen et al., 2010; Maffiuletti, Bizzini, Desbrosses, Babault, & Munzinger, 2007). In relation to the COP measures it has also been shown that within-day reliability was moderate to high (ICC between 0.57 and 0.95) depending on what measure used (Lin, Seol, Nussbaum, & Madigan, 2008; Ruhe, Fejer, & Walker, 2010)

3.3.4 Experimental Procedure

During the participants’ visits to the laboratory for the pre- and post- training tests, the procedures as outlined in section 3.2.4 were performed. The experimental procedure for maximal strength and postural recording was the same as per Study Two and has been explained in detail in section 3.2.4 of this chapter. For application of SEMG surface electrodes the same procedure explained in section 3.1.3 of this chapter was repeated. This was completed by the same investigator at both pre and post testing sessions.

3.3.5 Control Condition & Tai Chi Training

Participants that were allocated into the control group were asked to maintain their current level of physical activity. They were also asked to refrain from participating in any extra or new physical activity for the duration of the 12 weeks of Tai Chi training.
The Tai Chi group was offered a training programme that required participation to attend three exercise sessions per week for 12 weeks. This length of intervention and number of sessions were based on previous reports that found significant improvements in physical function (Audette et al., 2006; Jacobson et al., 1997). The duration of training in each session was approximately 60 minutes which was broken down into a 20 mins warm up and 40 mins TC practice. The warm up consisted of 22 dynamic modified TC movements. The TC training was based on the 13-form Yang style TC (Appendix F). The first 6 weeks of TC training the participants were taught the 13-forms and in the following 6 weeks the participants repeatedly practiced the movement sequences at a slow pace. The training participants were encouraged to avoid any strenuous activities and other training interventions during the training period. All TC sessions were conducted by a qualified TC instructor who had been practicing TC for greater than five years. A detailed training program of the warm up exercises and 13-form Yang style TC is shown in Appendix F.

3.3.6 Data Analysis

Data analysis was conducted in accordance with section 3.1.5 of Study One.

3.3.7 Statistical Analysis

Descriptive statistical analyses, including means and standard deviations, were calculated for MVC, HQR, DPR and coactivation levels and postural parameters by gender and experimental group.

Data for MVC, HQR, DPR, strength task coactivation, postural parameters and coactivation during postural tasks was submitted to two factor [group (2) × trial (2)] repeated measures General Linear Model (GLM) with group as the between-subject factors and trial as the within-subject factor. If a significant main effect or interaction was found, a post-hoc analysis with Bonferroni adjustment was conducted to identify the significant difference between the
mean values. For all data analyses (repeated measures GLM) assumption for the use of that particular statistical test were examined and met beforehand. The α level was set at $p \leq 0.05$. All statistical methods were performed using SPSS software version 19.0 for Windows (SPSS Inc, Chicago, IL, 2010).
Chapter 4: Study One
The effects of joint angle and gender on strength ratios and coactivation of the agonists and antagonists at the knee and ankle joints, and their correlations with postural control

4.1 Study Outline

Aims:

1. To determine whether the lower limb muscle strength, the agonist/antagonist strength ratio and strength task coactivation are affected by joint angle and gender.
2. To investigate the relationship between lower limb maximal strength and agonist/antagonist strength ratio with postural control measures.

Null Hypotheses:

1. Lower limb muscular strength, strength ratio (HQR and DPR) and strength task coactivation are not altered by joint angle changes.
2. Lower limb muscular strength, strength ratio (HQR and DPR) and strength task coactivation are not different between genders.
3. Lower limb muscular strength and strength ratio (HQR and DPR) are not related to the ability to control posture in young adults.

Design and results summary:

This study consisted of an observational evaluation of the differences between torque measures at different knee and ankle joint angles, between genders and an analysis of the correlations between the variables of interest. Statistical analysis involved examination of main effects, interactions and post-hoc comparisons. If a significant effect or interaction was
detected post-hoc analyses with Bonferroni adjustment were conducted to detect significant
differences between genders and angles (presented below).

Comparisons of muscle strength between genders showed that males were stronger in all
muscles at all joint angles than females. This was not associated with the activation levels as
there were no gender differences found in maximal SEMG amplitude. Females exhibited
greater levels of coactivation during strength tests of the AP and AD. For the KE and KF females showed higher coactivation at 30° and 90°, respectively. There was generally no
significant difference in HQR or DPR between genders at any of the joint angles.

Comparisons between joint angles showed that for the KE there was an increase in strength as
the knee angle increased from 30° to 90° while the KF showed no differences in strength at
these joint angles. There were no differences in maximal SEMG between joint angles within
either the KE or KF. For both the KE and KF there were no differences in coactivation
between joint angles. The HQR significantly increased from 90° to 60° to 30° for both gender
separated or pooled. Generally the strength of AP increased from +20° to neutral to -20° while
that of the AD was weaker at -20° compared with that at neutral and +20°. For both AP and
AD muscle groups there were generally no differences in coactivation level, as indicated by
the maximal SEMG amplitude, between joint angles. The DPR significantly increased from -20° to neutral and to +20° for either gender separated or pooled.

Correlation analyses found weak to moderate positive correlations (r = 0.395 to 0.661)
between MVC and Mean Vel and Diff Co (st) (Y and R), while no significant correlations
between strength ratios and posture variables were found.
4.2  Results

4.2.1  Maximal Voluntary Contraction Torque

The observed means and standard deviations of MVC for KE, KF (at 90°, 60° and 30° from full extension), AP and AD [at neutral, 20° plantarflexed (+20°) and 20° dorsiflexed (-20°)] at the three joint angles are presented in Table 4-1.

Table 4-1. Maximal voluntary contraction torque for KE, KF, AP and AD at three selected joint angles.

<table>
<thead>
<tr>
<th></th>
<th>Male</th>
<th>Female</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>90°</td>
<td>60°</td>
<td>30°</td>
</tr>
<tr>
<td>KE (N.m)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>243.6</td>
<td>164.2</td>
<td>98.6</td>
<td>141.5</td>
</tr>
<tr>
<td>(91.3)</td>
<td>(43.3)</td>
<td>(22.7)</td>
<td>(36.8)</td>
</tr>
<tr>
<td>KF (N.m)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>105.1</td>
<td>111.6</td>
<td>110.9</td>
<td>67.5</td>
</tr>
<tr>
<td>(29.6)</td>
<td>(32.4)</td>
<td>(34.2)</td>
<td>(11.3)</td>
</tr>
<tr>
<td>AP (N.m)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>76.1</td>
<td>133.1</td>
<td>181.8</td>
<td>63.6</td>
</tr>
<tr>
<td>(33.4)</td>
<td>(39.2)</td>
<td>(36.6)</td>
<td>(19.5)</td>
</tr>
<tr>
<td>AD (N.m)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>47.9</td>
<td>50.2</td>
<td>38.4</td>
<td>29.9</td>
</tr>
<tr>
<td>(11.1)</td>
<td>(11.6)</td>
<td>(11.6)</td>
<td>(4.1)</td>
</tr>
</tbody>
</table>

Values in the table are Mean (SD)

A two factor repeated measures GLM (gender × joint angle) was used for each of the four muscle groups (KE, KF, AD and AP).

4.2.1.1  Knee Extensors & Flexors

A significant main effect of angle was found for the KE [F = 88.32, df = (2, 22), p < 0.001]. Post hoc comparisons, with Bonferroni adjustment, showed that the KE were significantly stronger at 90° than that at both 60° and 30° (p < 0.001) and 60° was significantly stronger than that at 30° (p < 0.001) (Figure 4-1). A significant main effect of angle was also shown for the KF [F = 10.35, df = (2, 22), p = 0.001], with post hoc comparisons (with Bonferroni adjustment) showing that the KF exhibited higher MVC at 60° as compared with 90° (p =
0.001) but not compared to 30° (p = 0.490), while there was no difference between 90° and 30° (p = 0.380) (Figure 4-1).

Figure 4-1. Comparisons between joint angles for the maximal voluntary contraction torque of KE and KF at 90°, 60° and 30° from full extension when the data of males and females were pooled. *: p ≤ 0.05.

A significant gender main effect (pooled joint angles) was found for both the KE [F = 13.20, df = (1, 23), p = 0.001] and KF [F = 16.55, df = (1, 23), p < 0.001]. Post hoc comparisons indicated that males exhibited significantly stronger contractions than females for both muscle groups (p ≤ 0.001).

No significant gender × angle interaction [F = 0.75, df = (2, 22), p = 0.485] was found for the KF. However, a significant gender × angle interaction [F = 5.87, df = (2, 22), p = 0.009] was found for the KE. Post hoc comparisons, with Bonferroni adjustment, revealed that changes in joint angle in male participants caused significant reductions in maximal torque from 90° to 60° to 30° [F = 57.78, df = (2, 22), p < 0.001] (Figure 4-2). For the females [F = 35.52, df = (2, 22), p < 0.001] it was found that changes in knee joint angle had a significant effect on maximal torque production between 90° and 30° (p = 0.001) and 60° and 30° (p < 0.001) but no difference between 90° and 60° (p = 0.496) (Figure 4-2).
Figure 4-2. Comparisons between joint angles for the maximal voluntary contraction torque of KE at 90°, 60° and 30° from full extension. Dotted line for males and solid line for females. * indicates significant difference (p ≤ 0.05) between consecutive joint angles. # indicates significant difference (p ≤ 0.05) between 90° and 30°.

When comparing strength differences between genders at each joint angle, it was found that males were significantly stronger than females in both the KE and KF muscle group’s at all joint angles (p < 0.001 to p < 0.05). The F statistics, degrees of freedom and significance values are presented in Table 4-2 (mean and standard deviation values are presented in Table 4-1).

Table 4-2. F statistics, degrees of freedom (df) and significance level for the comparison between genders for the KE & KF maximal voluntary contraction at all joint angles. *: p ≤ 0.05

<table>
<thead>
<tr>
<th></th>
<th>Knee Extensors</th>
<th>Knee Flexors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>90°</td>
<td>60°</td>
</tr>
<tr>
<td>F</td>
<td>13.83</td>
<td>8.09</td>
</tr>
<tr>
<td>df</td>
<td>1, 23</td>
<td>1, 23</td>
</tr>
<tr>
<td>Sig</td>
<td>0.001*</td>
<td>0.009*</td>
</tr>
</tbody>
</table>
4.2.1.2  Ankle Plantarflexors and Dorsiflexors

A significant main effect of angle was found for the AP [F = 182.84, df = (2, 22), p < 0.001]. Post hoc comparisons, with Bonferroni adjustment, showed that the AP were significantly stronger at -20° compared with that at both neutral (p < 0.001) and +20° (p < 0.001), while at neutral it was significantly stronger than that at +20° (p < 0.001) (Figure 4-3). A significant main effect of angle was also found for the AD [F = 68.48, df = (2, 22), p < 0.001]. Post hoc comparisons, with Bonferroni adjustment, found that the AD were significantly weaker at -20° compared with that at neutral (p < 0.001) and +20° (p < 0.001), but no difference was found between neutral and +20° (p = 0.721) (Figure 4-3).

![Figure 4-3. The maximal voluntary contraction torque of AP and AD at neutral, +20° and -20° when the data of male and female participants were pooled. *: p ≤ 0.05.]

A significant gender main effect (pooled joint angles) was found for both the AP [F = 5.01, df = (1, 23), p = 0.035] and AD [F = 30.93, df = (1, 23), p < 0.001]. Post hoc comparisons showed that males exhibited significantly stronger contractions than females for both muscle groups (p ≤ 0.035).
A significant gender × angle interaction was found for both the AP [F = 7.16, df = (2, 22), p = 0.004] and AD [F = 6.00, df = (2, 22), p = 0.008]. Post hoc comparisons, with Bonferroni adjustment, showed that the AP of both males [F = 124.11, df = (2, 22), p < 0.001] and females [F = 63.45, df = (2, 22), p < 0.001] were significantly stronger at -20° when compared to that at both neutral (p < 0.001) and +20° (p < 0.001), while at neutral it was stronger compared with that at +20° (p < 0.001) (Figure 4-4). Both males [F = 54.88, df = (2, 22), p < 0.001] and females [F = 18.14, df = (2, 22), p < 0.001] presented significantly weaker AD at -20° as compared to that at both neutral (p < 0.001) and +20° (males p < 0.001; females p = 0.009), while no differences were found between neutral and +20° for either gender (male p = 0.382; female p = 1.000) (Figure 4-4).

When comparing strength differences between genders, it was found that males were significantly stronger than females in both the AP and AD muscle groups at all joint angles (p < 0.001 to p < 0.05) except for the AP at +20° which showed no significant difference between genders (p = 0.261) (Figure 4-5). The F statistics, degrees of freedom, and significance values are presented in Table 4-3 (mean and standard deviation values are presented in Table 4-1).
Table 4-3. F statistics, degrees of freedom (df) and significance level for the comparison between genders for the KE, KF, AP and AD maximal voluntary contraction at all joint angles. *: p ≤ 0.05

<table>
<thead>
<tr>
<th></th>
<th>Ankle Plantarflexors</th>
<th>Ankle Dorsiflexors</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Neut +20 -20</td>
<td>Neut +20 -20</td>
</tr>
<tr>
<td>F</td>
<td>6.45 1.33 5.75</td>
<td>32.74 29.62 18.63</td>
</tr>
<tr>
<td>df</td>
<td>1, 23 1, 23 1, 23</td>
<td>1, 23 1, 23 1, 23</td>
</tr>
<tr>
<td>Sig</td>
<td>0.018* 0.261 0.025*</td>
<td>&lt;0.001* &lt;0.001* &lt;0.001*</td>
</tr>
</tbody>
</table>

Neut: neutral.

Figure 4-5. The maximal voluntary contraction torque of AP at ankle joint angle of neutral, +20° and -20° in male and female participants. *: p ≤ 0.05.
4.2.2 Maximal SEMG Amplitude

The observed means and standard deviations of the maximal SEMG amplitude (Root Mean Square, RMS) during MVC tests in KE, KF, AP and AD at all joint angles are presented in Table 4-4.

Table 4-4. SEMG (RMS) amplitude during maximal voluntary contractions for KE, KF, AP and AD at different joint angles.

<table>
<thead>
<tr>
<th></th>
<th>Male</th>
<th>Female</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>KE (mV)</td>
<td>90°  60°  30°</td>
<td>90°  60°  30°</td>
<td>90°  60°  30°</td>
</tr>
<tr>
<td>0.096</td>
<td>(0.059) 0.070 0.075</td>
<td>0.066 0.049 0.056</td>
<td>0.080 0.059 0.065</td>
</tr>
<tr>
<td>KF (mV)</td>
<td>0.070 0.081 0.081</td>
<td>0.047 0.046 0.036</td>
<td>0.058 0.063 0.057</td>
</tr>
<tr>
<td>AP (mV)</td>
<td>0.095 0.098 0.089</td>
<td>0.062 0.068 0.059</td>
<td>0.078 0.083 0.073</td>
</tr>
<tr>
<td>AD (mV)</td>
<td>0.143 0.165 0.167</td>
<td>0.123 0.135 0.144</td>
<td>0.133 0.150 0.155</td>
</tr>
<tr>
<td>+20° Neutral -20°</td>
<td>+20° Neutral -20°</td>
<td>+20° Neutral -20°</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(0.041) (0.040) (0.039)</td>
<td>(0.041) (0.050) (0.063)</td>
<td>(0.044) (0.047) (0.054)</td>
</tr>
<tr>
<td></td>
<td>(0.073) (0.088) (0.079)</td>
<td>(0.071) (0.073) (0.075)</td>
<td>(0.071) (0.080) (0.076)</td>
</tr>
</tbody>
</table>

Values in the table are Mean (SD)

A two factor repeated measures GLM (gender × joint angle) was used for each of the four muscle groups (KE, KF, AD and AP).

4.2.2.1 Knee Extensors & Flexors

It was found that for the KE, a main effect of angle [F = 5.23, df = (2, 22), p = 0.014] existed however no gender main effect [F = 1.24, df = (1, 23), p = 0.277] and no significant interaction for gender × angle [F = 0.58, df = (2, 22), p = 0.571]. Post hoc comparisons, with Bonferroni adjustment, showed that there were significantly higher muscle activations at 90° compared with both 60° (p = 0.010) and 30° (p = 0.044), while there were no difference between 60° and 30° (p = 0.159). Analysis of the KF, revealed no main effect of gender [F = 3.26, df = (1, 23), p = 0.084] or angle [F = 1.02, df = (2, 22), p = 0.377] and no significant interaction for gender × angle [F = 1.00, df = (2, 22), p = 0.383].
4.2.2.2  Ankle Plantarflexors and Dorsiflexors

Analysis of the AP revealed no main effect of gender [F = 2.94, df = (1, 23), p = 0.100] or angle [F = 2.24, df = (2, 22), p = 0.130] and no significant interaction for gender × angle [F = 0.07, df = (2, 22), p = 0.933]. Analysis of the AD, revealed a main effect of angle [F = 6.90, df = (1, 23), p = 0.005] but not for gender [F = 0.65, df = (2, 22), p = 0.428] and no significant interaction for gender × angle [F = 0.26, df = (2, 22), p = 0.770]. Post hoc comparisons, with Bonferroni adjustment, showed that the AD exhibited significantly higher levels of muscle activation at -20° when compared to +20° (p = 0.003), while there were no differences between -20° and neutral (p = 0.865) and neutral and +20° (p = 0.097).
4.2.3  **Strength Ratio**

The observed means and standard deviations of HQR and DPR at the three selected joint angles are presented in Table 4-5.

**Table 4-5. HQR and DPR values at each joint angle.**

<table>
<thead>
<tr>
<th></th>
<th>Male</th>
<th>Female</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>HQR</td>
<td>90°</td>
<td>60°</td>
<td>30°</td>
</tr>
<tr>
<td></td>
<td>0.45</td>
<td>0.69</td>
<td>1.11</td>
</tr>
<tr>
<td></td>
<td>(0.08)</td>
<td>(0.13)</td>
<td>(0.21)</td>
</tr>
<tr>
<td></td>
<td>90°</td>
<td>60°</td>
<td>30°</td>
</tr>
<tr>
<td></td>
<td>0.49</td>
<td>0.62</td>
<td>0.96</td>
</tr>
<tr>
<td></td>
<td>(0.10)</td>
<td>(0.11)</td>
<td>(0.13)</td>
</tr>
<tr>
<td></td>
<td>90°</td>
<td>60°</td>
<td>30°</td>
</tr>
<tr>
<td></td>
<td>0.47</td>
<td>0.65</td>
<td>1.03</td>
</tr>
<tr>
<td></td>
<td>(0.09)</td>
<td>(0.12)</td>
<td>(0.19)</td>
</tr>
<tr>
<td>DPR</td>
<td>+20°</td>
<td>Neutral</td>
<td>-20°</td>
</tr>
<tr>
<td></td>
<td>0.64</td>
<td>0.42</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>(0.20)</td>
<td>(0.15)</td>
<td>(0.10)</td>
</tr>
<tr>
<td></td>
<td>+20°</td>
<td>Neutral</td>
<td>-20°</td>
</tr>
<tr>
<td></td>
<td>0.50</td>
<td>0.33</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>(0.13)</td>
<td>(0.10)</td>
<td>(0.06)</td>
</tr>
<tr>
<td></td>
<td>+20°</td>
<td>Neutral</td>
<td>-20°</td>
</tr>
<tr>
<td></td>
<td>0.56</td>
<td>0.37</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>(0.18)</td>
<td>(0.13)</td>
<td>(0.08)</td>
</tr>
</tbody>
</table>

Values in the table are Mean (SD)

A two factor repeated measures GLM (gender × joint angle) was used for each of the two strength ratios (HQR and DPR).

4.2.3.1  **Hamstring to Quadriceps Ratio**

Within the HQR there was a main effect of joint angle \([F = 92.09, \text{df} = (2, 22), p < 0.001]\).

Post hoc comparisons, with Bonferroni adjustment, showed that the HQR was significantly higher at 30° (\(p < 0.001\)) from full knee extension when compared to that at both 60° and 90°, while at 60° (\(p < 0.001\)) it was also significantly higher than that at 90° (Figure 4-6).
Figure 4-6. The comparisons of HQR at knee joint angles of 90°, 60° and 30° when the data of males and females were pooled. *: p ≤ 0.05.

It was shown that there was no main effect of gender \([F = 2.78, \text{df} = (1, 23), p = 0.109]\), however there was a significant interaction for gender \(\times\) angle \([F = 3.89, \text{df} = (2, 22), p = 0.036]\). When the comparisons were performed for males and females separately, with Bonferroni adjustment, significant differences between joint angles were found for both males \([F = 62.89, \text{df} = (2, 22), p < 0.001]\) and females \([F = 31.85, \text{df} = (2, 22), p < 0.001]\). In both the male and female participants it was seen that the HQR at 30° \((p ≤ 0.001)\) was significantly higher than at both 60° and 90°, while at 60° \((p ≤ 0.001)\) it was also higher than at 90° (Figure 4-7).

Figure 4-7. The comparisons of HQR at knee joint angles of 90°, 60° and 30° in males (left) and females (right). *: p ≤ 0.05.
When comparing HQR differences between genders, it was found that there was no difference in HQR at both $90^\circ$ [$F = 1.61$, df = (1, 23), $p = 0.218$] and $60^\circ$ [$F = 1.93$, df = (1, 23), $p = 0.178$]. However at $30^\circ$ it was shown that males had a significantly higher HQR than females [$F = 4.70$, df = (1, 23), $p = 0.041$] (Figure 4-8).

Figure 4-8. The comparisons of HQR between genders at knee joint angles of $90^\circ$, $60^\circ$ and $30^\circ$. *: $p \leq 0.05$.

### 4.2.3.2 Dorsiflexor to Plantarflexor Ratio

There was a main effect of joint angle [$F = 114.74$, df = (2, 22), $p < 0.001$] for the DPR. Post hoc comparisons, with Bonferroni adjustment, showed that the comparisons between ankle joint angles found that the DPR was significantly higher at $+20^\circ$ ($p < 0.001$) compared to that at both neutral and $-20^\circ$, while at neutral ($p < 0.001$) it was also significantly higher compared to $-20^\circ$ (Figure 4-9).
A significant main effect of gender \([F = 7.11, \text{df} = (1, 23), \text{p} = 0.014]\) was found which indicated that when the DPR of all joint angles were pooled males had a significantly higher DPR value. An interaction analysis between gender and angle found that there were no significant interaction effect of gender \(\times\) angle \([F = 1.59, \text{df} = (2, 22), \text{p} = 0.226]\) for the DPR.
4.2.4 Coactivation of Agonist and Antagonist in Strength Tasks

The observed means and standard deviations of the SEMG coactivation levels during KE, KF, AP and AD MVC at the selected joint angles are presented in Table 4-6. To evaluate the level of coactivation, the most commonly applied method was used (Simoneau et al., 2007b): the SEMG (RMS) data recorded from a muscle that was acting as the antagonist was divided by the corresponding RMS recorded during the MVC when the same muscle was acting as the agonist, and the result was expressed as a percentage. This method was applied to all muscle groups measured.

Table 4-6. Coactivation level (%) of antagonist muscle during maximal voluntary contractions of the KE, KF, AP and AD at each of the selected joint angles.

<table>
<thead>
<tr>
<th></th>
<th>Male 90°</th>
<th>Male 60°</th>
<th>Male 30°</th>
<th>Female 90°</th>
<th>Female 60°</th>
<th>Female 30°</th>
<th>Pooled 90°</th>
<th>Pooled 60°</th>
<th>Pooled 30°</th>
</tr>
</thead>
<tbody>
<tr>
<td>KE</td>
<td>14.28</td>
<td>11.42</td>
<td>10.06</td>
<td>35.20</td>
<td>20.56</td>
<td>23.26</td>
<td>25.16</td>
<td>16.17</td>
<td>16.93</td>
</tr>
<tr>
<td></td>
<td>(10.37)</td>
<td>(7.37)</td>
<td>(5.18)</td>
<td>(43.49)</td>
<td>(17.69)</td>
<td>(11.79)</td>
<td>(33.30)</td>
<td>(14.25)</td>
<td>(11.27)</td>
</tr>
<tr>
<td>KF</td>
<td>5.01</td>
<td>8.68</td>
<td>9.23</td>
<td>14.89</td>
<td>15.72</td>
<td>18.22</td>
<td>10.14</td>
<td>12.34</td>
<td>13.90</td>
</tr>
<tr>
<td></td>
<td>(2.55)</td>
<td>(7.67)</td>
<td>(13.06)</td>
<td>(15.77)</td>
<td>(14.48)</td>
<td>(19.58)</td>
<td>(12.36)</td>
<td>(12.03)</td>
<td>(17.05)</td>
</tr>
<tr>
<td>AP</td>
<td>7.94</td>
<td>6.78</td>
<td>8.26</td>
<td>17.13</td>
<td>14.13</td>
<td>15.67</td>
<td>12.72</td>
<td>10.60</td>
<td>12.11</td>
</tr>
<tr>
<td></td>
<td>(4.87)</td>
<td>(4.30)</td>
<td>(7.87)</td>
<td>(11.22)</td>
<td>(8.40)</td>
<td>(14.99)</td>
<td>(9.79)</td>
<td>(7.60)</td>
<td>(12.45)</td>
</tr>
<tr>
<td>AD</td>
<td>8.94</td>
<td>9.02</td>
<td>7.88</td>
<td>20.65</td>
<td>19.62</td>
<td>23.06</td>
<td>15.03</td>
<td>14.53</td>
<td>15.78</td>
</tr>
<tr>
<td></td>
<td>(7.85)</td>
<td>(7.32)</td>
<td>(6.09)</td>
<td>(10.34)</td>
<td>(10.81)</td>
<td>(13.63)</td>
<td>(10.83)</td>
<td>(10.59)</td>
<td>(13.03)</td>
</tr>
</tbody>
</table>

Values in the table are Mean (SD)

A two factor repeated measures GLM (gender × joint angle) was used for each of the four muscle groups (KE, KF, AD and AP).

4.2.4.1 Hamstring and Quadriceps Coactivation

No significant main effect of angle was found for either the KE [F = 1.06, df = (2, 22), p = 0.365] or the KF [F = 2.22, df = (2, 22), p = 0.133]. When data for all joint angles were pooled it was found that there was a significant gender main effect for the KE [F = 5.81, df =
(1, 23), p = 0.04] but not for the KF [F = 3.21, df = (1, 23), p = 0.086]. Post hoc comparisons showed that males exhibited significantly lower coactivation levels than females for KE when acting as the antagonist (Figure 4-10). There were also no significant gender × angle interactions found for the KE [F = 0.51, df = (2, 22), p = 0.606] or KF [F = 0.91, df = (2, 22), p = 0.415].

![Figure 4-10. Comparisons of KE coactivation levels between genders (main effect of Gender). *: p ≤ 0.05.](image)

### 4.2.4.2 Dorsiflexor and Plantarflexor Coactivation

No significant main effect of angle was found for either the AP [F = 3.25, df = (2, 22), p = 0.058] or the AD [F = 0.59, df = (2, 22), p = 0.565]. When data for all joint angles were pooled it was found that there was a significant gender main effect for both the AP [F = 6.60, df = (1, 23), p = 0.017] (Figure 4-11) and AD [F = 11.57, df = (1, 23), p = 0.002] (Figure 4-12). Post hoc comparisons showed that males exhibited significantly lower coactivation levels than females within both the AP and AD when either was acting as the antagonist. There were also no significant gender × angle interactions found for the AP [F = 0.46, df = (2, 22), p = 0.637] or AD [F = 2.17, df = (2, 22), p = 0.138].

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Figure 4-11. Comparisons of AP coactivation levels between genders (main effect of Gender). *: $p \leq 0.05$.

Figure 4-12. Comparisons of AD coactivation levels between genders (main effect of Gender). *: $p \leq 0.05$. 

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4.2.5 Correlations between Muscle Strength and Strength Ratio with Postural Control Variables

4.2.5.1 Correlations between MVC and Postural Control Variables

4.2.5.1.1 Traditional Parameters

Of the eight traditional postural parameters only three showed significant correlations with maximal strength measures (Table 4-6). However, many of these correlations were only at weak to moderate levels (r values ranged from 0.395 to 0.649) (Berg & Latin, 2008).

For the KE at 90° the MVC was significantly and positively correlated with Mean Velocity (Mean Vel) \( (r = 0.452, p = 0.023) \) and Mean Vel AnPo \( (r = 0.432, p = 0.031) \). For the KE at 60° there were significant and positive correlations found with Mean Vel \( (r = 0.475, p = 0.016) \), Mean Vel MeLa \( (r = 0.456, p = 0.022) \) and Mean Vel AnPo \( (r = 0.430, p = 0.032) \). For the KE at 30° there were significant and positive correlations found with Mean Vel \( (r = 0.635, p = 0.001) \), Mean Vel MeLa \( (r = 0.528, p = 0.007) \) and Mean Vel AnPo \( (r = 0.629, p = 0.001) \).

For the KF at 90° the MVC was significantly and positively correlated with Mean Vel \( (r = 0.649, p < 0.001) \), Mean Vel MeLa \( (r = 0.554, p = 0.004) \), Mean Vel AnPo \( (r = 0.622, p = 0.001) \) and Sway Area \( (r = 0.456, p = 0.022) \). For the KF at 60° there were significant and positive correlations found with Mean Vel \( (r = 0.568, p = 0.003) \), Mean Vel MeLa \( (r = 0.557, p = 0.004) \), Mean Vel AnPo \( (r = 0.490, p = 0.013) \) and Sway Area \( (r = 0.449, p = 0.024) \). For the KF at 30° there were significant and positive correlations found with Mean Vel \( (r = 0.587, p = 0.002) \), Mean Vel MeLa \( (r = 0.567, p = 0.003) \), Mean Vel AnPo \( (r = 0.515, p = 0.008) \) and Sway Area \( (r = 0.477, p = 0.016) \).

There were no significant correlations between traditional postural parameters and strength measures of the AP at any of the selected ankle joint angles \( (p > 0.05) \).
For the MVC of the AD at neutral there were significant and positive correlations with Mean Vel (r = 0.462, p = 0.020), Mean Vel AnPo (r = 0.471, p = 0.017) and Sway Area (r = 0.439, p = 0.028) but no correlation with Mean Vel MeLa (p > 0.05). For the AD at +20° there were significant and positive correlations with Mean Vel (r = 0.457, p = 0.022) and Mean Vel AnPo (r = 0.493, p = 0.012) but no correlation with Mean Vel MeLa or Sway Area (p > 0.05). However, at -20° the AD showed no significant correlations with any of the traditional Mean Vel measures (p > 0.05), but did show a significant and positive correlation with Sway Area (r = 0.423, p = 0.035).

Table 4-7. Correlations between traditional postural parameters and maximal strength of the KE and KF at knee joint angles of 90°, 60° and 30° and, AP and AD at ankle joint angles of neutral (neut), +20° and -20°. Values in the table are correlation coefficients (r). *: p ≤ 0.05.

<table>
<thead>
<tr>
<th></th>
<th>Mean Dist</th>
<th>Mean Dist MeLa</th>
<th>Mean Dist AnPo</th>
<th>Mean Vel</th>
<th>Mean Vel MeLa</th>
<th>Mean Vel AnPo</th>
<th>95% CCA</th>
<th>Sway Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>KE 90°</td>
<td>0.051</td>
<td>0.125</td>
<td>0.008</td>
<td>0.452 *</td>
<td>0.395</td>
<td>0.432 *</td>
<td>0.008</td>
<td>0.271</td>
</tr>
<tr>
<td>KE 60°</td>
<td>0.035</td>
<td>-0.004</td>
<td>0.036</td>
<td>0.475 *</td>
<td>0.456 *</td>
<td>0.430 *</td>
<td>0.002</td>
<td>0.265</td>
</tr>
<tr>
<td>KE 30°</td>
<td>0.046</td>
<td>0.136</td>
<td>-0.001</td>
<td>0.635 *</td>
<td>0.528 *</td>
<td>0.629 *</td>
<td>-0.005</td>
<td>0.340</td>
</tr>
<tr>
<td>KF 90°</td>
<td>0.200</td>
<td>0.176</td>
<td>0.154</td>
<td>0.649 *</td>
<td>0.554 *</td>
<td>0.622 *</td>
<td>0.156</td>
<td>0.456 *</td>
</tr>
<tr>
<td>KF 60°</td>
<td>0.225</td>
<td>0.197</td>
<td>0.174</td>
<td>0.568 *</td>
<td>0.557 *</td>
<td>0.490 *</td>
<td>0.170</td>
<td>0.449 *</td>
</tr>
<tr>
<td>KF 30°</td>
<td>0.239</td>
<td>0.212</td>
<td>0.192</td>
<td>0.587 *</td>
<td>0.567 *</td>
<td>0.515 *</td>
<td>0.176</td>
<td>0.477 *</td>
</tr>
<tr>
<td>AP neut</td>
<td>0.092</td>
<td>-0.143</td>
<td>0.157</td>
<td>0.360</td>
<td>0.359</td>
<td>0.325</td>
<td>0.024</td>
<td>0.232</td>
</tr>
<tr>
<td>AP +20°</td>
<td>0.111</td>
<td>-0.045</td>
<td>0.133</td>
<td>0.289</td>
<td>0.237</td>
<td>0.298</td>
<td>0.044</td>
<td>0.183</td>
</tr>
<tr>
<td>AP -20°</td>
<td>0.046</td>
<td>-0.168</td>
<td>0.104</td>
<td>0.324</td>
<td>0.281</td>
<td>0.316</td>
<td>-0.028</td>
<td>0.188</td>
</tr>
<tr>
<td>AD neut</td>
<td>0.248</td>
<td>0.245</td>
<td>0.199</td>
<td>0.462 *</td>
<td>0.360</td>
<td>0.471 *</td>
<td>0.185</td>
<td>0.439 *</td>
</tr>
<tr>
<td>AD +20°</td>
<td>0.127</td>
<td>0.188</td>
<td>0.078</td>
<td>0.457 *</td>
<td>0.329</td>
<td>0.493 *</td>
<td>0.068</td>
<td>0.319</td>
</tr>
<tr>
<td>AD -20°</td>
<td>0.293</td>
<td>0.268</td>
<td>0.248</td>
<td>0.316</td>
<td>0.283</td>
<td>0.295</td>
<td>0.224</td>
<td>0.423 *</td>
</tr>
</tbody>
</table>
4.2.5.1.2 Diffusion Parameters

Of the eighteen stabilogram diffusion postural parameters only six showed consistent correlations with maximal strength measures (Table 4-7). However, many of these correlations were only weak to moderate in strength (r values ranged from 0.400 to 0.664).

The KE MVC at 90° showed significant and positive correlations with the stabilogram diffusion parameters of Diffusion Coefficient Y short term [Diff Co Y (st)] (r = 0.585, p = 0.002) and Diff Co R (st) (r = 0.532, p = 0.006). At 60° the KE showed significant and positive correlations with the stabilogram diffusion parameters of Diff Co Y (st) (r = 0.529, p = 0.007) and Diff Co R (st) (r = 0.521, p = 0.008). At 30° the KE showed significant and positive correlations with the stabilogram diffusion parameters of Critical Point Coordinates X (Crit Point Coords X) (r = 0.414, p = 0.040), Diff Co X (st) (r = 0.488, p = 0.013), Diff Co Y (st) (r = 0.611, p = 0.001) and Diff Co R (st) (r = 0.617, p = 0.001).

The KF MVC at 90° showed significant and positive correlations with the stabilogram diffusion parameters of Crit Point Coords X (r = 0.476, p = 0.016), Diff Co X (st) (r = 0.506, p = 0.010), Crit Point Coords Y (r = 0.412, p = 0.041), Diff Co Y (st) (r = 0.634, p = 0.001), Crit Point Coords R (r = 0.459, p = 0.021) and Diff Co R (st) (r = 0.641, p = 0.001). At 60° the KF showed significant and positive correlations with the stabilogram diffusion parameters of Crit Point Coords X (r = 0.448, p = 0.025), Diff Co X (st) (r = 0.541, p = 0.005), Crit Point Coords Y (r = 0.400, p = 0.048), Diff Co Y (st) (r = 0.597, p = 0.002), Crit Point Coords R (r = 0.435, p = 0.030) and Diff Co R (st) (r = 0.629, p = 0.001). At 30° the KF showed significant and positive correlations with the stabilogram diffusion parameters of Crit Point Coords X (r = 0.500, p = 0.011), Diff Co X (st) (r = 0.558, p = 0.004), Crit Point Coords Y (r = 0.415, p = 0.039), Diff Co Y (st) (r = 0.632, p = 0.001), Crit Point Coords R (r = 0.465, p = 0.019) and Diff Co R (st) (r = 0.661, p < 0.001).
The AP MVC at neutral showed significant and positive correlations with the stabilogram diffusion parameters of Diff Co Y (st) ($r = 0.510$, $p = 0.009$) and Diff Co R (st) ($r = 0.480$, $p = 0.015$). At $+20^0$ the AP only showed a significant and positive correlations with the stabilogram diffusion parameters of Diff Co Y (st) ($r = 0.445$, $p = 0.026$). At $-20^0$ the AP showed significant and positive correlations with the stabilogram diffusion parameters of Diff Co Y (st) ($r = 0.414$, $p = 0.040$) and Diff Co R (st) ($r = 0.406$, $p = 0.044$).

The AD MVC at ankle joint angle of neutral showed significant and positive correlations with the stabilogram diffusion parameters of Crit Point Coords X ($r = 0.444$, $p = 0.026$), Diff Co Y (st) ($r = 0.664$, $p < 0.001$), Crit Point Coords R ($r = 0.449$, $p = 0.024$) and Diff Co R (st) ($r = 0.585$, $p = 0.002$). At $+20^0$ the AD showed significant and positive correlations with the stabilogram diffusion parameters of Diff Co Y (st) ($r = 0.613$, $p = 0.001$) and Diff Co R (st) ($r = 0.534$, $p = 0.006$). At $-20^0$ the AD showed significant and positive correlations with the stabilogram diffusion parameters of Crit Point Coords X ($r = 0.479$, $p = 0.015$), Diff Co Y (st) ($r = 0.595$, $p = 0.002$), Crit Point Coords R ($r = 0.459$, $p = 0.021$) and Diff Co R (st) ($r = 0.533$, $p = 0.006$).
Table 4-8. Correlation between stabilogram diffusion postural parameters and maximal strength of the KE and KF at knee joint angles of 90°, 60° and 30° and, AP and AD at ankle joint angles of neutral (neut), +20° and -20°. Values in the table are correlation coefficients (r). *: p ≤ 0.05.

<table>
<thead>
<tr>
<th></th>
<th>KE 90°</th>
<th>KE 60°</th>
<th>KE 30°</th>
<th>KF 90°</th>
<th>KF 60°</th>
<th>KF 30°</th>
<th>AP neut</th>
<th>AP +20°</th>
<th>AP -20°</th>
<th>AD neut</th>
<th>AD +20°</th>
<th>AD -20°</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Crit Point X</td>
<td>Crit Point Coords X</td>
<td>Diff Co X (st)</td>
<td>Diff Co X (lt)</td>
<td>Scaling Ex X (st)</td>
<td>Scaling Ex X (lt)</td>
<td>Crit Point Y</td>
<td>Crit Point Coords Y</td>
<td>Diff Co Y (st)</td>
<td>Diff Co Y (lt)</td>
<td>Scaling Ex Y (st)</td>
<td>Scaling Ex Y (lt)</td>
</tr>
<tr>
<td>KE 90°</td>
<td>-0.091</td>
<td>0.306</td>
<td>0.319</td>
<td>0.062</td>
<td>0.065</td>
<td>-0.122</td>
<td>-0.110</td>
<td>0.305</td>
<td>0.585 *</td>
<td>-0.073</td>
<td>0.234</td>
<td>-0.244</td>
</tr>
<tr>
<td>KE 60°</td>
<td>-0.058</td>
<td>0.255</td>
<td>0.389</td>
<td>-0.052</td>
<td>0.222</td>
<td>-0.232</td>
<td>-0.095</td>
<td>0.312</td>
<td>0.529 *</td>
<td>-0.054</td>
<td>0.193</td>
<td>-0.276</td>
</tr>
<tr>
<td>KE 30°</td>
<td>-0.027</td>
<td>0.414 *</td>
<td>0.488 *</td>
<td>0.096</td>
<td>0.184</td>
<td>-0.126</td>
<td>-0.180</td>
<td>0.285</td>
<td>0.611 *</td>
<td>-0.095</td>
<td>0.313</td>
<td>-0.354</td>
</tr>
<tr>
<td>KF 90°</td>
<td>-0.008</td>
<td>0.476 *</td>
<td>0.506 *</td>
<td>0.142</td>
<td>0.118</td>
<td>-0.126</td>
<td>0.028</td>
<td>0.412 *</td>
<td>0.634 *</td>
<td>0.069</td>
<td>0.257</td>
<td>-0.187</td>
</tr>
<tr>
<td>KF 60°</td>
<td>-0.101</td>
<td>0.448 *</td>
<td>0.541 *</td>
<td>0.137</td>
<td>0.107</td>
<td>-0.136</td>
<td>0.024</td>
<td>0.400 *</td>
<td>0.597 *</td>
<td>0.105</td>
<td>0.142</td>
<td>-0.119</td>
</tr>
<tr>
<td>KF 30°</td>
<td>-0.011</td>
<td>0.500 *</td>
<td>0.558 *</td>
<td>0.118</td>
<td>0.088</td>
<td>-0.176</td>
<td>-0.013</td>
<td>0.415 *</td>
<td>0.632 *</td>
<td>0.118</td>
<td>0.135</td>
<td>-0.134</td>
</tr>
<tr>
<td>AP neut</td>
<td>-0.080</td>
<td>0.220</td>
<td>0.321</td>
<td>-0.179</td>
<td>0.267</td>
<td>-0.281</td>
<td>-0.045</td>
<td>0.365</td>
<td>0.510 *</td>
<td>0.090</td>
<td>0.167</td>
<td>-0.042</td>
</tr>
<tr>
<td>AP +20°</td>
<td>-0.164</td>
<td>0.137</td>
<td>0.196</td>
<td>-0.027</td>
<td>0.039</td>
<td>-0.099</td>
<td>0.082</td>
<td>0.316</td>
<td>0.445 *</td>
<td>0.094</td>
<td>0.071</td>
<td>0.112</td>
</tr>
<tr>
<td>AP -20°</td>
<td>0.063</td>
<td>0.285</td>
<td>0.299</td>
<td>-0.108</td>
<td>0.165</td>
<td>-0.301</td>
<td>0.016</td>
<td>0.264</td>
<td>0.414 *</td>
<td>0.052</td>
<td>0.124</td>
<td>-0.055</td>
</tr>
<tr>
<td>AD neut</td>
<td>0.061</td>
<td>0.444 *</td>
<td>0.315</td>
<td>0.157</td>
<td>0.065</td>
<td>-0.098</td>
<td>0.389</td>
<td>0.664 *</td>
<td>0.073</td>
<td>0.133</td>
<td>-0.128</td>
<td>-0.079</td>
</tr>
<tr>
<td>AD +20°</td>
<td>0.063</td>
<td>0.357</td>
<td>0.276</td>
<td>0.137</td>
<td>0.022</td>
<td>0.003</td>
<td>-0.256</td>
<td>0.295</td>
<td>0.613 *</td>
<td>-0.049</td>
<td>0.249</td>
<td>-0.232</td>
</tr>
<tr>
<td>AD -20°</td>
<td>0.116</td>
<td>0.479 *</td>
<td>0.306</td>
<td>0.141</td>
<td>0.072</td>
<td>0.000</td>
<td>-0.165</td>
<td>0.387</td>
<td>0.595 *</td>
<td>0.143</td>
<td>-0.029</td>
<td>-0.024</td>
</tr>
</tbody>
</table>
4.2.5.2 Correlations between HQR and DPR and Postural Control Variables

4.2.5.2.1 Traditional Parameters

When conducting correlation analyses between the traditional postural parameters and HQR data at knee joint angles of 90°, 60° and 30° there were no significant correlations (p > 0.05) except for between Sway Area and the HQR at 30° (r = 0.410, p = 0.042) (Table 4-8). No significant correlations were found when correlating the traditional parameters with the DPR at ankle joint angles of neutral, +20° or -20° (p > 0.05) (Table 4-8).

4.2.5.2.2 Diffusion Parameters

When conducting correlation analyses between stabilogram diffusion postural parameters and the HQR at knee joint angles of 90°, 60° and 30° there were no significant correlations observed (p > 0.05) except when correlating HQR 30° with Diff Co X (st) (r = 0.408, p = 0.043) and HQR 30° with Crit Point Coords R (r = 0.401, p = 0.047) (Table 4-9). No significant correlations were found when correlating stabilogram diffusion with the DPR at neutral, +20° or -20° joint angles (p > 0.05) (Table 4-9).

Table 4-9. Correlations between traditional postural parameters and HQR at knee joint angles of 90°, 60° and 30° and DPR at ankle joint angles of neutral (neut), +20° and -20°. Values in the table are correlation coefficients (r). *: p ≤ 0.05.

<table>
<thead>
<tr>
<th></th>
<th>Mean Dist</th>
<th>Mean Dist</th>
<th>Mean Dist</th>
<th>Mean Vel</th>
<th>Mean Vel</th>
<th>Mean Vel</th>
<th>95% CCA</th>
<th>Sway Area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MeLa</td>
<td>AnPo</td>
<td>MeLa</td>
<td>AnPo</td>
<td>MeLa</td>
<td>AnPo</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HQR 90°</td>
<td>0.198</td>
<td>-0.048</td>
<td>0.235</td>
<td>0.062</td>
<td>0.046</td>
<td>0.056</td>
<td>0.248</td>
<td>0.129</td>
</tr>
<tr>
<td>HQR 60°</td>
<td>0.296</td>
<td>0.359</td>
<td>0.197</td>
<td>0.063</td>
<td>0.148</td>
<td>-0.031</td>
<td>0.248</td>
<td>0.263</td>
</tr>
<tr>
<td>HQR 30°</td>
<td>0.347</td>
<td>0.192</td>
<td>0.323</td>
<td>0.232</td>
<td>0.357</td>
<td>0.091</td>
<td>0.303</td>
<td>0.410 *</td>
</tr>
<tr>
<td>DPR neut</td>
<td>0.161</td>
<td>0.301</td>
<td>0.084</td>
<td>-0.086</td>
<td>-0.169</td>
<td>-0.029</td>
<td>0.148</td>
<td>0.109</td>
</tr>
<tr>
<td>DPR +20°</td>
<td>0.074</td>
<td>0.291</td>
<td>-0.013</td>
<td>0.322</td>
<td>0.275</td>
<td>0.305</td>
<td>0.080</td>
<td>0.262</td>
</tr>
<tr>
<td>DPR -20°</td>
<td>0.228</td>
<td>0.350</td>
<td>0.149</td>
<td>-0.210</td>
<td>-0.176</td>
<td>-0.213</td>
<td>0.205</td>
<td>0.112</td>
</tr>
</tbody>
</table>
Table 4-10. Correlations between stabilogram diffusion parameters and HQR at knee joint angles of 90°, 60° and 30° and DPR at ankle joint angles of neutral (neut), +20° and -20°. Values in the table are correlation coefficients (r). *: p ≤ 0.05.

<table>
<thead>
<tr>
<th></th>
<th>Crit Point X</th>
<th>Crit Point Coords X</th>
<th>Diff Co X (st)</th>
<th>Diff Co X (lt)</th>
<th>Scaling Ex X (st)</th>
<th>Scaling Ex X (lt)</th>
<th>Crit Point Y</th>
<th>Crit Point Coords Y</th>
<th>Diff Co Y (st)</th>
<th>Diff Co Y (lt)</th>
<th>Scaling Ex Y (st)</th>
<th>Scaling Ex Y (lt)</th>
<th>Crit Point R</th>
<th>Crit Point Coords R</th>
<th>Diff Co R (st)</th>
<th>Diff Co R (lt)</th>
<th>Scaling Ex R (st)</th>
<th>Scaling Ex R (lt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HQR 90°</td>
<td>0.134</td>
<td>0.030</td>
<td>0.043</td>
<td>-0.022</td>
<td>0.109</td>
<td>0.013</td>
<td>0.377</td>
<td>0.092</td>
<td>-0.174</td>
<td>0.246</td>
<td>-0.121</td>
<td>0.213</td>
<td>0.373</td>
<td>0.087</td>
<td>-0.102</td>
<td>0.219</td>
<td>-0.090</td>
<td>0.225</td>
</tr>
<tr>
<td>HQR 60°</td>
<td>-0.075</td>
<td>0.301</td>
<td>0.245</td>
<td>0.301</td>
<td>-0.187</td>
<td>0.140</td>
<td>0.216</td>
<td>0.097</td>
<td>0.056</td>
<td>0.209</td>
<td>-0.120</td>
<td>0.249</td>
<td>0.049</td>
<td>0.156</td>
<td>0.137</td>
<td>0.243</td>
<td>-0.169</td>
<td>0.285</td>
</tr>
<tr>
<td>HQR 30°</td>
<td>0.023</td>
<td>0.392</td>
<td><strong>0.408</strong></td>
<td>0.065</td>
<td>-0.063</td>
<td>-0.221</td>
<td>0.254</td>
<td>0.379</td>
<td>0.328</td>
<td>0.323</td>
<td>-0.152</td>
<td>0.173</td>
<td>0.192</td>
<td><strong>0.401</strong></td>
<td>0.390</td>
<td>0.315</td>
<td>-0.152</td>
<td>0.142</td>
</tr>
<tr>
<td>DPR neut</td>
<td>0.134</td>
<td>0.073</td>
<td>-0.160</td>
<td>0.258</td>
<td>-0.222</td>
<td>0.253</td>
<td>-0.203</td>
<td>-0.073</td>
<td>0.038</td>
<td>0.002</td>
<td>-0.120</td>
<td>0.062</td>
<td>-0.086</td>
<td>-0.016</td>
<td>-0.038</td>
<td>0.049</td>
<td>-0.179</td>
<td>0.079</td>
</tr>
<tr>
<td>DPR +20°</td>
<td>0.177</td>
<td>0.343</td>
<td>0.275</td>
<td>0.223</td>
<td>-0.069</td>
<td>0.128</td>
<td>-0.291</td>
<td>0.067</td>
<td>0.225</td>
<td>-0.054</td>
<td>0.171</td>
<td>-0.372</td>
<td>-0.104</td>
<td>0.191</td>
<td>0.267</td>
<td>-0.001</td>
<td>0.137</td>
<td>-0.324</td>
</tr>
<tr>
<td>DPR -20°</td>
<td>0.072</td>
<td>0.084</td>
<td>-0.130</td>
<td>0.208</td>
<td>-0.159</td>
<td>0.259</td>
<td>-0.151</td>
<td>0.011</td>
<td>0.039</td>
<td>0.085</td>
<td>-0.228</td>
<td>0.176</td>
<td>-0.102</td>
<td>0.052</td>
<td>-0.025</td>
<td>0.112</td>
<td>-0.240</td>
<td>0.171</td>
</tr>
</tbody>
</table>

* These values are significant at the p ≤ 0.05 level.
4.3 Discussion:

There were three major findings of Study One. Firstly, it was found that although males were significantly stronger than females in all muscle groups at all of the selected joint angles, there were generally no gender differences in HQR or DPR. Furthermore it was also found that for the AP and AD muscle groups, females exhibited greater levels of coactivation than males. Secondly, both the HQR and DPR appear to be angle-dependant as there was a significant increase in HQR from knee joint angle of $90^0$ to $30^0$ and the DPR increased from ankle joint angle of $-20^0$ to $+20^0$. However, strength task coactivation was not affected by joint angle changes. The third major finding was that although there were weak to moderate positive and significant correlations between MVC and Mean Vel and Diff Co st (Y and R), there was no significant correlations found between any postural measures and the HQR and DPR.

4.3.1 Effects of Joint Angle on MVC, Coactivation & Strength Ratios

It has been well established that the tension produced during isometric muscular contractions depends heavily on the length at which that muscle is held. This relationship is commonly referred to as either the “length-tension” or “torque-angle” relationship (Alonso et al., 2009; Widmaier et al., 2004). This relationship can be partially explained in terms of the sliding filament theory. When a muscle is stretched beyond its optimal length (the length at which the myosin and actin filaments develop the greatest overlap and therefore isometric tension), the actin filaments are pulled past the myosin filaments which changes the amount of overlapping and therefore reduces the tension generation. Just as when lengthening the muscle, tension declines when muscle length is less than optimal. This can be due to a combination of factors including: 1) repulsive forces caused by $Z$ bands butting into adjacent myosin filaments, 2)
overlapping sets of the actin filaments interfering with the cross-bridges’ ability to bind and cause tension, and 3) increased lateral distance between actin and myosin filaments (Alonso et al., 2009; Widmaier et al., 2004). It must be noted, however, that the shape of the torque-angle curve is not purely the result of intrinsic muscle and tendon properties (e.g. muscle architecture, tendon and muscle elasticity, tendon moment arm length etc.) (Fukunaga, Roy, Shellock, Hodgson, & Edgerton, 1996; Kawakami, Kubo, Kanhisa, & Fukunaga, 2002; Maganaris, Baltzopoulos, & Sargeant, 1998, 1999) but is also influenced by neural parameters such as muscle activation and agonist/antagonist coactivation (Billot et al., 2011; Hahn, 2011; Mademli, Arampatzis, Morey-Klapsing, & Brüggemann, 2004; Simoneau et al., 2007b).

4.3.1.1 Ankle Dorsi- and Plantarflexors

In the current study the AP MVC torque declined linearly as the ankle was plantarflexed while there was only a significant decline in AD torque when the ankle joint was placed in a dorsiflexed position. This joint angle specificity for both the AP and AD torque production was consistent with previous investigations (Billot et al., 2011; Miyamoto & Oda, 2003; Simoneau et al., 2007b).

It was seen in the current study that the AP maximal torque declined by 28.4% from ankle joint angle of -20\(^\circ\) to neutral and a further 39.4% from neutral to +20\(^\circ\) (total decline from -20\(^\circ\) to +20\(^\circ\) was 56.6%). This torque decline is very similar to that reported by Billot et al. (2011), who found a decline in maximal AP torque from -20\(^\circ\) to +20\(^\circ\) of 60.4% within a group of young men (27.4 ± 3.0 years). In another study, Simoneau et al. (2007b) analysed the maximal AP torque in three joint angles and found the muscle group to be significantly affected by joint angle, such that maximal torque decreased as the joint angle became more plantarflexed from -20\(^\circ\) to neutral to +20\(^\circ\). This trend seems to persist even when changing knee joint angles as shown by Miyamoto & Oda (2003). In that study eight male participant (23.6 ± 1.9 years) were asked to perform maximal isometric AP contractions at ankle joint
angles from -10° to +30° (10° increments) with the knee joint fixed at either 90° or 180° (full extension). In both knee joint conditions it was found that the AP maximal torque significantly declined at each 10° increment (starting from a dorsiflexed position and working to a plantarflexed position).

The findings of the current study, in relation to AD maximal torque production, were however dissimilar to that of Billot et al. (2011) but similar to that of Simoneau et al. (2007b). In the current study it was found that AD torque significantly declined when the ankle joint was placed in a dorsiflexed position compared with either a neutral or plantarflexed position. Simoneau et al. (2007b) revealed similar findings to the current study in that there was a significant difference between joint angles with the lowest dorsiflexion torque being at -20°. However, whereas in this study there was only a significant decline in torque at -20°, in the Simoneau study there was a linear decline when going from +20° to neutral to -20°. Contrary to these results Billot et al. (2011) established that the optimal joint angle for maximal AD torque was -10°, which was shown to exhibit significantly higher torque levels when compared with -20°, neutral, +10° and +20°.

The linear decline in MVC torque in the AP of this study could not be explained by alterations in maximal agonist SEMG activity (RMS) as it was not statistically different between joint angles. This is supported by the findings of Simoneau et al. (2007b) who found that there was no change in agonist muscle activity between joint angles (20° dorsiflexed to neutral to 20° plantarflexed). It was suggested by those authors that the passive tension of the AP, when at an ankle joint angle of -20°, was quite high (6% and 9% of the total AP MVC, for young and older adults respectively) and may partially account for the higher torque levels found when the AP muscle group is stretched. This is similar to the findings of Miyamoto and Oda (2003) in which it was shown that the soleus SEMG amplitude (RMS) during maximal isometric contractions did not change significantly across all joint angles tested, even though
maximal torque did. However, in another study Billot et al. (2011) revealed that the maximal muscle activity significantly declined between all joint angles from -20° to +20° (10° changes between trials), although within that study the maximal SEMG amplitude (RMS) was normalised to the amplitude of the M-wave of the same muscle. This normalisation procedure was used to account for peripheral influences (neuromuscular propagation failure and/or changes in impedance) from the SEMG recording. Therefore it may be suggested that future studies should utilise both SEMG and normalised SEMG recordings, which may help to elucidate whether the angle dependant changes in AP torque are, in part, a result of activation changes in the contracting muscle.

Just as revealed within the AP, there were no changes in maximal SEMG amplitude (RMS) between joint angles when assessing the AD. This is similar to the findings of Billot et al. (2011) who found that although there were significant changes in AD MVC, there was no effect of joint angle for the RMS/M-wave ratio of the tibialis anterior muscle. Contrary to these two findings however, Simoneau et al. (2007b) discovered that the joint dependant changes in AD MVC were coupled with an increased tibialis anterior SEMG activity as the muscle was stretched. Due to the coupling of increased MVC with increases in muscle activation the authors concluded that, in the case of the AD torque, output may be modulated more by neural factors than mechanical factors. Because in the current study there were no muscle activity differences between joint angles, this conclusion was not tenable, therefore the torque changes in the AP and AD are most likely due to mechanical factors such as the torque-angle relationship, tendon moment arm length, or passive tension produced by stretched muscles (Fukunaga et al., 1996; Maganaris et al., 1998, 1999; Morse, Thom, Birch, & Narici, 2005; Simoneau et al., 2007b) and not due to increased neuromuscular facilitation or CNS drive.
Another factor that may play a role in the force production capacity of a muscle/muscle group is the relative activity of the antagonistic muscle/muscle group. Simultaneous activity of the agonist and antagonist muscle groups (i.e. coactivation) has been shown to occur with both static and dynamic contractions (Billot et al., 2011; Billot, Simoneau, Van Hoecke, & Martin, 2010; Mademli et al., 2004; Remaud et al., 2007; Simoneau et al., 2007b). This motor behaviour has the potential to reduce the external net torque produced at a joint and has been suggested as a possible mechanism for maximal strength differences between joint angles. However the effects of joint angle on the level of antagonist coactivation has yielded varying results and this topic needs further investigation to determine if coactivation has a significant effect on force production. In the current study there were no significant differences in coactivation level for either muscle group between joint angles. This could be seen as an indication that coactivation would not contribute to the angle dependant change in MVC of the AP or AD. This is contrary to the findings of Simoneau et al. (2007b), who found that the level of coactivation at the ankle joint during isometric plantarflexion and dorsiflexion increased between joint angles from 20° dorsiflexed, neutral (0°), to 20° plantarflexed. The difference in the level of coactivation (for both muscle groups) was observed to be higher in the plantarflexed position compared with other joint angles. This led to the suggestion that the mechanical impact of AP coactivation may have a significant effect on AD resultant torque. A potential reason for the difference in results between the current study and Simoneau et al. (2007b) is the populations used. Within the Simoneau et al. (2007b) study both young and older adults were tested, whereas only young were used in the current study. As has been shown previously ageing has many effects on the neuromuscular system including a decreased reciprocal inhibition and a concomitant increase in coactivation (Hortobagyi & Devita, 2006). Later studies investigated this possible phenomenon by estimating the antagonist torque (based on the SEMG bio-feedback method) during agonist contractions (Billot et al., 2011; Billot et al., 2010). It was shown that the estimated level of torque
produced by the AP during maximal AD assessment has a significant effect on the shape of
the MVC-angle relationship of the dorsiflexors. It is therefore suggested that further research
be conducted in relation to the mechanical contributions of the antagonist muscle during
either AP or AD to clarify the role that coactivation plays in maximal torque assessment of
the ankle joint.

4.3.1.2 Knee Extensors & Flexors

In the current study, the KE and KF MVC torques were significantly affected by joint angle.
The KE declined quite linearly as the knee joint was extended while there was only a
significant decline in KF MVC torque when the knee joint was placed in a flexed position
(90°). This joint angle specificity for both the KE and KF torque production is consistent with
previous investigations that have found that KE are strongest between 70° and 90° while the
KF are generally stronger in more extended joint angles (60° to 30°) (Alonso et al., 2009;
Babault et al., 2003; Becker & Awiszus, 2001; Savelberg & Meijer, 2004; Sosnoff et al.,
2010).

The current study revealed that the KE torque significantly declined when taking the knee
from a flexed position (90°) to an extended position (30°). This is similar to other findings
(Babault et al., 2003; Sosnoff et al., 2010) where the maximal KE torque was significantly
higher at joint angles greater than 55° compared with joint angles below 30°. Several reasons
have been suggested for the variations in maximal torque with joint angle changes. One such
suggestion is that the level of muscle activation is altered with changes in joint angle (Babault
et al., 2003). Babault et al. (2003) found that with shortened quadriceps femoris muscles (35°)
there was a higher level of activation compared with longer muscle (55° and 75°) during
isometric contractions. The authors suggested that the facilitated muscle activation may in
part compensate for the mechanical disadvantage of the shortened quadriceps. However, in
the current study there was no associated significant change in maximal SEMG amplitude
(RMS) of the KE between joint angles which suggests that intrinsic muscle factors may be the main cause of angle changes in MVC measures. Authors have attributed the increase in maximal torque production to the increase in sarcomere length up until the optimal and maximal crossbridge interaction (Becker & Awiszus, 2001). In fact, Becker & Awiszus (2001) found that changes in knee joint angle from $30^0$ to $90^0$ flexion yielded significant increases in maximal torque production between $30^0$ and $75^0$ but no significant changes were detected in voluntary activation. It was suggested by the authors that the changes in torque could be due to changes in actin-myosin overlap.

In relation to the KF maximal torque of this study, it was found that the only change in torque occurred at $90^0$ which was significantly lower than at both $60^0$ and $30^0$ joint angles. However, the decline in the SEMG (RMS) amplitude of 7.9% ($60^0$ to $90^0$) and 4.9% ($30^0$ to $90^0$) did not reach statistical significance. Thus it appears that the reduction in maximal torque at the shorter muscle length ($90^0$) may also be due to intrinsic muscle factors such as repulsive forces between thick filaments at the Z-bands, increased lateral distance between the actin and myosin filaments, or double overlapping of thin filaments (Alonso et al., 2009). The observed minimal changes in KF maximal torque are similar to that found in Savelberg & Meijer (2004), in which it was seen that during isometric contractions at knee joint angles ranging from $0^0$ to $110^0$ flexed, there were very little differences in force production. However in this study (Savelberg & Meijer, 2004) there was no assessment of muscle activation levels. It is therefore suggested that further research to be conducted to ascertain the relationship between muscle activation changes and muscle strength between joint angles.

Another factor that has been proposed to have an effect on maximal strength output is the level of antagonist coactivation. However there is limited evidence on the effects of altered knee joint angles on antagonistic activation during maximal strength tasks. In the current study it was seen that there were no differences in coactivation levels between joint angles for
either the KE or KF. This suggests that no matter what the knee joint angle is, the torque produced by antagonist muscle groups remains stable. This was similar to the findings of O’Brien et al. (2009) who found that antagonist coactivation and the estimated moment produced by antagonist coactivation did not change across joint angles. Remaud et al. (2007), on the other hand, found that for both isotonic and isokinetic contractions, hamstrings coactivation was on average 15.2% higher at 85° compared to that observed at 45°. These authors hypothesized that hamstrings coactivation would increase as hamstring muscles’ moment arm decreased. This would compensate moment arm variations during the movement and would allow hamstring muscles to develop a constant opposing torque around the joint. However, further research is required to investigate the influencing factor on coactivation mechanisms such as disynaptic reciprocal inhibition. For example this reflex pathway is said to be the main regulatory pathway for coactivation levels (Hortobagyi & Devita, 2006) and elucidation of joint angle effects on this spinal reflex pathway may help to clarify the effects of joint angle change on coactivation levels.

### 4.3.1.3 Strength Ratios

It is common to use the HQR as an indicator of knee joint muscle strength properties and for assessing knee joint functionality (Aagaard et al., 1998; Coombs & Garbutt, 2002). In the past this involved measuring the HQR during dynamic contractions (either concentric or eccentric) at differing velocities (Aagaard et al., 1998; Coombs & Garbutt, 2002; Rosene et al., 2001). To the author’s knowledge however, there have been very few investigations that have measured HQR and DPR in isometric contractions, let alone the effects of joint angle on these isometric ratios. This seems surprising, given that muscle length changes can have significant effects on the force-producing capacity of a muscle/muscle group.

Within the current study there was a significant increase in the HQR when the knee joint was extended from 90° to 60° to 30°. This linear increase in the HQR can be explained by the fact
that the KE MVC showed a significant linear decline at the more extended knee joint angles while the KF MVC remained relatively unchanged through the three joint angles. The same increase in the HQR when the knee joint was gradually extended was seen in both male and female participants. There was also a significant increase in the DPR when the ankle joint was taken from the 20° dorsiflexed position (-20°) to neutral to 20° plantarflexed (+20°). This is similar to the findings of Simoneau et al. (2007b) who found that the DPR depended on the joint angle assessed and became greater as the joint was plantarflexed. As with the HQR, this angle–dependent change in the DPR can be explained by the fact that the AP MVC significantly declined when going from the dorsiflexed to plantarflexed position, while the AD MVC remained relatively stable through the joint angles tested. These angle dependant alterations in the DPR exhibited, like the HQR, were the same joint angle effects whether considering males or females separately.

4.3.2 Effects of Gender on MVC, Coactivation & Strength Ratios

It has been reported in the literature that males produce significantly greater maximal muscle torque in most large muscle groups of the body than do females (Maughan, Watson, & Weir, 1983b; Yasuda et al., 2005). Traditionally, anatomical and physiological aspects, such as muscle cross–sectional areas differences between genders, are said to influence the strength differences between males and females (Staron et al., 2000). However, in recent years there has been an increased interest into other gender-related differences in physiological systems (Deschenes et al., 2009). One physiological area of particular interest is the differences between genders in relation to neuromuscular functioning. For example, an investigation on muscle fatigue patterns (as measured by SEMG activity) has found that fatigability is more
pronounced in men (Clark et al., 2005). This has led to the thought that there may be gender-related differences in central activation, neuromuscular junction transmission and membrane excitability (Clark et al., 2005). It is therefore pertinent to examine the potential muscle activation and coactivation differences between genders.

4.3.2.1 MVC, Muscle Activation & Coactivation

Within the current study there were significant gender differences in maximal torque of all muscle groups and all joint angles except for the AP at 20° plantarflexed. In all of the differences it was seen that males were significantly stronger than females. However there were no gender differences in any of the maximal SEMG recordings. This is similar to several studies that have found gender differences in maximal strength of the lower limb muscle groups with no difference in muscle activation (Kent-Braun & Ng, 1999; Kent-Braun, Ng, Doyle, & Towse, 2002; Russ & Kent-Braun, 2003; Yasuda et al., 2005). It has been suggested that the gender difference in maximal strength could be due to different fibre-type characteristics (Yasuda et al., 2005). In one study it was found that males had a greater percentage of type II fibre area in the vastus lateralis compared with females, and females had a higher percentage of type I fibre area compared with males (Yasuda et al., 2005). This higher percentage of type II fibres may help to explain why males had greater maximal strength due to the higher force-generating capacity of type II fibres (Yasuda et al., 2005). However, the current study did not explore fibre type distribution differences between genders and thus it may be suggested that further study in this area is required.

A novel finding of this study, however, was the gender difference in agonist/antagonist coactivation during maximal strength assessment. Females exhibited significantly higher levels of activation of both the AP and AD when acting as the antagonist. This was also found in the KE and KF but only at two joint angles it reached statistical significance. The higher antagonist activation during strength assessment in females may hinder their ability to
produce maximal torque that is comparable to males. To the author’s knowledge, there is no literature on the gender differences in coactivation and therefore it is suggested that this topic be further investigated.

4.3.2.2 *Strength Ratios*

From the comparisons for HQR and DPR between genders it was found that at 30° knee flexion, females had a significantly lower HQR than males but all other angles showed no gender difference. As there were generally no differences between genders for either the HQR or DPR, it may be suggested that the strength difference between agonist/antagonist pairs (i.e. the percentage difference between KE and KF or AP and AD) is relatively the same between genders. To the author’s knowledge there are no reports that have analysed the isometric strength ratios and the differences between genders when assessing these ratios. In the limited number of studies completed, gender differences have been found in relation to the HQR. Holm & Vollestad (2008) analysed gender differences in a group of children from 7 to 12 years of age by completing isokinetic contractions of the KE and KF at 60°/s and 240°/sec. From their results it was found that females had significantly lower strength ratios at 60°/sec in comparison to males, and the hamstring muscles in the young females were relatively weaker when compared with their quadriceps. However, comparisons between the findings of that study and the current one should be undertaken with caution. The current study used isometric contractions while the Holm and Vollestad (2008)’s study used isokinetic contractions which can have a significant effect on the strength output of a muscle group. Also in the Holm and Vollestad’s study the participants were children and their neuromuscular system was not fully developed, while in the current study the participants were mature young adults. Therefore, further analysis of the gender effects on HQR and DPR during isometric contractions is needed. This may help to clarify if females do indeed exhibit
relatively weaker hamstring muscles compared to their quadriceps which would lead to lower HQRs in females.

4.3.3 Correlations between MVC, Strength Ratio and Postural Control

When analysing the whole group it was found that out of the eight traditional and eighteen stabilogram diffusion parameters only three and six parameters respectively showed repeated correlations with maximal strength measures. These correlations however were shown to be weak to moderate in strength (r values ranged from 0.395 to 0.664) and were dependant on the muscle group analysed.

When considering the relationship between maximal strength and traditional parameters the strengths of KE and KF showed weak to moderate positive correlations with Mean Vel, Mean Vel MeLa and Mean Vel AnPo, while the stabilogram diffusion parameters of Diff Co R (st), Diff Co X (st) and Diff Co Y (st) also showed weak to moderate significant and positive correlations with the MVC of both muscle groups at all joint angles. Only the KF were positively correlated with Sway Area in traditional parameters and Crit Point Coords R, Crit Point Coords X and Crit Point Coords Y of the diffusion parameters. When considering the AP and AD it was found that the AP did not correlate with any traditional parameters and the only diffusion parameters that consistently correlated with torque measures were Diff Co R (st) and Diff Co Y (st). As for the AD, it was found that significant positive correlations existed between most maximal torque measures and traditional parameters of Mean Vel, Mean Vel AnPo and Sway Area. For the diffusion parameters there were significant positive correlations between most Crit Point Coords R, Crit Point Coords X, Diff Co R (st) and Diff Co Y (st).
The amount of force a muscle produces is a major contributor to the maintenance of posture. It appears that this musculoskeletal function, as a characteristic of postural control, is important in generating basic acceleration vectors to control posture (Lord et al., 1991a). Lower extremity muscle weakness has been identified as a risk factor contributing to falls in the older populations (Lord et al., 1991a). For example, it has been suggested that in situations of reduced ankle proprioceptive inputs, older subjects are more reliant on motor outputs such as muscular strength (Lord et al., 1991b). However, in the current study the participants were healthy young adults who should have little deterioration in sensory systems of the body that impact upon postural control. Therefore, the significant positive correlations found between the Mean Vel measures and maximal strength of the KE, KF, and AD of young adults may suggest an alteration in the postural control strategy of stronger young individuals. It may be hypothesised that within young healthy adults with intact sensory modalities muscular strength is not a limiting factor in postural control. The postural control system in this case may exhibit a certain level of “relaxation” of the postural control boundaries due to the fact that the relative strength of the lower limb muscle groups could easily accommodate for the increased velocity of postural movements. This hypothesis can be supported by the finding that the KF and AD strength was positively correlated with Sway Area. This suggests that not only were stronger individuals exhibiting greater COP velocities, they may also be experiencing increased total COP areas. This could be interpreted as further “relaxation” of the postural control system in young healthy individuals that is easily controlled by relatively strong muscles of the lower limb.

In relation to the diffusion parameters, the Diff Co (st) and the maximal torque of the KE, KF and AD showed significant positive relationships while the Crit Point Coords and KF and AD maximal torque also showed significant positive correlations. These correlations indicate that the stronger participants exhibit significantly higher levels of stochastic activity of the COP in the first section of the stabilogram diffusion and take longer to switch over from the short
term to the long term time series. This can be interpreted as further “relaxation” of the postural control system in strong healthy young adults. Traditionally muscular strength has been found to be a limiting factor in the maintenance of posture (Lord et al., 1991a). However, many of the studies that have come to this conclusion have been in relation to older individuals. For example it was found by Bezerra et al. (2009) that moderate negative correlations were found between COP mean velocity ML and maximal strength of the knee extensors and flexors within a group of individuals aged between 18 and 77. The possible reason for the difference in findings between that study and the current study is the age range of the participants. Due to these differences it is suggested that possibly maximal strength is not a limiting factor in the control of posture in healthy young adults and future studies that employ correlation analyses between postural control and maximal strength should separate age groups. This may help to clarify age related and strength related differences in postural control strategies. It should also be noted that many other potential influencing factors may have had an impact on the significant and positive correlations observed in this study. For example, within the young group the stronger participants may have also been less anxious, and thus produced a less constrained sway path. It may also be possible that the significant correlations found within the current study may have been due to the number of correlations conducted at the same time. These questions were not analysed within the current thesis and are areas for further investigations.

Within both the traditional and diffusion postural parameters there were very few significant correlations with the HQR and no correlations with the DPR. The HQR at 30° was found to have significant positive relationships with Sway Area, Diff Co X (st) and Diff Co R (st). These positive relationships are contrary to previous findings that found the HQR to be negatively correlated with postural parameters such as mean velocity and short term diffusion coefficients (Bezerra et al., 2008). The authors concluded that a higher HQR may be associated with better postural control performance, however the current study suggests that
higher HQRs are detrimental to postural control. A possible reason for the difference in findings between studies could be related to the pooling of age groups in the Bezerra et al. study. This pooling of age groups may have altered the data point and caused a “false” negative correlation. For example in the same study by Bezzera et al. (2008) it was found that the HQR of older adults was significantly lower compared with middle aged adults (due to the greater age-related decline in hamstring strength relative to the quadriceps muscle group). Couple this with the greater stochastic activity and velocities of the COP in older individuals (when compared to young) (Collins et al., 1995; Prieto et al., 1996) it may lead to the “drifting” of older adults’ data points to the bottom right of the x-y correlation plot, while the data points of the young adults may have drifted to the upper left due to their lower COP velocities and short term diffusion coefficients, and higher HQR values. Therefore the current study suggests that within healthy young adults the HQR and DPR may have little overall effect on postural control and that future studies should take care in the separation of age groups when conducting correlation analyses between maximal torque and postural control measures.
4.4 Conclusions

The results of this study indicate that although there was a significant difference in the maximal strength of the KE, KF, AP and AD between male and female participants, this did not translate to alteration in the HQR and DPR between genders. This confirms that the relative strength difference between agonist/antagonist pairs of the lower limb is not affected by gender.

The results of this study also found that coactivation was significantly higher in females, especially when considering the AP and AD. This may indicate that a potential mechanism for the strength difference between genders may be the increased antagonist coactivation during maximal strength tasks. However it needs to be elucidated what potential neuromuscular mechanisms may have contributed to this phenomenon.

The joint angle of both the knee and ankle joints also had a significant impact on the maximal torque of the KE and AP respectively. This effect of joint angle on the strength of these two muscle groups had a significant influence on the HQR and DPR. This led to the rejection of the null hypothesis in relation to lower limb muscular strength and strength ratio, as there were significant increases in these variables. It was also found that there were no alterations in coactivation of agonist/antagonist pairs due to joint angle changes. Therefore in relation to the strength task coactivation measures in hypothesis one the null hypothesis can be accepted.

From the results of this study it can be suggested that the more extended knee joint angle (i.e. 30°) would be most appropriate for assessing the relationship between the maximal strength and functional tasks such as postural control. This is because the relative strength difference between the KE and KF was found to be the least at more extended knee joint angles (i.e. higher HQR) and these joint angles are closer to those seen during functional tasks. Therefore,
future studies that investigate the functional importance of maximal strength and strength ratios should closely consider the joint angle at which maximal strength is assessed.

Finally, it was found within this study that there were weak to moderate positive relationships between the maximal strength and mainly two postural parameters (Mean Vel and Diff Co st) with a majority of postural measures showing no relationships with maximal strength measures. It was also found that there were no significant correlations between the strength ratios of the lower limb and postural control variables. Therefore the null hypothesis that no significant correlation exists between the control of posture and strength ratios is accepted. The results of this study indicate that young individuals who are stronger exhibit greater sway velocities and stochastic COP movement. This begs the question whether maximal strength per se is a major factor in the maintenance of posture or whether it would be more appropriate to assess the relative strength and its relationship with posture. Therefore future studies should investigate both the absolute strength (i.e. MVC) and relative strength (i.e. percent of MVC) of the lower limb muscle groups and their relationship with functional tasks such as postural control.
Chapter 5: Study Two
An investigation of the effects of age and gender on lower limb strength ratios, strength task coactivation, postural control and postural task coactivation

5.1 Study Outline

Aims:

1. To determine whether lower limb muscle strength and the agonist/antagonist strength ratios are affected by age and gender.
2. To determine whether the ability to control posture in altered sensory conditions is affected by age and gender.
3. To determine whether the strength task coactivation and postural task coactivation in lower limb muscles are affected by age and gender.

Null Hypotheses:

1. Ageing does not affect lower limb muscular strength, agonist/antagonist strength ratios or strength task coactivation.
2. Gender does not affect lower limb muscular strength, agonist/antagonist strength ratios or strength task coactivation.
3. Ageing does not affect the ability to control posture in altered sensory conditions (firm or compliant surface and eyes open or closed).
4. Gender does not affect the ability to control posture in altered sensory conditions (firm or compliant surface and eyes open or closed).
5. The level of coactivation during postural tasks is not affected by ageing during postural tasks with altered sensory conditions.
Design and results summary:

This study was a cross-sectional analysis of the age related changes in postural maintenance and strength ratios of the lower limb. Statistical analysis involved examination of main effects, interactions and post-hoc comparisons. If a significant effect or interaction was detected, post-hoc analyses, with Bonferroni adjustment, were conducted to detect significant differences between genders and age groups (presented below).

Comparisons between young and older age groups showed that the young adult group (YG) were generally stronger in all four muscle groups. This corresponded with generally higher muscle activations levels within the YG for the KE and KF, however within the AP and AD there were little differences between the age groups. The KE and AD of the older adult group (OG) showed higher levels of coactivation when compared with the YG. Generally the YG demonstrated greater HQR values while the OG had greater DPR levels. Postural control data showed that the OG showed significantly larger Mean Vel, Sway Area, Crit Point Coords, Diff Co st and lower Scal Ex lt. All other postural measures showed no significant differences between the two age groups.

Comparisons between genders found that males were significantly stronger than females in both young and older adults. This was not associated with maximal SEMG amplitude as there were only a few cases of males exhibiting higher muscle activation levels. Within the KE, KF and AD females nearly always showed greater levels of coactivation during maximal strength tasks. There were however, no differences between genders within either the HQR or DPR. Postural analysis showed that male participants generally had higher Mean Dist, Mean Vel, Area measures, Crit Point Coords and Diff Co st levels. All other postural measures showed no gender differences.
5.2  Results

5.2.1  Anthropometric comparisons between Groups

Independent t-tests were conducted to determine if there were significant difference in anthropometric measures of weight, height and BMI between males and females of each age group. The results of the independent t-tests analysis showed that within the YG the males were significantly taller (t = 6.65, df = 23, p < 0.001) and heavier (t = 3.59, df = 23, p = 0.002), but no difference was found in body mass index (t = 0.33, df = 23, p = 0.743). In the OG however, there were significant differences in all three measures [height (t = 5.34, df = 28, p < 0.001); weight (t = 5.63, df = 28, p < 0.001); and body mass index (t = 2.78, df = 28, p = 0.01)].

5.2.2  Maximal Voluntary Contraction Torque

The observed means and standard deviations of MVC for KE, KF (at 30°), AP and AD (at neutral) for the Young Group (YG), Older Group (OG) and Pooled Groups (PG) are presented in Table 5-1.

Table 5-1. Maximal voluntary contraction torque for KE, KF, AP and AD for young group (YG), older group (OG) and pooled groups (PG). #: indicates pooled results of male and female participants.

<table>
<thead>
<tr>
<th></th>
<th>Male</th>
<th>Female</th>
<th>Total #</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>YG</td>
<td>OG</td>
<td>PG</td>
</tr>
<tr>
<td>KE</td>
<td>98.60 (22.70)</td>
<td>62.86 (16.54)</td>
<td>78.74 (26.33)</td>
</tr>
<tr>
<td>KF</td>
<td>110.87 (34.25)</td>
<td>55.31 (27.25)</td>
<td>80.00 (41.08)</td>
</tr>
<tr>
<td>AP</td>
<td>133.05 (39.16)</td>
<td>78.01 (29.95)</td>
<td>102.47 (43.69)</td>
</tr>
<tr>
<td>AD</td>
<td>50.15 (11.57)</td>
<td>35.09 (7.85)</td>
<td>41.79 (12.16)</td>
</tr>
</tbody>
</table>

Values in the table are Mean (SD)
5.2.2.1 Knee Extensors and Flexors

A main effect of age group was found for both the KE [F = 61.50, df = (1, 51), p < 0.001] and KF [F = 44.59, df = (1, 51), p < 0.001]. Post hoc comparisons between age groups for maximal torque found that the YG was significantly stronger than the OG for both the KE and KF (Figure 5-1).

![Figure 5-1. Comparison of young and older groups' maximal voluntary contraction torque of the KE and KF when the data of males and females were pooled. *: p ≤ 0.05.](image)

When comparing strength differences between genders (gender main effect), it was found that males were significantly stronger in both KE [F = 26.82, df = (1, 51), p < 0.001] and KF [F = 18.24, df = (1, 51), p < 0.001] compared to females when age groups were pooled (Figure 5-2). These gender differences in strength were similar for KE and KF when examined separately for each age group (Table 5-1). However, there were no significant interactions (age group × gender) for either the KE [F = 0.66, df = (1, 51), p = 0.420] or KF [F = 3.83, df = (1, 51), p = 0.056].
Figure 5-2. Comparisons of genders maximal voluntary contraction torque of the KE and KF when age groups were pooled. *: $p \leq 0.05$.

5.2.2.2 Ankle Plantarflexors and Dorsiflexors

A main effect of age group was found for both the AP [$F = 28.95$, $df = (1, 51)$, $p < 0.001$] and AD [$F = 20.71$, $df = (1, 51)$, $p < 0.001$]. Post hoc comparisons between age groups for maximal torque found that the YG was significantly stronger than the OG for both the AP and AD (Figure 5-3).

Figure 5-3. Comparison of young and older groups’ maximal voluntary contraction torque of the KE and KF when the data of males and females were pooled. *: $p \leq 0.05$. 
When comparing strength differences between genders (gender main effect), it was found that males were significantly stronger in both the AP \( [F = 8.88, \text{df} = (1, 51), p = 0.004] \) and AD \( [F = 48.08, \text{df} = (1, 51), p < 0.001] \) compared to females when age groups were pooled (Figure 5-4).

![Figure 5-4. Comparisons of the maximal voluntary contraction torque of the AP and AD between male and female participants when age groups were pooled. *: p ≤ 0.05.](image)

There was no significant interaction (age group × gender) for the AP \( [F = 1.38, \text{df} = (1, 51), p = 0.245] \), however there was an interaction for the AD \( [F = 6.28, \text{df} = (1, 51), p = 0.015] \). Post hoc comparisons revealed that the ageing process caused a greater decline in maximal strength in males. This was highlighted in the young males who exhibited significantly stronger AD than older males \( [F = 24.36, \text{df} = (1, 51), p < 0.001] \), however there was no significant difference between young females and older females \( [F = 2.14, \text{df} = (1, 51), p = 0.150] \) (Figure 5-5).
Figure 5-5. Comparisons of young and older groups’ maximal voluntary contraction torque of the AD when genders were separated. Dotted line for males and solid line for females. *: p ≤ 0.05.
5.2.3 Maximal SEMG Amplitude

The observed means and standard deviations of the maximal SEMG amplitude (Root Mean Square, RMS) for KE, KF (at 30°), AP and AD (at neutral) for the Young Group (YG), Older Group (OG) and Pooled Groups (PG) are presented in Table 5-2.

Table 5-2. SEMG (RMS) amplitude during maximal voluntary contractions for KE, KF, AP and AD for young group (YG), older group (OG) and pooled groups (PG). # Indicates the data from the gender groups were pooled.

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<td>OG</td>
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<tr>
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<td>(0.073)</td>
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Values in the table are Mean (SD)

5.2.3.1 Knee Extensors and Flexors

A main effect of age group was found for both the KE [F = 5.71, df = (1, 51), p = 0.021] and KF [F = 7.31, df = (1, 51), p = 0.009]. Comparisons of the maximal SEMG (RMS) between groups found that in both the KE and KF there were significantly higher muscle activation levels in the YG compared with the OG when the data of males and females were pooled (Figure 5-6).
A main effect analysis of gender found a significant effect in both the KE \( F = 6.15, \text{df} = (1, 51), p = 0.017 \) and KF \( F = 10.96, \text{df} = (1, 51), p = 0.002 \). When comparing muscle activation differences between genders, it was found that males presented significantly higher levels of muscle activation in both the KE and KF compared to females when age groups were pooled (Figure 5-7). For both the KE \( F = 0.62, \text{df} = (1, 51), p = 0.434 \) and KF \( F = 1.41, \text{df} = (1, 51), p = 0.241 \) there were no significant interactions of age group \( \times \) gender.
5.2.3.2  Ankle Plantarflexors and Dorsiflexors

No significant main effect of age group was shown for either the AP [F = 3.53, df = (1, 51), p = 0.066] or AD [F = 1.07, df = (1, 51), p = 0.305]. Main effect analysis of gender however did reveal a significant effect for the AP [F = 9.71, df = (1, 51), p = 0.003]. Comparisons of muscle activation between genders found that males had significantly higher activation of the AP compared to females (Figure 5-8). No significant gender main effect was found for the AD [F = 2.80, df = (1, 51), p = 0.101]. There were also no significant age group × gender interactions for either the AP [F = 0.98, df = (1, 51), p = 0.326] or AD [F = 0.12, df = (1, 51), p = 0.733].

![Figure 5-8. Comparisons of the maximal SEMG (RMS) amplitude of the AP and AD between male and female participants when age groups were pooled. *: p ≤ 0.05.](image-url)
5.2.4 Strength Ratio

The observed means and standard deviations of HQR (at 30°) and DPR (at neutral) for the Young Group (YG), Older Group (OG) and Pooled Groups (PG) are presented in Table 5-3.

Table 5-3. HQR and DPR values for the young group (YG), older group (OG) and pooled groups (PG). # Indicates pooled data from male and female participants.

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<td>PG</td>
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<td>HQR (30°)</td>
<td>1.11 (0.21)</td>
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<td>0.97 (0.30)</td>
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<td>DPR (Neutral)</td>
<td>0.42 (0.15)</td>
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<td>0.47 (0.21)</td>
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Values in the table are Mean (SD)

5.2.4.1 Hamstring to Quadriceps Ratio

Age group analysis revealed a significant main effect for the HQR [F = 6.89, df = (1, 51), p = 0.011] with the YG exhibiting a significantly higher HQR compared to the OG (Figure 5-9). A main effect of gender was found to be non-significant [F = 0.98, df = (1, 51), p = 0.326] while there was also a lack of significant age group × gender interaction [F = 1.94, df = (1, 51), p = 0.169].
5.2.4.2 Dorsiflexor to Plantarflexor Ratio

Age group analysis revealed a significant main effect for the DPR \([F = 5.49, \text{df} = (1, 51), p = 0.023]\) with the YG exhibiting a significantly lower DPR compared to the OG (Figure 5-10). The main effect of gender was found to be non-significant \([F = 1.86, \text{df} = (1, 51), p = 0.178]\) while there was also a lack of significant age group \(\times\) gender interaction \([F = 0.14, \text{df} = (1, 51), p = 0.708]\).
5.2.5  Strength Task Coactivation

The observed means and standard deviations of the SEMG coactivation levels during KE, KF (at 30°), AP and AD (at neutral) for the Young Group (YG), Older Group (OG) and Pooled Groups (PG) are presented in Table 5-4.

### Table 5-4. Coactivation level (%) of antagonist muscle during maximal voluntary contractions of the KE, KF, AP and AD for the young group (YG), older group (OG) and pooled groups (PG). #: indicates combined gender groups.

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<td>21.13 (13.34)</td>
<td>36.15 (18.10)</td>
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<td>KF (%)</td>
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<td>12.27 (11.43)</td>
<td>23.06 (18.59)</td>
<td>17.46 (16.09)</td>
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<td>AP (%)</td>
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<td>12.83 (18.32)</td>
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<td>AD (%)</td>
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<td>11.97 (12.26)</td>
<td>28.77 (17.94)</td>
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Values in the table are Mean (SD)

5.2.5.1  Hamstring and Quadriceps Coactivation

Analysis of age group differences in coactivation revealed a significant main effect within both the KE [F = 11.52, df = (1, 49), p = 0.001] and KF [F = 4.35, df = (1, 49), p = 0.042]. It was shown that the OG had significantly higher antagonistic muscle activity compared with the YG when either of the muscle groups were acting as the antagonist (Figure 5-11).
When comparing antagonist muscle activation differences between genders (gender main effect analysis), it was found that females presented significantly higher coactivation level in both the KE \( [F = 15.97, \text{df} = (1, 49), p < 0.001] \) and KF \( [F = 8.51, \text{df} = (1, 49), p = 0.005] \) compared to males (Figure 5-12). Interaction analysis (age group × gender) for both the KE \( [F = 0.07, \text{df} = (1, 51), p = 0.795] \) and KF \( [F = 0.63, \text{df} = (1, 51), p = 0.432] \) was shown to be non-significant.
Main effect comparisons between age groups found no difference in the coactivation level for the AP when it acted as an antagonist [$F = 1.75, \text{df} = (1, 51), p = 0.192$]. When investigating the group differences in AD, it was shown that the OG demonstrated significantly higher antagonistic activity when compared with the YG [$F = 8.38, \text{df} = (1, 51), p = 0.006$] (Figure 5-13).

**Figure 5-13.** Comparisons of coactivation levels between the young and older groups for the AP and AD when the data of male and female participants were pooled. *: $p \leq 0.05$.

Comparisons of muscle coactivation between male and female participants (gender main effect) found that when groups were pooled there was no difference within the AP [$F = 2.96, \text{df} = (1, 51), p = 0.092$]. Comparison between genders for the AD found that females displayed significantly higher antagonistic activation compared to males [$F = 18.18, \text{df} = (1, 51), p < 0.001$] (Figure 5-14). No significant age group $\times$ gender interactions were found for either the AP [$F = 0.29, \text{df} = (1, 51), p = 0.596$] or AD [$F = 2.32, \text{df} = (1, 51), p = 0.134$].
Figure 5-14. Comparisons between males and females’ coactivation levels within AP and AD when age groups were pooled. *: p ≤ 0.05.
5.2.6 Postural Control Traditional Parameters

5.2.6.1 Mean Distance Measures

The observed means and standard deviations of the mean distance measures under the four sensory conditions for the Young Group (YG), Older Group (OG) and Pooled Groups (PG) are presented in Table 5-5.

Table 5-5. Mean distance measures (Mean Dist, Mean Dist AnPo and Mean Dist MeLa) (mm) of male, female and pooled gender groups (Total) participants COP under the four SOT conditions for the young group (YG), older group (OG) and pooled age groups (PG).

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<td>8.28</td>
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<td>4.62</td>
<td>8.15</td>
<td>6.01</td>
<td>4.27</td>
</tr>
<tr>
<td></td>
<td>(1.85)</td>
<td>(1.62)</td>
<td>(1.13)</td>
<td>(2.67)</td>
<td>(1.93)</td>
<td>(1.73)</td>
<td>(2.32)</td>
<td>(1.79)</td>
<td>(1.53)</td>
</tr>
</tbody>
</table>

Values in the table are Mean (SD)
For each of the three mean distance measures (Mean Dist, Mean Dist AnPo and Mean Dist MeLa) a two factor multivariate GLM was conducted across the four SOT conditions individually.

**Mean Dist**

The Mean Dist analysis revealed main effect of gender \([F = 4.56, df = (4, 48), p = 0.003]\) but no effect of age group \([F = 0.28, df = (4, 48), p = 0.897]\) and no significant interaction for age group \(\times\) gender \([F = 1.28, df = (4, 48), p = 0.289]\).

Comparisons between male and female participants found that the male participants had significantly higher Mean Dist in SOT 2 \([F = 8.01, df = (1, 51), p = 0.007]\), SOT 3 \([F = 5.58, df = (1, 51), p = 0.022]\) and SOT 4 \([F = 19.14, df = (1, 51), p < 0.001]\), but no difference was found in SOT 1 \([F = 3.68, df = (1, 51), p = 0.061]\) (Figure 5-15).

![Figure 5-15. Comparisons of Mean Dist between male and female participants at each of the four SOT conditions when groups were pooled. *: p ≤ 0.05.](image-url)
The Mean Dist AnPo analysis revealed main effect of gender \( [F = 3.38, \text{df} = (4, 48), p = 0.016] \) but no effect of age group \( [F = 0.74, \text{df} = (4, 48), p = 0.570] \) and no significant interaction for age group \( \times \) gender \( [F = 0.96, \text{df} = (4, 48), p = 0.436] \).

Comparisons between male and female participants found that the male participants had significantly higher Mean Dist AnPo in SOT 2 \( [F = 7.34, \text{df} = (1, 51), p = 0.009] \) and SOT 4 \( [F = 13.99, \text{df} = (1, 51), p < 0.001] \), but no differences were found in SOT 1 \( [F = 2.24, \text{df} = (1, 51), p = 0.141] \) or SOT 3 \( [F = 3.71, \text{df} = (1, 51), p = 0.060] \), (Figure 5-16).

![Figure 5-16. Comparisons of Mean Dist AnPo between male and female participants at each of the four SOT conditions when groups were pooled. *: p ≤ 0.05](image)

The Mean Dist MeLa analysis revealed main effect of gender \( [F = 3.52, \text{df} = (4, 48), p = 0.013] \) but no effect of age group \( [F = 1.31, \text{df} = (4, 48), p = 0.280] \) and no significant interaction for age group \( \times \) gender \( [F = 0.95, \text{df} = (4, 48), p = 0.443] \).

Comparisons between male and female participants found that the male participants had significantly higher Mean Dist MeLa in SOT 1 \( [F = 5.67, \text{df} = (1, 51), p = 0.021] \), SOT 3 \( [F =}
5.33, df = (1, 51), p = 0.025] and SOT 4 [F = 13.76, df = (1, 51), p = 0.001], but no difference was found in SOT 2 [F = 2.53, df = (1, 51), p = 0.118] (Figure 5-17).

Figure 5-17. Comparisons of Mean Dist MeLa between males and females at each of the four SOT conditions when groups were pooled. *: p ≤ 0.05
### 5.2.6.2 Mean Velocity Measures

The observed means and standard deviations of the mean distance measures under the four sensory conditions for the Young Group (YG), Older Group (OG) and Pooled Groups (PG) are presented in Table 5-6.

**Table 5-6. Mean velocity measures (Mean Vel, Mean Vel AnPo and Mean Vel MeLa) (mm/s) of male, female and pooled participants (total) under the four SOT conditions for the young group (YG), older group (OG), pooled age groups (PG) and pooled gender groups (Total).**

<table>
<thead>
<tr>
<th></th>
<th>YG</th>
<th>OG</th>
<th>PG</th>
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<tbody>
<tr>
<td></td>
<td>Mean Vel</td>
<td>Mean Vel</td>
<td>Mean Vel</td>
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<tr>
<td></td>
<td>Mean Vel AnPo</td>
<td>Mean Vel AnPo</td>
<td>Mean Vel AnPo</td>
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<tr>
<td></td>
<td>Mean Vel MeLa</td>
<td>Mean Vel MeLa</td>
<td>Mean Vel MeLa</td>
</tr>
<tr>
<td>SOT1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(mm/s)</td>
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<td></td>
<td></td>
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<tr>
<td>SOT1</td>
<td>11.26</td>
<td>14.52</td>
<td>13.07</td>
</tr>
<tr>
<td></td>
<td>(2.24)</td>
<td>(3.76)</td>
<td>(3.53)</td>
</tr>
<tr>
<td>SOT2</td>
<td>14.18</td>
<td>21.45</td>
<td>18.22</td>
</tr>
<tr>
<td>(mm/s)</td>
<td>(4.31)</td>
<td>(8.09)</td>
<td>(7.53)</td>
</tr>
<tr>
<td>SOT3</td>
<td>12.37</td>
<td>17.66</td>
<td>15.31</td>
</tr>
<tr>
<td>(mm/s)</td>
<td>(2.52)</td>
<td>(4.04)</td>
<td>(4.32)</td>
</tr>
<tr>
<td>SOT4</td>
<td>18.76</td>
<td>30.46</td>
<td>25.26</td>
</tr>
<tr>
<td>(mm/s)</td>
<td>(4.81)</td>
<td>(8.31)</td>
<td>(9.06)</td>
</tr>
</tbody>
</table>

|        |               |                |                |
|        | Mean Vel      | Mean Vel       | Mean Vel       |
|        | Mean Vel AnPo | Mean Vel AnPo  | Mean Vel AnPo  |
|        | Mean Vel MeLa | Mean Vel MeLa  | Mean Vel MeLa  |
| SOT1   |                |                |                |
| (mm/s) |                |                |                |
| SOT1   | 9.93           | 11.44          | 10.74          |
| (mm/s) | (1.44)         | (3.12)         | (2.56)         |
| SOT2   | 12.40          | 14.63          | 13.59          |
| (mm/s) | (2.11)         | (4.53)         | (3.72)         |
| SOT3   | 11.08          | 15.05          | 13.21          |
| (mm/s) | (1.73)         | (3.45)         | (3.40)         |
| SOT4   | 15.61          | 20.59          | 18.28          |
| (mm/s) | (2.62)         | (4.81)         | (4.63)         |

|        |               |                |                |
|        | Mean Vel      | Mean Vel       | Mean Vel       |
|        | Mean Vel AnPo | Mean Vel AnPo  | Mean Vel AnPo  |
|        | Mean Vel MeLa | Mean Vel MeLa  | Mean Vel MeLa  |
| SOT1   |                |                |                |
| (mm/s) |                |                |                |
| SOT1   | 10.57          | 12.98          | 11.88          |
| (mm/s) | (1.95)         | (3.74)         | (3.26)         |
| SOT2   | 13.25          | 18.04          | 15.86          |
| (mm/s) | (3.40)         | (7.32)         | (6.30)         |
| SOT3   | 11.70          | 16.36          | 14.24          |
| (mm/s) | (2.20)         | (3.92)         | (3.99)         |
| SOT4   | 17.12          | 25.53          | 21.71          |
| (mm/s) | (4.07)         | (8.35)         | (7.91)         |

Values in the table are Mean (SD)

For each of the three mean velocity measures (Mean Vel, Mean Vel AnPo and Mean Vel MeLa) a two factor multivariate GLM was conducted across the four SOT conditions.
Mean Vel

The Mean Vel analysis revealed main effects of gender \([F = 4.62, \text{df} = (4, 48), p = 0.003]\) and age group \([F = 12.47, \text{df} = (4, 48), p < 0.001]\) but no significant interaction for age group × gender \([F = 1.45, \text{df} = (4, 48), p = 0.233]\).

Comparisons between the age groups at each of the SOT conditions found that the OG exhibited significantly higher Mean Vel values at SOT 1 \([F = 9.55, \text{df} = (1, 51), p = 0.003]\), SOT 2 \([F = 10.73, \text{df} = (1, 51), p = 0.002]\), SOT 3 \([F = 29.85, \text{df} = (1, 51), p < 0.001]\) and SOT 4 \([F = 29.67, \text{df} = (1, 51), p < 0.001]\) (Figure 5-18).

![Figure 5-18. Comparisons of Mean Vel between YG and OG at each of the four SOT conditions when the data of male and female participants were pooled. *: p ≤ 0.05.](image)

Comparisons between male and female participants with pooled age groups found that the male participants had significantly higher Mean Vel values in SOT 1 \([F = 8.14, \text{df} = (1, 51), p = 0.006]\), SOT 2 \([F = 8.82, \text{df} = (1, 51), p = 0.005]\), SOT 3 \([F = 5.29, \text{df} = (1, 51), p = 0.026]\) and SOT 4 \([F = 18.03, \text{df} = (1, 51), p < 0.001]\) (Figure 5-19).
The Mean Vel AnPo analysis revealed main effects of gender \(F = 3.65, \text{df} = (4, 48), p = 0.011\) and age group \(F = 13.16, \text{df} = (4, 48), p < 0.001\) but no significant interaction for age group × gender \(F = 1.15, \text{df} = (4, 48), p = 0.345\).

Comparisons between age groups at each of the SOT conditions found that the OG exhibited significantly higher Mean Vel AnPo values at SOT 1 \(F = 18.13, \text{df} = (1, 51), p < 0.001\), SOT 2 \(F = 15.07, \text{df} = (1, 51), p < 0.001\), SOT 3 \(F = 39.88, \text{df} = (1, 51), p < 0.001\) and SOT 4 \(F = 34.35, \text{df} = (1, 51), p < 0.001\) (Figure 5-20).
Comparisons between male and female participants with pooled age groups found that the male participants had significantly higher Mean Vel AnPo values in SOT 1 \( [F = 6.61, \text{df} = (1, 51), p = 0.013] \), SOT 2 \( [F = 7.68, \text{df} = (1, 51), p = 0.008] \) and SOT 4 \( [F = 11.37, \text{df} = (1, 51), p = 0.001] \) but no difference was found in SOT 3 \( [F = 1.99, \text{df} = (1, 51), p = 0.165] \) (Figure 5-21).
Mean Vel MeLa

The Mean Vel MeLa analysis revealed main effects of gender \([F = 4.92, \text{df} = (4, 48), p = 0.002]\) and age group \([F = 3.56, \text{df} = (4, 48), p = 0.013]\) but no significant interaction for age group \(\times\) gender \([F = 1.63, \text{df} = (4, 48), p = 0.181]\).

Comparisons between age groups at each of the SOT conditions found that the OG exhibited significantly higher Mean Vel MeLa values at SOT 3 \([F = 5.64, \text{df} = (1, 51), p = 0.021]\) and SOT 4 \([F = 8.63, \text{df} = (1, 51), p = 0.005]\), but no differences existed at SOT 1 \([F = 0.46, \text{df} = (1, 51), p = 0.499]\) or SOT 2 \([F = 2.42, \text{df} = (1, 51), p = 0.126]\) (Figure 5-22).

![Figure 5-22.](image)

Comparisons between male and female participants with pooled age groups found that the male participants had significantly higher Mean Vel MeLa values in SOT 1; \([F = 7.04, \text{df} = (1, 51), p = 0.011]\), SOT 2; \([F = 7.26, \text{df} = (1, 51), p = 0.010]\), SOT 3; \([F = 9.64, \text{df} = (1, 51), p = 0.003]\) and SOT 4; \([F = 20.13, \text{df} = (1, 51), p < 0.001]\) (Figure 5-23).
Figure 5-23. Comparisons of Mean Vel MeLa between male and female participants at each of the four SOT conditions when age groups were pooled. *: p ≤ 0.05.
## 5.2.6.3 Area Measures

The observed means and standard deviations of the area measures 95% Confidence Circle Area (95% CCA) and Sway Area under the four sensory conditions for the Young Group (YG), Older Group (OG) and Pooled Groups (PG) are presented in Table 5-7.

### Table 5-7. 95% CCA (mm$^2$) and Sway Area (mm$^2$/s) measures under the four SOT conditions for the male, female and pooled (Total) participants in the young group (YG), older group (OG) and pooled age groups (PG).

<table>
<thead>
<tr>
<th></th>
<th>Male YG</th>
<th>Male OG</th>
<th>Male PG</th>
<th>Female YG</th>
<th>Female OG</th>
<th>Female PG</th>
<th>Total YG</th>
<th>Total OG</th>
<th>Total PG</th>
</tr>
</thead>
<tbody>
<tr>
<td>95% CCA</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>SOT1 (mm$^2$)</td>
<td>379.04 (206.34)</td>
<td>481.10 (224.24)</td>
<td>435.74 (218.54)</td>
<td>354.87 (209.19)</td>
<td>332.79 (209.19)</td>
<td>343.04 (197.88)</td>
<td>366.48 (219.53)</td>
<td>406.94 (219.53)</td>
<td>388.55 (211.57)</td>
</tr>
<tr>
<td>SOT2 (mm$^2$)</td>
<td>497.74 (283.97)</td>
<td>612.31 (258.91)</td>
<td>561.39 (271.25)</td>
<td>435.02 (133.80)</td>
<td>346.01 (127.24)</td>
<td>387.34 (135.63)</td>
<td>465.13 (216.64)</td>
<td>479.16 (241.90)</td>
<td>472.78 (228.77)</td>
</tr>
<tr>
<td>SOT3 (mm$^2$)</td>
<td>587.71 (295.81)</td>
<td>725.59 (333.72)</td>
<td>664.31 (319.16)</td>
<td>469.31 (196.59)</td>
<td>464.62 (251.31)</td>
<td>466.80 (251.64)</td>
<td>526.14 (251.15)</td>
<td>595.11 (338.14)</td>
<td>563.76 (301.06)</td>
</tr>
<tr>
<td>SOT4 (mm$^2$)</td>
<td>905.70 (454.26)</td>
<td>1275.50 (688.19)</td>
<td>1111.14 (614.32)</td>
<td>678.01 (277.60)</td>
<td>543.51 (298.31)</td>
<td>605.95 (320.92)</td>
<td>787.30 (351.72)</td>
<td>909.50 (622.19)</td>
<td>853.95 (516.38)</td>
</tr>
<tr>
<td>Sway Area</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>SOT1 (mm$^2$/s)</td>
<td>20.60 (10.02)</td>
<td>27.32 (10.25)</td>
<td>24.33 (10.52)</td>
<td>16.23 (4.82)</td>
<td>17.19 (5.91)</td>
<td>16.75 (5.35)</td>
<td>18.33 (7.91)</td>
<td>22.25 (9.70)</td>
<td>20.47 (9.07)</td>
</tr>
<tr>
<td>SOT2 (mm$^2$/s)</td>
<td>27.15 (12.50)</td>
<td>47.46 (26.32)</td>
<td>38.44 (23.34)</td>
<td>22.47 (4.64)</td>
<td>22.40 (7.02)</td>
<td>22.43 (5.93)</td>
<td>24.72 (9.39)</td>
<td>34.93 (22.82)</td>
<td>30.29 (18.58)</td>
</tr>
<tr>
<td>SOT3 (mm$^2$/s)</td>
<td>26.98 (8.21)</td>
<td>42.81 (15.42)</td>
<td>35.78 (14.86)</td>
<td>22.21 (6.40)</td>
<td>26.58 (7.65)</td>
<td>24.55 (7.31)</td>
<td>24.50 (7.57)</td>
<td>34.69 (14.53)</td>
<td>30.06 (12.85)</td>
</tr>
<tr>
<td>SOT4 (mm$^2$/s)</td>
<td>52.53 (23.67)</td>
<td>99.29 (39.58)</td>
<td>78.51 (40.51)</td>
<td>37.12 (8.62)</td>
<td>41.49 (12.08)</td>
<td>39.46 (10.66)</td>
<td>44.52 (18.86)</td>
<td>70.39 (41.12)</td>
<td>58.63 (35.14)</td>
</tr>
</tbody>
</table>

Values in the table are Mean (SD)

For each of the two area measures a two factor multivariate GLM was conducted across the four SOT conditions.
Sway Area

The Sway Area analysis revealed main effects of gender [F = 7.73, df = (4, 48), p < 0.001] and age group [F = 5.42, df = (4, 48), p = 0.001] while there was also a significant interaction for age group × gender [F = 3.00, df = (4, 48), p = 0.028].

Group comparisons at each of the SOT conditions found that the OG exhibited significantly higher sway areas in SOT 2 [F = 5.76, df = (1, 51), p = 0.020], SOT 3 [F = 13.16, df = (1, 51), p = 0.001] and SOT 4 [F = 14.63, df = (1, 51), p < 0.001], however there was no difference between groups in SOT 1 [F = 3.06, df = (1, 51), p = 0.086] (Figure 5-24).

![Figure 5-24. Comparisons of Sway Area between YG and OG at each of the four SOT conditions when the data of male and female participants were pooled. *: p ≤ 0.05.](image)

Comparisons between male and female participants with pooled age groups found that the male participants had significantly higher Sway Area measures in SOT 1 [F = 10.91, df = (1, 51), p = 0.002], SOT 2 [F = 12.43, df = (1, 51), p = 0.001], SOT 3 [F = 14.24, df = (1, 51), p < 0.001] and SOT 4 [F = 30.00, df = (1, 51), p < 0.001] (Figure 5-25).
Comparisons between age groups with the data from male and female participants analysed separately found that older males had significantly higher sway areas in SOT 1; \(F = 4.59, \text{df} = (1, 51), p = 0.037\), SOT 2 \(F = 11.34, \text{df} = (1, 51), p = 0.001\), SOT 3 \(F = 15.82, \text{df} = (1, 51), p < 0.001\) and SOT 4 \(F = 23.95, \text{df} = (1, 51), p < 0.001\). For the female participants it was seen that there were no age group difference in SOT 1; \(F = 0.10, \text{df} = (1, 51), p = 0.756\), SOT 2 \(F < 0.001, \text{df} = (1, 51), p = 0.991\), SOT 3 \(F = 1.26, \text{df} = (1, 51), p = 0.267\), or SOT 4 \(F = 219, \text{df} = (1, 51), p = 0.642\) (Figure 5-26).
Comparisons between genders, within each age group, found that the YG exhibited no significant gender difference in SOT 1 \( [F = 1.81, \text{df} = (1, 51), \text{p} = 0.184] \), SOT 2 \( [F = 0.57, \text{df} = (1, 51), \text{p} = 0.455] \), SOT 3 \( [F = 1.35, \text{df} = (1, 51), \text{p} = 0.251] \), or SOT 4 \( [F = 2.44, \text{df} = (1, 51), \text{p} = 0.125] \). The OG however, did show that males had significantly greater sway areas in SOT 1 \( [F = 11.73, \text{df} = (1, 51), \text{p} = 0.001] \), SOT 2 \( [F = 19.43, \text{df} = (1, 51), \text{p} < 0.001] \), SOT 3 \( [F = 18.72, \text{df} = (1, 51), \text{p} < 0.001] \) and SOT 4 \( [F = 41.17, \text{df} = (1, 51), \text{p} < 0.001] \) compared to females (Figure 5-27).

![Figure 5-27. Comparisons of Sway Area between male and female participants at each of the four SOT conditions when considering the OG only. *: p ≤ 0.05.](image)

95% CCA

The 95% CCA analysis revealed a main effect of gender \( [F = 4.05, \text{df} = (4, 48), \text{p} = 0.007] \) but no effect of age group \( [F = 0.40, \text{df} = (4, 48), \text{p} = 0.807] \) and no significant interaction for age group × gender \( [F = 1.23, \text{df} = (4, 48), \text{p} = 0.312] \).

Comparisons between male and female participants with pooled age groups (gender main effect analysis) found that the male participants had significantly higher 95% CCA measures in SOT 2 \( [F = 8.30, \text{df} = (1, 51), \text{p} = 0.006] \), SOT 3 \( [F = 5.91, \text{df} = (1, 51), \text{p} = 0.019] \) and SOT 4 \( [F = 16.24, \text{df} = (1, 51), \text{p} < 0.001] \), however no gender difference was found in SOT 1 \( [F = 2.32, \text{df} = (1, 51), \text{p} = 0.134] \) (Figure 5-28).
Figure 5-28. Comparisons of 95% CCA between male and female participants at each of the four SOT conditions when age groups were pooled. *: p ≤ 0.05.
5.2.7 Postural Control Diffusion Parameter

5.2.7.1 Critical Point Measures

The observed means and standard deviations of Critical Point (Crit Point) and Critical Point Coordinate (Crit Point Coord) measures under the four sensory conditions for the Young Group (YG), Older Group (OG) and Pooled Groups (PG) are presented in Tables 5-8 and 5-9.

Table 5-8. Critical Point measures (Crit Point R, Crit Point Y and Crit Point X) (s) of male, female and pooled (Total) participants’ data under the four SOT conditions for the young group (YG), older group (OG) and pooled age groups (PG).

<table>
<thead>
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<th>YG</th>
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<th>OYG</th>
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<td>(s)</td>
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<td>(0.18)</td>
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<td>(0.38)</td>
<td>(0.46)</td>
<td>(0.44)</td>
<td></td>
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Values in the table are Mean (SD)
Table 5-9. Critical Point Coordinate measures (Crit Point Coord R, Crit Point Coord Y and Crit Point Coord X) (mm$^2$) of male, female and pooled (Total) participants’ data under the four SOT conditions for the young group (YG), older group (OG) and pooled age groups (PG).

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<td>Crit Point Coord X</td>
<td>Crit Point Coord R</td>
<td>Crit Point Coord Y</td>
<td>Crit Point Coord X</td>
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<td>23.60 (9.63)</td>
<td>11.29 (4.17)</td>
<td>48.13 (20.02)</td>
<td>30.72 (14.72)</td>
<td>17.24 (10.22)</td>
<td>42.25 (18.29)</td>
<td>27.56 (13.00)</td>
<td>14.59 (8.53)</td>
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<tr>
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<td>52.93 (19.28)</td>
<td>37.05 (13.62)</td>
<td>16.51 (9.04)</td>
<td>78.39 (39.91)</td>
<td>50.30 (22.73)</td>
<td>26.80 (22.80)</td>
<td>67.08 (34.37)</td>
<td>44.41 (20.04)</td>
<td>22.23 (18.48)</td>
</tr>
<tr>
<td>SOT3</td>
<td>53.72 (24.59)</td>
<td>39.71 (15.15)</td>
<td>18.74 (7.74)</td>
<td>91.60 (62.04)</td>
<td>63.20 (36.98)</td>
<td>31.84 (27.27)</td>
<td>74.76 (51.93)</td>
<td>52.76 (31.22)</td>
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<td>44.55 (19.93)</td>
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<td>162.78 (93.97)</td>
<td>100.98 (53.44)</td>
<td>73.06 (58.38)</td>
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</table>

Values in the table are Mean (SD)

For each of the three Crit Point measures (Crit Point R, Crit Point Y and Crit Point X) a two factor multivariate GLM was conducted across the four SOT conditions. This was repeated for the three Crit Point Coord measures (Crit Point Coord R, Crit Point Coord Y and Crit Point Coord X).
**Crit Point R**

The Crit Point R analysis revealed main effect of age group \([F = 4.06, \text{df} = (4, 48), p = 0.006]\) but no effect of gender \([F = 1.18, \text{df} = (4, 48), p = 0.332]\) and no significant interaction for age group \(\times\) gender \([F = 0.61, \text{df} = (4, 48), p = 0.659]\).

Comparisons between the YG and OG found no differences in any of the SOT conditions except for SOT 4 with the YG exhibiting greater critical time intervals compared to the OG (Table 5-10).

**Table 5-10.** F statistics, degrees of freedom (df) and significance level for the age group comparisons of Crit Point R measures at each of the four SOT conditions. *: \(p \leq 0.05\).

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<th>SOT4</th>
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</table>

**Crit Point Y**

The Crit Point Y analysis revealed no main effect of either gender \([F = 1.50, \text{df} = (4, 48), p = 0.216]\) or age group \([F = 1.33, \text{df} = (4, 48), p = 0.273]\) and no significant interaction for age group \(\times\) gender \([F = 0.50, \text{df} = (4, 48), p = 0.740]\).

**Crit Point X**

The Crit Point X analysis revealed no main effect of either gender \([F = 0.59, \text{df} = (4, 48), p = 0.674]\) or age group \([F = 1.81, \text{df} = (4, 48), p = 0.143]\) and no significant interaction for age group \(\times\) gender \([F = 0.26, \text{df} = (4, 48), p = 0.900]\).
**Crit Point Coord R**

The Crit Point Coord R analysis revealed main effect of gender \([F = 6.33, \text{df} = (4, 48), p < 0.001]\) but no effect of age group \([F = 1.89, \text{df} = (4, 48), p = 0.127]\) and no significant interaction for age group \(\times\) gender \([F = 1.71, \text{df} = (4, 48), p = 0.163]\).

Comparisons between male and female participants with pooled age groups found that the male participants had significantly larger mean square displacements in SOT 1 \([F = 12.96, \text{df} = (1, 51), p = 0.001]\), SOT 2 \([F = 15.27, \text{df} = (1, 51), p < 0.001]\), SOT 3 \([F = 5.39, \text{df} = (1, 51), p = 0.024]\) and SOT 4 \([F = 21.68, \text{df} = (1, 51), p < 0.001]\) (Figure 5-29).

![Figure 5-29. Comparisons of Crit Point Coord R between males and females at each of the four SOT conditions when age groups were pooled. *: p ≤ 0.05.](image)

**Crit Point Coord Y**

The Crit Point Coord Y analysis revealed main effect of gender \([F = 5.47, \text{df} = (4, 48), p = 0.001]\) but no effect of age group \([F = 1.94, \text{df} = (4, 48), p = 0.120]\) and no significant interaction for age group \(\times\) gender \([F = 1.72, \text{df} = (4, 48), p = 0.161]\).

Comparisons between male and female participants with pooled age groups (gender main effect) found that the male participants had significantly higher mean square displacements in
SOT 1 \[F = 5.97, \text{ df} = (1, 51), p = 0.018\], SOT 2 \[F = 11.65, \text{ df} = (1, 51), p = 0.001\], SOT 3 \[F = 8.21, \text{ df} = (1, 51), p = 0.006\] and SOT 4 \[F = 21.69, \text{ df} = (1, 51), p < 0.001\] (Figure 5-30).

Figure 5-30. Comparisons of Crit Point Coord Y between males and females at each of the four SOT conditions when age groups were pooled. *: \(p \leq 0.05\).

**Crit Point Coord X**

The Crit Point Coord X analysis revealed main effect of gender \[F = 4.86, \text{ df} = (4, 48), p = 0.002\] but no effect of age group \[F = 1.70, \text{ df} = (4, 48), p = 0.165\] and no significant interaction for age group \(\times\) gender \[F = 1.82, \text{ df} = (4, 48), p = 0.140\].

Comparisons between male and female participants with pooled age groups found that the male participants had significantly higher mean square displacements in SOT 1 \(F = 14.60, \text{ df} = (1, 51), p < 0.001\], SOT 2 \(F = 6.74, \text{ df} = (1, 51), p = 0.012\] and SOT 4 \(F = 12.59, \text{ df} = (1, 51), p = 0.001\], but no difference was seen in SOT 3 \(F = 3.78, \text{ df} = (1, 51), p = 0.057\] (Figure 5-31).
Figure 5-31. Comparisons of Crit Point Coord X between males and females at each of the four SOT conditions when age groups were pooled. *: p ≤ 0.05.
5.2.7.2   Diffusion Coefficient Measures

The observed means and standard deviations of Diffusion Coefficient short term (Diff Co st) and Diffusion Coefficient long term (Diff Co lt) measures under the four sensory conditions for the Young Group (YG), Older Group (OG) and Pooled Groups (PG) are presented in Tables 5-11 and 5-12.

Table 5-11. Diffusion Coefficient short term measures (Diff Co st R, Diff Co st Y and Diff Co st X) (mm$^2$/s) of male, female and pooled (Total) participants under the four SOT conditions for the young group (YG), older group (OG) and pooled age groups (PG).

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<td>(7.66)</td>
<td>(5.23)</td>
<td>(3.10)</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>52.67</td>
<td>36.22</td>
<td>16.57</td>
<td></td>
<td></td>
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<tr>
<td>(mm$^2$/s)</td>
<td>(22.42)</td>
<td>(14.58)</td>
<td>(9.67)</td>
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<tr>
<td></td>
<td>Mean (SD)</td>
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Values in the table are Mean (SD)
Table 5-12. Diffusion Coefficient long term measures (Diff Co lt R, Diff Co lt Y and Diff Co lt X) (mm²/s) of male, female and pooled (Total) participants COP under the four SOT conditions for the young group (YG), older group (OG) and pooled age (PG) groups.

<table>
<thead>
<tr>
<th></th>
<th>YG</th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>Diff Co lt R</td>
<td>Diff Co lt Y</td>
<td>Diff Co lt X</td>
<td></td>
</tr>
<tr>
<td>SOT1</td>
<td>3.56</td>
<td>2.76</td>
<td>0.73</td>
<td>4.41</td>
</tr>
<tr>
<td>(mm²/s)</td>
<td>(3.31)</td>
<td>(3.06)</td>
<td>(0.64)</td>
<td>(3.46)</td>
</tr>
<tr>
<td>SOT2</td>
<td>3.64</td>
<td>3.13</td>
<td>0.48</td>
<td>3.50</td>
</tr>
<tr>
<td>(mm²/s)</td>
<td>(3.66)</td>
<td>(3.46)</td>
<td>(0.48)</td>
<td>(2.10)</td>
</tr>
<tr>
<td>SOT3</td>
<td>5.77</td>
<td>4.54</td>
<td>1.15</td>
<td>4.53</td>
</tr>
<tr>
<td>(mm²/s)</td>
<td>(3.98)</td>
<td>(3.99)</td>
<td>(0.52)</td>
<td>(3.86)</td>
</tr>
<tr>
<td>SOT4</td>
<td>6.87</td>
<td>5.16</td>
<td>1.78</td>
<td>5.27</td>
</tr>
<tr>
<td>(mm²/s)</td>
<td>(4.87)</td>
<td>(4.39)</td>
<td>(2.63)</td>
<td>(8.57)</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th></th>
<th>O G</th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Diff Co lt R</td>
<td>Diff Co lt Y</td>
<td>Diff Co lt X</td>
<td></td>
</tr>
<tr>
<td>SOT1</td>
<td>3.88</td>
<td>3.23</td>
<td>0.64</td>
<td>3.08</td>
</tr>
<tr>
<td>(mm²/s)</td>
<td>(2.69)</td>
<td>(2.57)</td>
<td>(0.58)</td>
<td>(2.32)</td>
</tr>
<tr>
<td>SOT2</td>
<td>3.46</td>
<td>2.64</td>
<td>0.85</td>
<td>2.89</td>
</tr>
<tr>
<td>(mm²/s)</td>
<td>(1.99)</td>
<td>(2.03)</td>
<td>(0.73)</td>
<td>(2.01)</td>
</tr>
<tr>
<td>SOT3</td>
<td>5.51</td>
<td>4.22</td>
<td>1.25</td>
<td>4.12</td>
</tr>
<tr>
<td>(mm²/s)</td>
<td>(3.27)</td>
<td>(2.30)</td>
<td>(1.26)</td>
<td>(4.18)</td>
</tr>
<tr>
<td>SOT4</td>
<td>4.11</td>
<td>3.05</td>
<td>1.02</td>
<td>2.55</td>
</tr>
<tr>
<td>(mm²/s)</td>
<td>(2.35)</td>
<td>(2.41)</td>
<td>(0.63)</td>
<td>(1.91)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>P G</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Diff Co lt R</td>
<td>Diff Co lt Y</td>
<td>Diff Co lt X</td>
<td></td>
</tr>
<tr>
<td>SOT1</td>
<td>3.73</td>
<td>3.00</td>
<td>0.68</td>
<td>3.75</td>
</tr>
<tr>
<td>(mm²/s)</td>
<td>(2.94)</td>
<td>(2.77)</td>
<td>(0.60)</td>
<td>(2.97)</td>
</tr>
<tr>
<td>SOT2</td>
<td>3.55</td>
<td>2.88</td>
<td>0.67</td>
<td>3.20</td>
</tr>
<tr>
<td>(mm²/s)</td>
<td>(2.85)</td>
<td>(2.76)</td>
<td>(0.64)</td>
<td>(2.05)</td>
</tr>
<tr>
<td>SOT3</td>
<td>5.64</td>
<td>4.37</td>
<td>1.20</td>
<td>4.33</td>
</tr>
<tr>
<td>(mm²/s)</td>
<td>(3.55)</td>
<td>(3.15)</td>
<td>(0.96)</td>
<td>(3.96)</td>
</tr>
<tr>
<td>SOT4</td>
<td>5.43</td>
<td>4.07</td>
<td>1.38</td>
<td>3.91</td>
</tr>
<tr>
<td>(mm²/s)</td>
<td>(3.95)</td>
<td>(3.59)</td>
<td>(1.87)</td>
<td>(6.25)</td>
</tr>
</tbody>
</table>

Values in the table are Mean (SD)

For each of the three Diff Co st measures (Diff Co st R, Diff Co st Y and Diff Co st X) a two factor multivariate GLM was conducted across the four SOT conditions. This was repeated for the three Diff Co lt measures (Diff Co lt R, Diff Co lt Y and Diff Co lt X).
**Diff Co lt R**

The Diff Co lt R analysis revealed no main effect of either gender \([F = 0.99, \text{df} = (4, 48), p = 0.424]\) or age group \([F = 0.63, \text{df} = (4, 48), p = 0.645]\) and also no significant interaction for age group \(\times\) gender \([F = 0.29, \text{df} = (4, 48), p = 0.884]\).

**Diff Co lt Y**

The Diff Co lt Y analysis revealed no main effect of gender \([F = 1.17, \text{df} = (4, 48), p = 0.338]\) or age group \([F = 0.77, \text{df} = (4, 48), p = 0.548]\) and also no significant interaction for age group \(\times\) gender \([F = 0.35, \text{df} = (4, 48), p = 0.842]\).

**Diff Co lt X**

The Diff Co lt X analysis revealed no main effect of gender \([F = 1.45, \text{df} = (4, 48), p = 0.232]\) or age group \([F = 1.14, \text{df} = (4, 48), p = 0.351]\) and no significant interaction for age group \(\times\) gender \([F = 0.53, \text{df} = (4, 48), p = 0.717]\).

**Diff Co st R**

The Diff Co st R analysis revealed main effect of gender \([F = 7.94, \text{df} = (4, 48), p < 0.001]\) and age group \([F = 4.63, \text{df} = (4, 48), p = 0.003]\) but no significant interaction for age group \(\times\) gender \([F = 2.15, \text{df} = (4, 48), p = 0.089]\).
Comparisons between the YG and OG found no significant group differences in SOT 1 [F = 2.80, df = (1, 51), p = 0.100] or SOT 2 [F = 2.83, df = (1, 51), p = 0.099]. However, in SOT 3 [F = 8.97, df = (1, 51), p = 0.004] and SOT 4 [F = 14.15, df = (1, 51), p < 0.001] the OG showed significantly higher mean square displacements per second compared with the YG (Figure 5-32).

Figure 5-32. Comparison of Diff Co st R between YG and OG at each of the four SOT conditions when the data of males and females were pooled. *: p ≤ 0.05.

Comparisons between male and female participants with pooled age groups found that the male participants had significantly higher mean square displacements in SOT 1 [F = 13.70, df = (1, 51), p = 0.001], SOT 2 [F = 10.49, df = (1, 51), p = 0.002], SOT 3 [F = 8.33, df = (1, 51), p = 0.006] and SOT 4 [F = 25.90, df = (1, 51), p < 0.001] (Figure 5-33).
Figure 5-33. Comparisons of Diff Co st R between males and females at each of the four SOT conditions when age groups were pooled. *: p ≤ 0.05.

Diff Co st Y

The Diff Co st Y analysis revealed main effect of gender [F = 5.17, df = (4, 48), p = 0.002] and age group [F = 3.80, df = (4, 48), p = 0.009] but no significant interaction for age group × gender [F = 1.52, df = (4, 48), p = 0.210].

Comparisons between the YG and OG found no group differences in SOT 2 [F = 3.36, df = (1,51), p = 0.073], however in SOT 1 [F = 5.04, df = (1,51), p = 0.029], SOT 3 [F = 10.45, df = (1,51), p = 0.002] and SOT 4. [F = 10.84, df = (1,51), p = 0.002] the OG exhibited significantly higher averaged Diff Co per second when compared with the YG (Figure 5-34).
Comparisons between male and female participants with pooled age groups found that the male participants had significantly higher mean square displacements in SOT 1 \([F = 12.52, \text{df} = (1, 51), p = 0.001]\), SOT 2 \([F = 11.29, \text{df} = (1, 51), p = 0.001]\), SOT 3 \([F = 5.37, \text{df} = (1, 51), p = 0.025]\) and SOT 4 \([F = 15.78, \text{df} = (1, 51), p < 0.001]\) (Figure 5-35).
**Diff Co st X**

The Diff Co st X analysis revealed main effect of gender \( [F = 6.33, \text{df} = (4, 48), p < 0.001] \) but no effect of age group \( [F = 2.33, \text{df} = (4, 48), p = 0.070] \) and no significant interaction for age group \( \times \) gender \( [F = 2.29, \text{df} = (4, 48), p = 0.073] \).

Comparisons between male and female participants with pooled groups found that the male participants had significantly higher Diff Co st X in SOT 1 \( [F = 9.40, \text{df} = (1, 51), p = 0.003] \), SOT 2 \( [F = 5.92, \text{df} = (1, 51), p = 0.019] \), SOT 3 \( [F = 8.80, \text{df} = (1, 51), p = 0.005] \) and SOT 4 \( [F = 18.51, \text{df} = (1, 51), p < 0.001] \) (Figure 5-36).

![Figure 5-36. Comparisons of Diff Co st X between males and females at each of the four SOT conditions when age groups were pooled. *: p ≤ 0.05.](image-url)
5.2.7.3 **Scaling Exponent Measures**

The observed means and standard deviations of Scaling Exponent short term (Scal Ex st) and Scaling Exponent long term (Scal Ex lt) measures under the four sensory conditions for the Young Group (YG), Older Group (OG) and Pooled Groups (PG) are presented in Tables 5-13 and 5-14.

**Table 5-13.** Scaling Exponent short term measures (Scal Ex st R, Scal Ex st Y and Scal Ex st X) of male, female and pooled (Total) participants under the four SOT conditions for the young group (YG), older group (OG) and pooled age (PG) groups.

<table>
<thead>
<tr>
<th></th>
<th>YG Scal Ex st R</th>
<th>YG Scal Ex st Y</th>
<th>YG Scal Ex st X</th>
<th>OG Scal Ex st R</th>
<th>OG Scal Ex st Y</th>
<th>OG Scal Ex st X</th>
<th>PG Scal Ex st R</th>
<th>PG Scal Ex st Y</th>
<th>PG Scal Ex st X</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Male</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT1</td>
<td>0.84 (0.04)</td>
<td>0.83 (0.06)</td>
<td>0.88 (0.03)</td>
<td>0.82 (0.05)</td>
<td>0.81 (0.06)</td>
<td>0.85 (0.04)</td>
<td>0.83 (0.05)</td>
<td>0.82 (0.06)</td>
<td>0.86 (0.04)</td>
</tr>
<tr>
<td>SOT2</td>
<td>0.85 (0.06)</td>
<td>0.84 (0.07)</td>
<td>0.88 (0.03)</td>
<td>0.85 (0.05)</td>
<td>0.85 (0.06)</td>
<td>0.85 (0.04)</td>
<td>0.85 (0.05)</td>
<td>0.84 (0.06)</td>
<td>0.86 (0.05)</td>
</tr>
<tr>
<td>SOT3</td>
<td>0.80 (0.04)</td>
<td>0.80 (0.06)</td>
<td>0.83 (0.06)</td>
<td>0.82 (0.04)</td>
<td>0.81 (0.06)</td>
<td>0.84 (0.04)</td>
<td>0.82 (0.04)</td>
<td>0.81 (0.06)</td>
<td>0.84 (0.05)</td>
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<tr>
<td>SOT4</td>
<td>0.85 (0.05)</td>
<td>0.85 (0.06)</td>
<td>0.86 (0.03)</td>
<td>0.85 (0.04)</td>
<td>0.86 (0.06)</td>
<td>0.85 (0.04)</td>
<td>0.85 (0.05)</td>
<td>0.85 (0.05)</td>
<td>0.85 (0.05)</td>
</tr>
<tr>
<td><strong>Female</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT1</td>
<td>0.81 (0.06)</td>
<td>0.79 (0.07)</td>
<td>0.87 (0.06)</td>
<td>0.83 (0.04)</td>
<td>0.82 (0.05)</td>
<td>0.84 (0.04)</td>
<td>0.82 (0.05)</td>
<td>0.81 (0.06)</td>
<td>0.85 (0.06)</td>
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<tr>
<td>SOT2</td>
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<td>0.85 (0.04)</td>
<td>0.86 (0.06)</td>
<td>0.83 (0.06)</td>
<td>0.84 (0.06)</td>
<td>0.83 (0.06)</td>
<td>0.84 (0.06)</td>
<td>0.84 (0.06)</td>
<td>0.84 (0.06)</td>
</tr>
<tr>
<td>SOT3</td>
<td>0.80 (0.04)</td>
<td>0.79 (0.04)</td>
<td>0.83 (0.05)</td>
<td>0.83 (0.05)</td>
<td>0.83 (0.05)</td>
<td>0.84 (0.05)</td>
<td>0.82 (0.05)</td>
<td>0.81 (0.06)</td>
<td>0.84 (0.05)</td>
</tr>
<tr>
<td>SOT4</td>
<td>0.84 (0.04)</td>
<td>0.85 (0.04)</td>
<td>0.85 (0.03)</td>
<td>0.86 (0.05)</td>
<td>0.87 (0.05)</td>
<td>0.84 (0.05)</td>
<td>0.85 (0.05)</td>
<td>0.86 (0.05)</td>
<td>0.84 (0.05)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>SOT1</td>
<td>0.83 (0.05)</td>
<td>0.81 (0.06)</td>
<td>0.87 (0.05)</td>
<td>0.82 (0.05)</td>
<td>0.81 (0.06)</td>
<td>0.85 (0.05)</td>
<td>0.82 (0.05)</td>
<td>0.81 (0.06)</td>
<td>0.86 (0.05)</td>
</tr>
<tr>
<td>SOT2</td>
<td>0.84 (0.05)</td>
<td>0.84 (0.05)</td>
<td>0.87 (0.05)</td>
<td>0.84 (0.05)</td>
<td>0.84 (0.05)</td>
<td>0.84 (0.05)</td>
<td>0.84 (0.05)</td>
<td>0.84 (0.05)</td>
<td>0.85 (0.05)</td>
</tr>
<tr>
<td>SOT3</td>
<td>0.81 (0.05)</td>
<td>0.80 (0.05)</td>
<td>0.83 (0.05)</td>
<td>0.83 (0.05)</td>
<td>0.82 (0.05)</td>
<td>0.85 (0.05)</td>
<td>0.82 (0.05)</td>
<td>0.81 (0.06)</td>
<td>0.84 (0.05)</td>
</tr>
<tr>
<td>SOT4</td>
<td>0.84 (0.05)</td>
<td>0.85 (0.05)</td>
<td>0.85 (0.03)</td>
<td>0.86 (0.05)</td>
<td>0.86 (0.05)</td>
<td>0.84 (0.05)</td>
<td>0.85 (0.05)</td>
<td>0.85 (0.05)</td>
<td>0.85 (0.05)</td>
</tr>
</tbody>
</table>

Values in the table are Mean (SD)
Table 5-14. Scaling Exponent long term measures (Scal Ex lt R, Scal Ex lt Y and Scal Ex lt X) of male, female and pooled (Total) participants under the four SOT conditions for the young group (YG), older group (OG) and pooled age (PG) groups (Total).

<table>
<thead>
<tr>
<th></th>
<th>YG</th>
<th>OG</th>
<th>PG</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Scal Ex lt R</td>
<td>Scal Ex lt Y</td>
<td>Scal Ex lt X</td>
</tr>
<tr>
<td>SOT1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>Female</td>
<td>Total</td>
</tr>
<tr>
<td></td>
<td>0.20 (0.10)</td>
<td>0.19 (0.14)</td>
<td>0.16 (0.08)</td>
</tr>
<tr>
<td>SOT2</td>
<td>0.16 (0.12)</td>
<td>0.17 (0.13)</td>
<td>0.10 (0.08)</td>
</tr>
<tr>
<td>SOT3</td>
<td>0.26 (0.08)</td>
<td>0.27 (0.10)</td>
<td>0.20 (0.07)</td>
</tr>
<tr>
<td>SOT4</td>
<td>0.17 (0.09)</td>
<td>0.19 (0.11)</td>
<td>0.13 (0.11)</td>
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<tr>
<td></td>
<td>Female</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT1</td>
<td>0.27 (0.11)</td>
<td>0.29 (0.13)</td>
<td>0.18 (0.09)</td>
</tr>
<tr>
<td>SOT2</td>
<td>0.19 (0.06)</td>
<td>0.18 (0.10)</td>
<td>0.19 (0.10)</td>
</tr>
<tr>
<td>SOT3</td>
<td>0.28 (0.12)</td>
<td>0.30 (0.10)</td>
<td>0.21 (0.14)</td>
</tr>
<tr>
<td>SOT4</td>
<td>0.14 (0.07)</td>
<td>0.16 (0.10)</td>
<td>0.13 (0.06)</td>
</tr>
</tbody>
</table>

Values in the table are Mean (SD)

For each of the three Scal Ex lt st measures (Scal Ex lt st R, Scal Ex lt st Y and Scal Ex lt st X) a two factor multivariate GLM was conducted across the four SOT conditions. This was repeated for the three Scal Ex lt It measures (Scal Ex lt It R, Scal Ex lt It Y and Scal Ex lt It X).
Scaling Ex lt R

The Scal Ex lt R analysis revealed main effect of age group \( [F = 4.13, \text{df} = (4, 48), p = 0.006] \) but no effect of gender \( [F = 1.45, \text{df} = (4, 48), p = 0.234] \) and no significant interaction for age group \( \times \) gender \( [F = 0.52, \text{df} = (4, 48), p = 0.723] \).

Comparisons between the YG and OG found no group differences in SOT 1 \( [F = 0.01, \text{df} = (1, 51), p = 0.943] \) or SOT 2 \( [F = 0.31, \text{df} = (1, 51), p = 0.578] \). However in SOT 3 \( [F = 10.24, \text{df} = (1, 51), p = 0.002] \) and SOT 4 \( [F = 6.93, \text{df} = (1, 51), p = 0.011] \) the OG showed significantly lower scaling exponents compared with the YG (Figure 5-37).

![Figure 5-37. Comparisons of Scal Ex lt R between YG and OG at each of the four SOT conditions when the data of males and females were pooled. *: p ≤ 0.05.](image)

Scaling Ex lt Y

The Scal Ex lt Y analysis revealed main effect of age group \( [F = 4.68, \text{df} = (4, 48), p = 0.003] \) but no effect of gender \( [F = 1.03, \text{df} = (4, 48), p = 0.401] \) and no significant interaction for age group \( \times \) gender \( [F = 0.81, \text{df} = (4, 48), p = 0.524] \).

Comparisons between the YG and OG found no age group differences in SOT 1 \( [F = 0.04, \text{df} = (1, 51), p = 0.847] \) or SOT 2 \( [F = 0.27, \text{df} = (1, 51), p = 0.609] \). However in SOT 3 \( [F = \)
11.97, df = (1, 51), p = 0.001] and SOT 4 [F = 6.28, df = (1, 51), p = 0.015] the OG showed significantly lower scaling exponents compared with the YG (Figure 5-38).

![Figure 5-38. Comparisons of Scal Ex lt Y between YG and OG at each of the four SOT conditions when the data of males and females were pooled. *: p ≤ 0.05.](image)

**Scaling Ex lt X**

Finally the Scal Ex lt X analysis revealed main effect of gender [F = 2.59, df = (4, 48), p = 0.048] but no effect of age group [F = 1.29, df = (4, 48), p = 0.289] and no significant interaction for age group × gender [F = 0.67, df = (4, 48), p = 0.620]. Comparisons between males and females found no differences in SOT 1 [F = 0.46, df = (1, 51), p = 0.501], SOT 3 [F = 0.05, df = (1, 51), p = 0.801], or SOT 4 [F = 2.88, df = (1, 51), p = 0.096]. However in SOT 2 it was found that females had a significantly higher Scal Ex lt X when compared to males [F = 6.31, df = (1, 51), p = 0.015].
**Scaling Ex st R**

The Scal Ex st R analysis revealed no main effect of either gender \(F = 0.29, \text{df} = (4, 48), p = 0.882\) or age group \(F = 1.25, \text{df} = (4, 48), p = 0.303\) and also no significant interaction for age group × gender \(F = 1.00, \text{df} = (4, 48), p = 0.417\).

**Scaling Ex st Y**

The Scal Ex st Y analysis revealed no main effect of either gender \(F = 0.22, \text{df} = (4, 48), p = 0.929\) or age group \(F = 0.71, \text{df} = (4, 48), p = 0.590\) and also no significant interaction for age group × gender \(F = 1.22, \text{df} = (4, 48), p = 0.317\).

**Scaling Ex st X**

Finally the Diff Co st X analysis revealed main effect of age group \(F = 3.59, \text{df} = (4, 48), p = 0.012\) but no effect of gender \(F = 0.92, \text{df} = (4, 48), p = 0.460\) and no significant interaction for age group × gender \(F = 0.12, \text{df} = (4, 48), p = 0.974\).

Comparisons between the YG and OG found no age group differences in SOT 1 \(F = 3.87, \text{df} = (1, 51), p = 0.055\), SOT 3 \(F = 0.97, \text{df} = (1, 51), p = 0.330\), or SOT 4 \(F = 0.38, \text{df} = (1, 51), p = 0.540\). However in SOT 2 \(F = 6.22, \text{df} = (1, 51), p = 0.016\) the OG showed significantly lower scaling exponents compared with the YG.
5.2.8  Postural Control Coactivation

The observed means and standard deviations of KF/KE and AD/AP coactivation measures during the four sensory conditions for the Young Group (YG), Older Group (OG) and Pooled Age Groups (PG) are presented in Table 5-15.

Table 5-15. KF/KE and AD/AP Coactivation measures during the four SOT conditions for the young group (YG), older group (OG) and pooled groups (PG) in male, female and pooled (Total) participants.

<table>
<thead>
<tr>
<th></th>
<th>Male</th>
<th>Female</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>YG</td>
<td>OG</td>
<td>PG</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>KF/KE Coactivation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT1</td>
<td>5.02 (12.21)</td>
<td>0.65 (8.92)</td>
<td>2.93 (8.92)</td>
</tr>
<tr>
<td>SOT2</td>
<td>5.66 (13.41)</td>
<td>0.79 (9.82)</td>
<td>3.33 (9.82)</td>
</tr>
<tr>
<td>SOT3</td>
<td>2.02 (2.07)</td>
<td>1.32 (1.73)</td>
<td>1.68 (1.73)</td>
</tr>
<tr>
<td>SOT4</td>
<td>3.35 (4.37)</td>
<td>1.49 (3.59)</td>
<td>2.46 (3.59)</td>
</tr>
<tr>
<td><strong>AD/AP Coactivation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT1</td>
<td>4.53 (7.25)</td>
<td>2.60 (2.52)</td>
<td>3.57 (5.40)</td>
</tr>
<tr>
<td>SOT2</td>
<td>4.18 (5.81)</td>
<td>2.50 (2.86)</td>
<td>3.34 (4.56)</td>
</tr>
<tr>
<td>SOT3</td>
<td>2.61 (3.90)</td>
<td>2.12 (1.79)</td>
<td>2.37 (2.98)</td>
</tr>
<tr>
<td>SOT4</td>
<td>3.16 (5.94)</td>
<td>2.87 (3.31)</td>
<td>3.02 (4.71)</td>
</tr>
</tbody>
</table>

Values in the table are Mean (SD)

For each of the coactivation measures (KF/KE and AD/AP) a two factor multivariate GLM was conducted across the four SOT conditions.

The KF/KE coactivation analysis revealed no main effect of either gender \(F = 0.42, \text{df} = (4, 35), p = 0.790\) or age group \(F = 1.88, \text{df} = (4, 35), p = 0.136\) and also no significant interaction for age group × gender \(F = 0.66, \text{df} = (4, 35), p = 0.626\).
The AD/AP analysis revealed no main effect of either gender [F = 0.49, df = (4, 42), p = 0.743] or age group [F = 1.82, df = (4, 42), p = 0.143] and also no significant interaction for age group × gender [F = 0.40, df = (4, 42), p = 0.808].
5.3 Discussion

There were three major findings of Study Two. Firstly the YG were found to be significantly stronger than the OG. This may be due to two factors: the OG demonstrated lower SEMG activity levels while also showing significantly higher levels of antagonist coactivation during MVC. It was also found that ageing had a significant effect on the strength ratios of the lower limb. Secondly it was shown that females displayed significantly higher antagonist coactivation during strength tasks. This was coupled with the findings that males exhibited greater levels of SEMG activity and muscle strength in all four muscle groups. Thirdly it was shown that the deterioration in postural control appeared to affect older males to a greater degree compared with older females.

5.3.1 Effects of Ageing on MVC, Strength Task Coactivation and Strength Ratio

The maximal amount of force a muscle or muscle group can produce, also termed maximal muscular strength, is extremely important for the production of functional movements and has repeatedly been linked to the ability to maintain functional independence (Vandervoort, 2002). Muscular strength is a complex process that requires the coordination and integration of many anatomical structures and physiological processes. With ageing there is a decline in the strength of nearly all muscles of the body especially those of the lower limb. Decrements of muscular strength occur at steady rates of approximately 1–2% per year (Vandervoort, 2002) and it has been found that 20% to 40% of muscular strength is lost from the third to the eighth decade (Doherty, 2003). However, it is often seen that the major decrease in strength occurs after the fifth decade (Doherty et al., 1993; Izquierdo, Ibanez, et al., 1999; Petrella et al., 2005). This significant reduction in muscular strength with ageing has been extensively studied with multiple mechanisms found to be contributing to this decline. Such mechanisms include a decrease in muscle mass, number of motor units, the number of motor units (MU)
recruited, the firing frequency of each MU, the coordination of agonist/antagonist activation and an increase in inhibitory reflexes (Arihara & Sakamoto, 1999; Burnett et al., 2000; Doherty et al., 1993; Enoka, 1997; Sale, 1987; Zhou, 2003). However, the strength ratio and coactivation of postural muscles in the lower limbs have not been extensively studied.

5.3.1.1 MVC, Muscle Activation & Coactivation

In the current study there was a significant age group effect on maximal torque measures of all four muscle groups. The YG exhibited significantly higher torque values when compared with the OG and this finding was repeated even when genders were separated except for the AD of female participants. In the case of the AD it was found that there was no age related decline in muscle strength between young and older females. This suggests that the KE, KF and AP strength is more age dependant in both genders while the AD strength is relatively unaltered in females with ageing in this population of participants. These findings are similar to that of other studies that have found muscular strength of the lower limb muscles decreases as people age (Connelly et al., 1999; Dalton et al., 2008; Izquierdo, Ibanez, et al., 1999; Kubo et al., 2007; Lanza et al., 2003; Macaluso et al., 2002; McNeil et al., 2005; Roos et al., 1999; Simoneau et al., 2005, 2007b; Thom et al., 2005).

In cross sectional studies by Izquierdo et al. (1999) and Macaluso et al. (2002) the maximal isometric strength of the KE and KF was investigated and it was found that the young group (age 21 ± 1 and 22.8 ± 5.7 years, respectively) were significantly stronger than the older adults (age 71 ± 5 and 69.5 ± 2.4 years, respectively) in both studies. In fact it has been shown that the maximal strength of the KE and KF can decrease by 43% - 52% (age range of 60 to 85 years) depending on the muscle group and joint angle assessed (Izquierdo, Ibanez, et al., 1999; Lanza et al., 2003; Macaluso et al., 2002; Roos et al., 1999). This level of decrease is similar to that found in the current study. When the data of males and females were pooled, it was seen that the KE torque of the OG decreased on average by 37.2% while the KF
decreased by 46.8%, compared with the YG. The age related decline in AP strength has been shown in the literature to exhibit similar age related declines, however the effects of ageing on the AD strength are less defined. For example, studies of the AP (Dalton et al., 2008; Simoneau et al., 2005; Thom et al., 2005) have found very similar reductions in maximal strength (decline of 37% - 40%) with the current findings (the AP maximal torque declined by 38.7% from the YG to the OG). Previous examinations of the AD strength changes with ageing have however yielded differing results (Lanza et al., 2003; McNeil et al., 2005; Simoneau et al., 2005, 2007b). Within the current study, when data from male and female participants were pooled, the AD maximal torque significantly declined by 23.5%. With genders separated however, it was seen that the older males were significantly weaker than young males (30.0% decline) while in the female participants there was no significant difference between age groups (14.6% decline). The declines within the pooled gender data and male only data are comparable to that of previous reports of between 21% and 31% (Connelly et al., 1999; Lanza et al., 2003; McNeil et al., 2005). On the other hand studies have found no age related differences in maximal AD strength. For example, Simoneau et al. (2005) tested 12 older men and 11 young men and found that the AD experienced a non-significant decline in strength of 6.7%. In a later study by the same authors (Simoneau et al., 2007b) 11 young males and 18 older males were tested for AD maximal strength and it was again found that age did not significantly affect the force production capacity of the AD. A potential explanation for the difference in findings between the Simoneau et al.’s studies and the current study may have been the use of only males in the Simoneau et al.’s studies. The current study had both male and female participants which is similar to other studies that have shown strength declines in the AD with both male and female participants (Lanza et al., 2003). Interestingly however, there was a significant age group by gender interaction that revealed that there was no difference between young and older females but a significant decline in strength with age for males. Therefore further examination of the age effect on AD
maximal torque should be conducted with gender being factored in as a potential influencing factor.

Coupled with the age decline in maximal torque of the KE and KF was an associated decrease in maximal activation of these muscle groups. This age related decline in muscular activation may indicate a reduced neuromuscular drive which may have contributed to the significantly lower maximal strengths seen in the OG. However, within the AP and AD there was no age related change in muscular activation. In relation to the KE and KF these findings are similar to that of previous studies (Macaluso et al., 2002; Roos et al., 1999). In two studies by Macaluso et al. (2002) and Roos et al. (Roos et al., 1999) there were not only significant age effects on muscular strength of the KE (found in both studies) and KF (found in Macaluso et al. only), but also an age related decline in maximal RMS SEMG amplitude. This age related decline in muscle activation could be attributable to decreased neural activation. However, there are many factors that may have contributed to the decreased RMS in the older adults such as a smaller number of recruited motor units (McNeil et al., 2005), decreased firing rates of the individual motor units (Connelly et al., 1999) or a decrease in motor unit synchronisation (Kamen & Roy, 2000). It should be noted that decreases in the maximal SEMG amplitude can also be the result of alteration in anatomical structure such as the age associated decline in muscle mass, muscle fibre size and an increase in non-contractile structures such as fat and connective tissue (Aagaard et al., 2010; Merletti, Farina, Gazzoni, & Schieroni, 2002). The relative roles of these mechanisms however cannot be distinguished with surface SEMG and is a limitation to the current study. In relation to the AP and AD the findings of previous research are equivocal with some researchers reported significant age related declines in maximal SEMG and twitch amplitudes (Dalton et al., 2008; Kubo et al., 2007; Thom et al., 2005), while others have found no such decrease (McNeil et al., 2005; Simoneau et al., 2005, 2007b). Simoneau et al. (2005) and (2007b) showed very similar results to that of the current study. In both of those studies ageing had a significant negative
effect on muscle strength and activation of the AP while there was neither a strength nor SEMG decrement in the AD. The current results suggest that there are in fact muscle specific alterations due to ageing at the ankle joint. The AP appears to be adversely affected by the ageing process to a greater degree whereas the AD appears to experience relatively little to no alterations in muscle activation and strength with age.

Coactivation level can also be influenced by the ageing process with healthy young individuals usually producing maximal torque at a joint by optimally scaling the activation of the prime movers and the concurrent activity of the antagonist muscles (Hortobagyi & Devita, 2006). On the other hand older adults tend to produce the desired torque with near complete activation of the agonist combined with a disproportionately heightened coactivation of the antagonist muscles. Greater coactivation can reduce the expression of muscle force at the joint through either or both the mechanical force opposition from the action of the antagonist muscles and reciprocal inhibition (Klass, Baudry, & Duchateau, 2007). To the author’s knowledge this is the first study that examined the antagonist activity of all four major muscle groups of the lower limb at once. Previous studies have either examined single muscles or agonist/antagonist pairs at either the knee or ankle joint while the results of these investigations have varied considerably (Izquierdo, Ibanez, et al., 1999; Macaluso et al., 2002; Simoneau et al., 2005, 2007b).

A novel finding in the current study was that the OG displayed significantly higher coactivation in the KE, KF and AD when acting as the antagonist during maximal torque measures. Depending on the muscle group examined these findings are similar to some earlier studies (Izquierdo, Ibanez, et al., 1999; Klass et al., 2007; Macaluso et al., 2002) but dissimilar to others (Izquierdo, Ibanez, et al., 1999; Macaluso et al., 2002; Morse et al., 2004; Simoneau et al., 2005, 2007b). In relation to the KE and KF, previous reports have found that there is no age effect on the activation level of the KE during knee flexion tasks while there is
a significant effect of age on the KF activation when completing knee extension tasks (Izquierdo, Ibanez, et al., 1999; Macaluso et al., 2002). In the current study it was found that for both knee muscle groups there was a significant effect of ageing with older adults exhibiting higher coactivation levels. During maximal knee flexion it was seen that the coactivation level of KE in the OG were 39.1% higher than the YG. This was similar to the difference between age groups seen in the KF during maximal knee extension with the OG having 33.0% higher levels of coactivation. Macaluso et al. (2002) and Izquierdo et al. (1999) found that, similar to the current findings, the KF appeared to exhibit greater levels of activation when acting as the antagonist muscle (i.e. during knee extension) in the OG. However, when considering the KE as the antagonist it was found in their studies that there was no difference between age groups. A possible explanation for the difference in findings between studies may be related to differences in the presence of adipose tissue of the older participants which can affect the level of cross-talk and hence the calculated coactivation (Macaluso et al., 2002). However, it has been shown that for SEMG recordings with the appropriate size of electrodes, correct placement over the muscle and short electrode distance, the effect of cross-talk could be disregarded in most cases involving the muscles of the extremities (Solomonow et al., 1994). Therefore the heightened level of coactivity in both the KE and KF, when acting as an antagonist, may in fact contribute to the significantly lower maximal strengths of these muscle groups when comparing the OG to the YG.

For the AP and AD coactivation levels during maximal isometric contractions most studies have found no difference between young and older adults (Klass et al., 2007; Morse et al., 2004; Simoneau et al., 2005, 2007b) or that young adults have greater levels of coactivation (Simoneau et al., 2005, 2007b). Within the current study it was seen that the AD of the OG exhibited coactivation levels 43.0% higher than the YG. The level of coactivation within the OG (25.51%) was relatively high compared to the study by Morse et al. (2004) and the studies conducted by Simoneau et al. [(2005) and (2007b)] (11% - 18%). In all three of these studies
it was found that the level of AD coactivation during plantarflexion was comparable between age groups, which suggested that the age related decline in muscular strength of the AP was due to decreases in factors such as specific tension, muscle cross sectional area and/or changes in excitation-contraction coupling with ageing (Payne & Delbono, 2004; Simoneau et al., 2007b). In the current study however, there was a significant increase in coactivation of the AD which could indicate that the net torque produced by the AP may have been influenced by the torque produced by the heightened AD. When analysing the AP coactivation level it was found that there was no significant difference between age groups in the current study. This is similar to the findings of Klass et al. (2007) who found that the SEMG activity of the soleus muscle during maximal dorsiflexion contractions was very similar in both older and young participants. This suggest that although the coactivation of the much larger AP may possibly have a detrimental effect on the force production capabilities of the AD, both young and old individuals experienced similar coactivation levels. Therefore, it is unlikely that the maximal torque difference between age groups is the result of antagonistic muscle activity.

The greater levels of antagonist activation seen in the OG may be explained by the age related changes in spinal reflex circuitry and cortical and subcortical mechanism associated with changes in coactivation (Hortobagyi & Devita, 2006). Some of the specific reflex pathways include disynaptic reciprocal inhibition, recurrent inhibition and presynaptic inhibition (Chalmers & Knutzen, 2004; Earles et al., 2001; Hortobagyi & Devita, 2006) which have all been shown to be modulated with ageing. Therefore it is suggested that future investigations should focus on age related changes in reflex pathways and its relation with coactivation level during muscular contractions.
5.3.1.2 **Strength Ratios**

To the author’s knowledge there is a scarcity of research on the effects of ageing on lowerlimb strength ratios when assessed by isometric contractions. In the current study it was found that the HQR of the YG was significantly higher than the OG when gender groups were pooled. This finding was repeated when males were analysed separately, however there was no difference between young and older females HQR values. This significant decline in HQR with ageing was due to the relatively larger decline in maximal torque of the KF (46.8% decline) compared with the KE (37.2% decline) in the pooled data, as well as in the male participants (KF declined by 50.1% and KE by 36.2%). This finding is similar to another report from our laboratory in which the HQR significantly declined from middle age to older participants (Bezerra et al., 2008). However, in that particular study there was no difference between the young group and the older group. The difference in findings between the current study and Bezerra et al. (2008) may have been due to knee joint angle at which the muscle strength was tested. In Bezerra et al. (2008) the knee joint was tested at 90° flexion and as seen in Study One of this thesis, alterations in knee joint angle seems to have a greater effect on the KE torque compared with the KF’s. Further research is needed to confirm whether such a difference is mainly due to joint angles or ageing.

Of the few studies conducted in relation to the DPR (Simoneau et al., 2005, 2007b) it has been shown that with ageing there is a significant increase in the DPR. Simoneau et al. (2005) and (2007b) had previously found that the DPR increased from 0.35 to 0.57 and 0.19 to 0.86 respectively depending on the joint angle assessed (from -20° to +20°). This pattern of findings was similar to those of this study in which there was a significant increase in DPR from the YG (0.37) to the OG (0.49) at the ankle joint angle of neutral (90°). It can be hypothesised that this age related increase in DPR (from young to older participants) was due to the relatively larger decline in maximal torque of the AP (38.7% decline) compared with
the AD (23.5% decline). However, further research is needed to examine the age related changes in DPR across different joint angles and contraction modes, while it is still unknown what functional relevance the DPR may have to functional tasks such as postural control.

5.3.2 Differences between Male and Female in MVC, Strength Task Coactivation and Strength Ratio

It has been shown that the maximal isometric strength of the lower limb muscle groups is typically greater in males than females (Lindle et al., 1997; Russ & Kent-Braun, 2003; Yasuda et al., 2005). Whether this maximal muscle strength is differentially affected by gender during the ageing process has, to the author’s knowledge, not been extensively examined. This seems somewhat surprising due to the recent findings of gender related differences in muscle fatigue (Clark et al., 2005; Hunter, Critchlow, & Enoka, 2004) which has led to the hypothesis that sex related differences in central activation, neuromuscular junction transmission and membrane excitability may exist. It is therefore appropriate to examine the possibility that ageing affects muscular strength, muscle activation and coactivation differently in males and females.

5.3.2.1 Muscle Strength, Muscle Activation and Coactivation

Within the current study it was found that males were significantly stronger in all four muscle groups when age groups were pooled. The female participants experienced a lower maximal muscle strength by 26.0% in the KE, 31.9% in the KF, 22.7% in the AP and 33.8% in the AD. No significant age group × gender interactions were found for the KE, KF or AP which suggest that the gender difference in maximal strength stays relatively constant throughout the ageing process within these three muscle groups. For the AD there was a significant interaction effect which showed that there was a more pronounced reduction in AD maximal strength with ageing in the male participants.
A potential mechanism for the gender strength differences was the associated SEMG differences between genders as observed in the current study. It was found that when age groups were pooled the male participants displayed significantly higher SEMG RMS levels during maximal contractions of the KE, KF and AP. These findings suggest a higher neuromuscular activation in male participants. These results are in conflict with two previous reports that have found no gender differences in maximal SEMG amplitude (Clark et al., 2005; Deschenes et al., 2009). Interestingly, these two studies also found that females exhibited higher muscle activation during fatiguing contractions (Clark et al., 2005) while males showed higher activation levels after a period of unloading (Deschenes et al., 2009). Clark et al. (2005) suggested from their findings that some possible mechanisms for the higher level of activation seen in females during fatiguing contractions was due to men being more susceptible to greater reductions in central activation, transmission failure at the neuromuscular junction or a decrease in muscle membrane excitability. Consequently the findings of significant gender differences in maximal SEMG amplitude in the current study may be the result of the above mentioned mechanisms. However, further research is needed in an effort to clarify the potential mechanisms in gender differences in muscle activation patterns when performing maximal strength tasks.

Another mechanism that may have contributed to the gender difference in maximal torque production is the level of coactivation. Interestingly, female participants in the current study exhibited heightened levels of coactivation in comparison to males when the KE, KF and AD were acting as the antagonist muscle group. To the author’s knowledge there has been no report in the literature on gender differences in agonist/antagonist coactivation levels or the postulated mechanisms that influence coactivation. It is therefore suggested that future research should investigate the gender influences on coactivation and the mechanisms that influence its level.
**5.3.2.2  ** *Strength Ratios*

Within the literature there is a scarcity of information in relation to the gender effects on strength ratios of the lower limb muscle groups, more specifically the HQR and DPR. Of the very limited studies in this area of interest it has been shown that the HQR was significantly lower in females (Holm & Vøllestad, 2008). However, that study (Holm & Vøllestad, 2008) analysed the gender differences in a group of prepubescent children while completing dynamic contraction. Therefore, direct comparison with the current study is not particularly appropriate as the current groups were assessed under isometric conditions and were mature young and older adults.

A novel finding of this study was that the HQR was similar between males (average 0.97) and females (0.92) when age groups were pooled. The lack of significant difference between genders was also seen when age groups were separated with no differences between YG males (1.11) and females (0.96) or OG males (0.86) and females (0.88). However, it appears that the relative strength difference between the KE and KF was similar for both the males and females resulting in similar HQR values. Similar relative strength differences between the KE and KF were repeated when considering the YG and OG separately, once again producing similar levels of strength ratios between the genders. Much like the HQR there were no significant gender effects on the DPR when age groups were either pooled (DPR for males 0.47 and females 0.40) or separated into young adults (DPR for males 0.42 and females 0.33) or older adults (DPR for males 0.52 and females 0.47). These findings also indicate that the relative strength difference between the AP and AD is similar between males and females.
5.3.3 Ageing and Gender Effects on Postural Control and Postural Task Coactivation

Postural control is a complex motor behaviour that involves the integration of a multiple of anatomical structures and physiological processes. The integration of sensory information is of utmost importance to the maintenance of posture and involves sensory inputs of proprioception, vision and vestibular sensibilities to guide and control posture and movement. This information is provided via kinaesthetic receptors located in the muscles, tendons, joints, skin, the eyes and vestibular receptors and provide essential feedback for the maintenance of postural control (Lord et al., 1991c). This sensory information is sent to the central nervous system for processing at several locations including the cerebellum, brainstem, basal nuclei and sensory-motor cortex (Lord et al., 1991b; Lord et al., 1994). Once the postural system has integrated all sensory information the CNS sends out appropriate motor responses to effector muscles in order to maintain the posture. These corrective movements imply the ability to choose appropriate motor responses based on past experience, to modify these responses on the basis of the continuous sensory input and to produce the needed muscular contraction to stabilize posture (Era et al., 1996).

Physiological changes are often seen with ageing resulting in a diminution of various systems within the body including changes in muscular and sensory systems which often results in a reduction in physical capability. Muscular strength decreases with age are partially due to the restructuring/augmentation of the skeletal muscles which includes a reduction in the size of existing muscle fibres (muscular atrophy) as well as a loss of muscle fibres (Timiras, 2003c). Other changes experienced with ageing include slowed reaction time, diminished reflexes (especially in the ankles) and proprioceptive changes. Structural changes of the nervous system also cause variations in the motor behaviour of older individuals including a loss of neurons in both the brain and spinal cord, neuronal dendrite atrophy which results in impaired
synaptic connections and diminished electrochemical reactions leading to the slowing of many neuronal processes (Timiras, 2003a). These changes have functional consequences such as a compromised balance and postural control, and slowed and more deliberate movements (Porth & Matfin, 2009; Timiras, 2003b).

5.3.3.1 Effects of Ageing on Postural Control and Postural Task Coactivation

With ageing it is often found that there is a decline in postural control capacity with an associated increase in the incidence of falls (Laughton et al., 2003). Examples of the detrimental effect of the ageing process on postural control can be seen in the stabilogram diffusion measures of Diff Co (st) and Crit Point. Within older adults it is often seen that there is a decrease in stability of the open-loop postural control mechanisms (Diff Co st) (Laughton et al., 2003) and also a greater delay in the start of the closed-loop postural control period (Crit Point) (Amiridis et al., 2003; Prieto et al., 1996). Both the delay in the onset of the closed-loop postural control and the larger instability of the open-loop postural control cause an increase in the short-term postural sway through endorsing a higher level of stochastic activity (Amiridis et al., 2003; Kuo & Zajac, 1993b). It is also common in the postural control literature to find that, when using measures of COP traditional summary statistics, older adult’s exhibit greater measured COP velocities, distances and amplitude and/or frequencies (Abrahamová & Hlavačka, 2008).

5.3.3.1.1 Traditional parameters

Both Mean Dist and Mean Vel are time-domain distance measures that are associated with either the displacement of the COP from the central point of the stabilogram, or the velocity of the COP. The mean distance (Mean Dist) is the mean of the time series (in either the AnPo or MeLa directions and/or the calculated RD) and represents the average distance from the
mean COP. The mean velocity (Mean Vel) is the average velocity of the COP and is also calculated for all three time series (RD, AP and ML). In effect, this normalizes the total excursions to the analysis interval (Prieto et al., 1996). Another type of COP traditional measure is the time-domain area measures which are statistically based estimates of the area enclosed by the stabilogram or are measures that model the stabilogram with a combination of distance measures respectively. Examples of the time-domain area measures include the 95% Confidence Circle Area (95% CCA) (Santos et al., 2008) and the Sway Area (Raymakers et al., 2005).

In the current study there were differing effects of ageing on postural control depending on the postural control measure assessed. In relation to Mean Dist AnPo, MeLa and RD measures in the current study there were no age group differences found and these results were the same through all four SOT conditions. This suggests that the average distance travelled by the COP away from the average COP location does not change when people age (Demura, Kitabayashi, & Aoki, 2008). The fact that there was no age related change in Mean Dist suggests that the efficacy of Mean Dist measures in detecting age related declines in postural control is questionable. The OG did however exhibit significantly higher mean velocities compared with the YG in most SOT conditions whether considering AnPo, MeLa, or RD measures. These results indicate that during the ageing process there is a reduction in the control of the postural control system which allows the COP to drift at increasing velocities (Abrahamová & Hlavačka, 2008; Prieto et al., 1996). Also there appears a potential gender influence on the age related decline in postural control when using Mean Vel as a postural control measures as there were significant Mean Vel increases when males aged. When considering the age group differences of the area measures it was found that there was no age group effect on the 95% CCA measure within any of the SOT conditions. Sway Area however was shown to significantly increase with age in SOT2, SOT3 and SOT4 when genders were pooled.
Depending on the postural control measure analysed, the current result are in agreement with some and disagreement with other previous findings. Previous reports have found significant ageing effect when analysing measures such as mean or RMS distance, mean velocity or COP speed and COP area measures such as Sway Area and 95% CCA (Abrahamová & Hlavačka, 2008; Amiridis et al., 2003; Hageman, Leibowitz, & Blanke, 1995; Low Choy, Brauer, & Nitz, 2003; Onambele, Narici, & Maganaris, 2006; Prado, Stoffregen, & Duarte, 2007; Prieto et al., 1996) while few studies have found no age effect on these or one of these measures (Demura et al., 2008; Prado et al., 2007). In the current study it was found that with ageing there were no changes in postural measures of mean distance or 95% CCA but there were significant increases in Mean Vel and Sway Area. Prieto et al. (1996) and Abrahamová and Hlavačka (2008) on the other hand found significant increases in distance measures (both Mean Distance and RMS Distance), mean velocity and Area measures (both 95% CCA and Sway Area) with ageing. Therefore it seems that in relation to traditional postural parameters measures such as Mean Vel and Sway Area are more sensitive to the age related decline in postural control compared to measures of Mean Dist.

5.3.3.1.2 Diffusion Parameters

Stabilogram-diffusion analysis (SDA) is based on the assumption that the movement of the COP represents the combined output of co-existing deterministic and stochastic mechanisms. The stabilogram-diffusion analysis involves the extraction of three sets of posturographic parameters: diffusion coefficients, scaling exponents and critical point coordinates (Collins et al., 1995). The diffusion coefficient is an average measure of the stochastic activity of a random walker, i.e. it is directly related to its jump frequency and/or amplitude, and can be thought of as an indicator of the relative stability of the system (Doyle et al., 2008). Quantification of the correlation between the step increments that make up an experimental time series is termed “scaling exponents” (Collins et al., 1995). This measure can provide an
indication whether the motion of the COP is more or less likely to continue moving in the same direction that it is currently moving (Doyle et al., 2008). From a physiological standpoint, SDA scaling exponents quantify the correlated behaviour of the respective postural control mechanisms, i.e., short-term scaling exponents characterize the drift-like dynamics of the open-loop postural control mechanisms, whereas the long-term scaling exponents characterize the antidrift-like dynamics of the closed-loop postural control mechanisms (Collins et al., 1995). The critical point coordinates approximate the transition region that separates the short-term and long-term regions. The estimation of the critical point coordinates is determined by the intersection point of the straight lines fitted to the two regions of the linear-linear version of the resultant stabilogram-diffusion plot (Collins & De Luca, 1993; Collins, et al., 1995). These coordinates approximate the temporal and spatial characteristics of the region over which the physiological postural control system switches from open-loop control to closed-loop control.

In the current investigation there were no differences between age groups in Crit Point measures whether with pooled genders or separated genders in any of the SOT conditions. These results indicate that there is no difference in the time point location when the postural control system switches from open-loop to closed-loop between young and older adults. In relation to the Crit Point Coord measures the only two SOT conditions that showed a significant increase with age (pooled gender data) was SOT3 and SOT4 (depending on sway direction). However, when gender data was separated it was found that there were no differences between young and older females but the older males exhibited significantly larger Crit Point Coord compared with young males in all SOT conditions (and across all three measures of R, X and Y). This indicates that there is a significant increase in the stochastic activity of the COP with ageing in males particularly. In relation to the Crit Point findings of the current study they are dissimilar to that of Collins et al. (1995) while the Crit Point Coord results are similar. Those authors found that not only there were age related
increases in critical mean square displacements, but also associated increases in critical time intervals from young to older age. They interpreted these findings as possible indirect evidence of the age related modification in the temporal interaction of the open-loop and closed-loop control mechanisms. Diminished muscle strength, reflexes and proprioception with age may have led to a reduced ability to detect small changes in joint position and the ability to produce appropriate response torques (Lord et al., 1991b). Thus according to the results of the current study older individuals may inadvertently allow the body segments to drift over larger displacements however not for longer time periods before corrective feedback mechanisms are utilised. However, caution should be taken when comparing the findings of the current study with those of Collins et al. (1995). Although within the current study no difference was found in Crit Point measures this may have been due to age, weight and height differences between the participants of the two studies. The participants of the current study were on average younger, lighter and shorter than those of the Collins et al.’s study. These anthropometric differences may account for the differences in findings between the studies.

Generally there was significantly higher Diff Co (st) in the OG compared with the YG. However this difference between age groups was mainly due to the increase in short term Diff Co seen in the older males compared to the young males (no differences between young and older females). When analysing the Diff Co (lt) measures it was found that there were no differences between age groups when gender data was either pooled or separated. These findings are similar to those of Laughton et al. (2003) who also found that ageing had a significant effect on the short term Diff Co but not the long term. A possible explanation that has been suggested for the age difference in short term Diff Co is that the corrective torque generated in proportion to the body sway is decreased with ageing leading to increased stochastic activity of the COP (Peterka, 2000). It may also be hypothesised that due to the age related decline in the human neuromuscular system there may be an increased time delay in
the sensing, transmission, processing and muscle activation in older adults which may increase the average frequency of COP movement (Laughton et al., 2003; Peterka, 2000).

No age group differences were detected when considering the Scal Ex (st) measures when the genders were either pooled or separated. This result suggests that the steady-state behaviour of the open-loop postural control mechanisms in older individuals is not different to young adults and thus perhaps just as stable, i.e. there is no difference between age groups in their tendency to drift away from a relative equilibrium point over the short term. This is different from the findings of Collins et al. (1995) who did find age group differences in Scal Ex (st) measures which they interpreted as suggesting that the COP of older participants tended to drift further from a relative equilibrium point leading to much higher short term scaling exponents. The Scal Ex (lt) on the other hand exhibited significant age related changes in the current study. However, it was found that these age-related declines in Scal Ex (lt) were only established in SOT3 and SOT4 when considering the Y (AP direction) and R (resultant calculation) measures and not in the X (ML direction). This result was the same as that found in the Collins et al. (1995) study. In contrast to the short term Scal Ex results it was found that the OG had smaller long term scaling exponents compared to the YG. This suggests that the steady state behaviour of the closed-loop postural control mechanism are more stable due to the more negatively correlated data, i.e. an increased probability that any movement away from a relative equilibrium point will be offset by corrective adjustments back towards the equilibrium position (Collins et al., 1995). This tightening of the postural control system may be interpreted as a tightening of the system to offset the effects of the increased tendency to drift during the short term period.

5.3.3.1.3 Postural Task Coactivation

The normalised SEMG ratios for TA/GL and BF/VL were calculated in order to determine the coactivation levels in each joint during postural maintenance. The SEMG RMS data was
calculated over a time period of 0.5 s period in the middle of the 30 second recording time and was normalised as a percentage of the amplitude displayed during maximum voluntary contractions (Benjuya et al., 2004).

It has been found that older people significantly increase the level of coactivation at the ankle joint during postural tasks (Benjuya et al., 2004; Hortobagyi & DeVita, 2000; Melzer et al., 2001). This increased coactivation is further enhanced when older people have restricted visual feedback, narrow base of support, or are required to undertake dual cognitive tasks while maintaining posture (Benjuya et al., 2004; Melzer et al., 2001). In contrast to these findings the present study found no significant difference in postural task coactivation at either the knee or ankle joints between the YG and OG, whether the genders were pooled or separated. This result suggests that the relative activation of the agonist/antagonist pairs at the knee and ankle joints remains stable throughout the ageing process. It has previously been speculated that older people adopt this coactivation strategy in an effort to stiffen the ankle joint which helps to reduce excessive movements thus decreasing postural sway (Melzer et al., 2001). In fact it was proposed by Collins et al. (1995) that older individuals may adopt a postural control strategy whereby they increase the net stiffness of their musculoskeletal system. This would involve increasing the level of muscular activity across the joints of the lower limb in an effort to reduce the greater tendency to drift from a relative equilibrium point (i.e. higher short term Scal Ex). Due to there being no significant difference between age groups postural coactivation level it appears that that hypothesis is not tenable. However the method used within the current study to measure postural coactivation level was different to other studies. Melzer et al. (2001) for example, recorded EMG activity of the AP and AD for 20 seconds during the postural tasks. This may have captured a more complete overview of the activation behaviour of the agonist/antagonist pair in comparison to the current study. Within the current study the EMG was recorded over a 0.5 second period in the middle of the total 30 seconds COP recording period. The fact that the EMG data was only a very short
snippet of the total recording time and the fact that the COP position or motion, which is likely to have an influence on the resulting EMG measures, was not taken into consideration may have led to the lack of significant findings in the current research. Therefore, further research should be conducted to investigate the influence of recording time, COP location/motion and dynamic postural tasks on the level of coactivation.

5.3.3.2 Differences between Males and Females in Postural Control and Postural Task Coactivation

5.3.3.2.1 Traditional parameters

In relation to the effects gender on postural control it was found that males exhibited significantly larger Mean Dist, faster Mean Vel and greater Sway Area (including 95% CCA) in comparison to female participants. These gender differences were the result of a significant decrease in postural control in the older males as there were no differences discovered between the young males and females. These findings were in contrast to previous findings that females are less stable in comparison with males (Butler, Menant, Tiedemann, & Lord, 2009; Riva et al., 2013). For example Butler et al. (2009) found that older women performed significantly worse than older men when performing seven different functional mobility tests including coordinated stability and near tandem stance. It was suggested that the possible mechanism for the decreased mobility in older women was due to the often found reduction in muscular strength and power in females. The result of the current study however may not be explained by this phenomenon as older males were found to be stronger than females in only the KE and AD and not the KF or AP.

The current findings may be explained by gender and age differences in anthropometric variables such as height, weight and body mass index. When independent t-tests were conducted between gender groups of the YG it was found that males were significantly taller
and heavier but no difference was found in body mass index. In the OG however, there were significant differences in all three measures. It has been shown previously that anthropometric variables such as weight and body mass index may be related to the differences found in postural control (Hue et al., 2007; Teasdale et al., 2007). In a study by Hue et al. (2007) it was investigated the influence of body weight on postural control in a group of 59 males (age range 24-61 years). The postural control measures analysed included many of the postural control measures used in the current study (i.e. Sway Area and Mean Dist) and other similar measures (i.e. RMS Velocity). It was found that a strong relationship existed between decreased postural control and anthropometric measures of weight and body mass index. Height was not found to be a major determinant of postural control ability and therefore the finding within the current study of a significant difference in height between genders may not have had an influence on the gender difference observed within Sway Area measures. Within the Teasdale et al. (2007) study weight loss (therefore a reduction in body mass index) resulted in significant improvements in postural control. However, caution should be exercised when comparing the results of Teasdale et al. (2007) with the current study as the comparison of COP measures after weight loss in individuals may be very different to a comparison between groups of heavier and lighter people. Consequently, the finding that the older males were significantly heavier and had a greater average body mass index may help to explain the results of significantly higher Sway Areas of COP. However, it is suggested that future studies that analyse gender differences in postural control should be conducted and also future studies that employ a design that includes both genders should recruit anthropometric-matched males and females. It should also be noted that the fact that height and weight were not included as a covariate in the analyses of gender is a limitation of the current study. It is therefore also suggested that future investigations analysing the effects of gender on postural control should add height and weight as covariates in the analyses of gender differences.
5.3.3.2.2 Diffusion parameters

Within the diffusion parameters it was found that there were no gender differences, with either pooled or separated age groups, in Crit Point, Diff Co (lt), Scal Ex (st), or Scal Ex (lt) measures. The only two measures to show significant gender differences were Crit Point Coord and Diff Co (st) and once again this was due mainly to significant differences between OG males and females. Older males appear to exhibit greater average displacements during the short term period compared to females which would have contributed to the greater displacements seen at the point of change over from the open-loop to closed-loop control periods. However, these results need to be taken with caution due to the differences between genders in anthropometric variables as discussed above.

5.3.3.2.3 Postural Task Coactivation

No differences in postural coactivation level were seen between genders with pooled age groups or separated age groups. This indicates that although there were gender differences in postural measure this did not result in a different strategy of muscular activation of the agonist/antagonist pairs between genders. This further supports the hypothesis that the gender differences found between older adults may be due to the anthropometric differences observed in the older males as opposed to any alterations in postural control strategy.
5.4 Conclusions

The results of this study provided new evidence for two of the possible mechanisms for the age associated decline in maximal strength. First, it was shown that older individuals experienced a significant decrease in muscle activation; and secondly they had heightened levels of antagonist coactivation during maximal strength tasks. This was seen in all four muscle groups of the lower limb and indicates that activation and coactivation changes with ageing may be a major contributor to the age related decline in maximal strength. In relation to the HQR and DPR measures it was shown that these ratios are differentially affected by the ageing process. Within the HQR the relatively larger age related decline in KF strength resulted in significantly lower ratio values in the OG. The DPR on the other hand exhibited a significant increase with age due mainly to the relatively larger decline in AP strength with ageing. These experimental findings lead to the rejection of the null hypothesis that ageing would not cause changes in muscular strength, strength ratio and strength task coactivation levels. These findings further pose the question of whether exercise programs should aim to target the KF and AP of older individuals in an effort to maintain the relative strength between agonist/antagonist pairs, and if this would be associated with improved daily functioning.

An interesting finding of this study was that there appears to be gender differences in the recruitment pattern of agonist/antagonist pairs of the knee and ankle joint. Female participants seem to adopt a muscle activation pattern that includes heightened activation of the antagonist muscle when undertaking maximal strength tasks. Compared with their male counterparts the females also exhibited significantly lower activation levels of the agonist muscle group. When considered together, these differing activation patterns between genders may have had the effect of significantly lowering maximal strength in both the young and older female participants.
Finally, in relation to postural control it was seen that ageing had an adverse effect on the ability to control posture. An interesting finding of this study was that older males appeared to experience the greatest deterioration in postural control than females. These age and gender differences were however not the result of altered levels of antagonist coactivation as no differences between the groups were found. This lead to the rejection of the third null hypothesis that ageing does not affect postural control while also accepting the fifth null hypothesis that postural coactivation is not affected by ageing. Future studies therefore, need to clarify the mechanisms for gender related differences in postural control which may include either anthropometric differences between males and females (i.e. body mass, height and BMI), differences in neuromuscular activation and innervation (e.g. postural reflexes, motor unit behaviour, etc), differences in sensory information propagation (e.g. proprioceptive differences), or differences in the perception/cognitive functioning.
Chapter 6: Study Three
Effects of Tai Chi training on postural control, coactivation and lower limb muscle strength ratio modulation

6.1 Study Outline

Aims:

1. To investigate the effect of 12 weeks of Tai Chi exercise on lower limb muscle strength, agonist/antagonist strength ratios and strength task coactivation.
2. To investigate the effect of 12 weeks of Tai Chi exercise on postural control and postural task coactivation.

Null Hypotheses:

1. Tai Chi, as an exercise intervention, does not cause changes in lower limb muscle strength, strength ratio (HQR and DPR) or strength task coactivation.
2. Tai Chi, as an exercise intervention, does not cause changes in postural control or postural control coactivation levels.

Design and results summary:

This study was a non-randomised, controlled trial with a test-retest design that aimed to analyse the changes in postural maintenance and strength ratio of the lower limb due to a Tai Chi exercise intervention. Statistical analysis involved examination of main effects, interactions and post-hoc comparisons. If a significant effect or interaction was detected, post-hoc analyses with Bonferroni adjustment were conducted to detect significant differences between groups and pre-post training (presented below).
Comparisons between the Tai Chi training group (TCG) and the control group (CG) showed that within the KE, AP and AD there were no group differences in MVC at either pre or post intervention. However, post intervention the KF of the TCG was significantly stronger than CG. There were also no differences between groups in SEMG activation levels within any of the muscle groups. A large majority of coactivation measures during strength tasks found no differences between the two groups either pre or post intervention period. At pre intervention there were no differences between groups in HQR levels, however at post intervention the TCG had significantly higher HQR values than the CG. Pre intervention data showed that the CG had significantly higher DPR levels than the TCG while the post intervention test found no group differences. All postural parameters showed no group differences at either pre or post intervention. In terms of postural coactivation it was found that at pre intervention the CG had significantly higher levels than the TCG, but post the intervention there was no difference between the two groups.

Comparisons between pre and post intervention revealed that within the TCG there were significant improvements in maximal strength of KE and KF while no changes were found in the CG or the AP and AD of the TCG. The maximal SEMG amplitude did not change within either the CG or the TCG. Strength task coactivation levels did not change from pre to post within the KE, AP or AD of the TCG and CG. Only the KF of the TCG showed a significant reduction in coactivation while the CG showed a significant increase from pre to post. Neither the HQR nor DPR strength ratio changed from pre to post intervention within either group. The only postural measures that showed some improvements with TC intervention were Sway Area and Crit Point X with all other measures showing no change. This was coupled with very few changes in coactivation levels during postural tasks.
6.2 Results

6.2.1 Adherence and Dropout Rate during Intervention

The TC intervention trial started with 27 older individuals however during the course of the intervention there were three dropouts due to health and family reason (experiencing vertigo during TC, heart attack and full time minder of partner). The adherence rate for the remaining 24 participants was on average 85% (on average 31 out of 36 possible TC sessions).

6.2.2 Maximal Voluntary Contraction Torque

The observed means and standard deviations of MVC for KE, KF (at 30°), AP and AD (at neutral) for the Tai Chi group (TCG) and Control Group (CG) are presented in Table 6-1.

<table>
<thead>
<tr>
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<th>Tai Chi</th>
<th>Control</th>
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<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
</tr>
<tr>
<td>KE (N.m)</td>
<td>51.71 (10.59)</td>
<td>57.66 (9.51)</td>
</tr>
<tr>
<td>KF (N.m)</td>
<td>44.52 (17.40)</td>
<td>52.23 (16.58)</td>
</tr>
<tr>
<td>AP (N.m)</td>
<td>67.80 (22.54)</td>
<td>79.42 (24.26)</td>
</tr>
<tr>
<td>AD (N.m)</td>
<td>27.95 (8.27)</td>
<td>30.81 (9.57)</td>
</tr>
</tbody>
</table>

Values in the table are Mean (SD)

6.2.2.1 Knee Extensors and Flexors

The two factor repeated measures GLM (group × trial) for the KE revealed main effect of trial [F = 8.70, df = (1, 37), p = 0.005] that showed that there was a significant increase in KE strength from pre to post intervention. Main effect analysis of group found no effect [F = 0.27, df = (1, 37), p = 0.607] however there was a significant group × trial interaction [F =
The two factor repeated measures GLM (group × trial) for the KF revealed no main effect for either group [F = 1.17, df = (1, 37), p = 0.287] or trial [F = 0.53, df = (1, 37), p = 0.472] however a significant group × trial interaction was found [F = 5.21, df = (1, 37), p = 0.028].

Post hoc comparisons found that in the TCG there was a significant strength increase pre to post intervention for both the KE [F = 24.47, df = (1, 37), p < 0.001] and KF [F = 5.88, df = (1, 37), p = 0.020] while there were no changes in maximal torque for either the KE [F = 0.02, df = (1, 37), p = 0.881] or KF [F = 0.98, df = (1, 37), p = 0.328] within the CG (Figure 6-1).

![Figure 6-1. Comparisons of the maximal voluntary contraction torque of the KE and KF for both the TCG and CG pre to post intervention period. *: p ≤ 0.05.](image)

The comparisons between groups for maximal KE strength found no significant differences at either pre [F = 1.33, df = (1, 37), p = 0.256] or post intervention [F = 0.05, df = (1, 37), p = 0.830]. Comparisons of the maximal KF between the two groups found no significant differences at pre [F = 0.002, df = (1, 37), p = 0.968], however at post intervention the TC was significantly stronger [F = 4.52, df = (1, 37), p = 0.040].
Figure 6-2. Comparisons of the maximal voluntary contraction torque of the KF for the TCG and CG pre and post intervention period. *: p ≤ 0.05.

6.2.2.2  Ankle Plantarflexors and Dorsiflexors

The AP and AD two factor repeated measures GLM (group × trial) revealed a main effect of trial in both the AP [F = 10.32, df = (1, 37), p = 0.003] and AD [F = 4.28, df = (1, 37), p = 0.046]. The trial main effect revealed that there was a significant increase in AP and AD strength from pre to post intervention. There were however no group main effects for either the AP [F = 1.43, df = (1, 37), p = 0.240] or AD [F = 1.30, df = (1, 37), p = 0.262] and there were also no significant interaction for group × trial within the AP [F = 1.51, df = (1, 37), p = 0.227] or AD [F = 1.42, df = (1, 37), p = 0.241].
6.2.3 Maximal SEMG Amplitude

The observed means and standard deviations of maximal SEMG amplitude (Root Mean Square, RMS) for KE, KF (at 30°), AP and AD (at neutral) for the TCG and CG are presented in Table 6-2.

Table 6-2. SEMG (RMS) amplitude during maximal voluntary contractions for KE, KF, AP and AD for the Tai Chi group (TCG) and Control Group (CG) pre and post the intervention period.

<table>
<thead>
<tr>
<th></th>
<th>Tai Chi Pre</th>
<th>Tai Chi Post</th>
<th>Control Pre</th>
<th>Control Post</th>
</tr>
</thead>
<tbody>
<tr>
<td>KE</td>
<td>0.046 (0.043)</td>
<td>0.070 (0.049)</td>
<td>0.058 (0.035)</td>
<td>0.078 (0.104)</td>
</tr>
<tr>
<td>KF</td>
<td>0.025 (0.023)</td>
<td>0.045 (0.039)</td>
<td>0.041 (0.032)</td>
<td>0.034 (0.029)</td>
</tr>
<tr>
<td>AP</td>
<td>0.052 (0.041)</td>
<td>0.053 (0.033)</td>
<td>0.057 (0.050)</td>
<td>0.048 (0.037)</td>
</tr>
<tr>
<td>AD</td>
<td>0.128 (0.069)</td>
<td>0.179 (0.100)</td>
<td>0.160 (0.126)</td>
<td>0.198 (0.117)</td>
</tr>
</tbody>
</table>

Values in the table are Mean (SD)

6.2.3.1 Knee Extensors and Flexors

The two factor repeated measures GLM (group × trial) for the KE revealed no main effect of trial [F = 3.57, df = (1, 36), p = 0.067] or group [F = 0.39, df = (1, 36), p = 0.538] and no significant interaction for group × trial [F = 0.03, df = (1, 36), p = 0.855].

The two factor repeated measures GLM (group × trial) for the KF revealed no main effect for either group [F = 0.08, df = (1, 35), p = 0.774] or trial [F = 0.88, df = (1, 35), p = 0.355] and no significant interaction for group × trial [F = 3.89, df = (1, 35), p = 0.057].
6.2.3.2 Ankle Plantarflexors and Dorsiflexors

The two factor repeated measures GLM (group × trial) for the AP revealed no main effect of trial \( F = 0.40, \text{df} = (1, 35), p = 0.531 \) or group \( F < 0.001, \text{df} = (1, 35), p = 0.992 \) and no significant interaction for group × trial \( F = 0.52, \text{df} = (1, 35), p = 0.476 \).

The two factor repeated measures GLM (group × trial) for the AD revealed main effect of trial \( F = 7.01, \text{df} = (1, 37), p = 0.012 \) but not for group \( F = 0.81, \text{df} = (1, 37), p = 0.374 \) and no significant interaction for group × trial \( F = 0.14, \text{df} = (1, 37), p = 0.711 \).
6.2.4 **Strength Ratios**

The observed means and standard deviations of the HQR (at 30°) and DPR (at neutral) for the TCG and CG are presented in Table 6-3.

**Table 6-3. HQR and DPR values for the Tai Chi group (TCG) and Control Group (CG).**

<table>
<thead>
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<th>Tai Chi</th>
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<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
<td>Pre</td>
<td>Post</td>
</tr>
<tr>
<td>HQR</td>
<td>0.85</td>
<td>(0.27)</td>
<td>0.77</td>
<td>(0.29)</td>
</tr>
<tr>
<td></td>
<td>(0.27)</td>
<td></td>
<td>(0.27)</td>
<td>(0.20)</td>
</tr>
<tr>
<td>DPR</td>
<td>0.46</td>
<td>(0.22)</td>
<td>0.61</td>
<td>(0.25)</td>
</tr>
<tr>
<td></td>
<td>(0.43)</td>
<td></td>
<td>(0.20)</td>
<td>(0.14)</td>
</tr>
</tbody>
</table>

Values in the table are Mean (SD)

**6.2.4.1 Hamstring to Quadriceps Ratio and Dorsiflexor to Plantarflexor Ratio**

The two factor repeated measures GLM (group × trial) for the HQR revealed no main effect of trial \( F = 0.02, \text{df} = (1, 37), \text{p} = 0.880 \) or group \( F = 3.73, \text{df} = (1, 37), \text{p} = 0.061 \) and no significant interaction for group × trial \( F = 2.70, \text{df} = (1, 37), \text{p} = 0.109 \).

The two factor repeated measures GLM (group × trial) for the DPR revealed main effect of group \( F = 4.78, \text{df} = (1, 37), \text{p} = 0.035 \) but no effect of trial \( F = 3.28, \text{df} = (1, 37), \text{p} = 0.078 \) and no significant interaction for group × trial \( F = 0.62, \text{df} = (1, 37), \text{p} = 0.435 \). The group main effect revealed that the TCG was significantly lower than the CG.
6.2.5   Strength Task Coactivation

The observed means and standard deviations of coactivation level for KE, KF (at 30°), AP and AD (at neutral) for the TCG and CG are presented in Table 6-4.

Table 6-4. Antagonist coactivation levels during maximal voluntary contractions for KE, KF, AP and AD for the Tai Chi group (TCG) and Control Group (CG) pre and post the intervention period.

<table>
<thead>
<tr>
<th></th>
<th>Tai Chi</th>
<th>Pre</th>
<th>Post</th>
<th>Control</th>
<th>Pre</th>
<th>Post</th>
</tr>
</thead>
<tbody>
<tr>
<td>KE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(%)</td>
<td>30.16 (17.71)</td>
<td>23.76 (15.55)</td>
<td>23.03 (11.87)</td>
<td>29.73 (22.99)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>KF</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(%)</td>
<td>21.57 (13.69)</td>
<td>14.52 (11.24)</td>
<td>12.27 (8.91)</td>
<td>22.91 (14.52)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AP</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(%)</td>
<td>14.63 (14.06)</td>
<td>15.13 (16.40)</td>
<td>14.89 (17.51)</td>
<td>13.76 (15.76)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AD</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(%)</td>
<td>23.27 (17.89)</td>
<td>25.92 (20.77)</td>
<td>27.49 (22.48)</td>
<td>28.60 (20.08)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Values in the table are Mean (SD)

6.2.5.1   Hamstring Quadriceps Coactivation

The two factor repeated measures GLM (group × trial) for the KE revealed no main effect of group [F = 0.01, df = (1, 34), p = 0.911] or trial [F = 0.003, df = (1, 34), p = 0.960] however there was a significant interaction for group × trial [F = 4.99, df = (1, 34), p = 0.032]. The two factor repeated measures GLM (group × trial) for the KF revealed no main effect for either group [F = 0.02, df = (1, 34), p = 0.903] or trial [F = 0.77, df = (1, 34), p = 0.388], however there was a significant interaction for group × trial [F = 18.49, df = (1, 34), p < 0.001].

Post hoc analysing of the levels of coactivity within the KE during knee flexion found no significant differences at either pre [F = 1.75, df = (1, 34), p = 0.194] or post intervention [F = 0.87, df = (1, 34), p = 0.359] when comparing between groups. The comparison between groups for KF coactivation found that pre intervention the TCG exhibited significantly higher
levels of coactivity \( [F = 5.06, \text{df} = (1, 34), p = 0.031] \), however, no significant difference was detected post the intervention period \( [F = 3.79, \text{df} = (1, 34), p = 0.060] \) (Figure 6-6).

![Figure 6-3. Comparisons of KE and KF coactivity levels between TCG and CG groups during maximal voluntary contractions. *: p ≤ 0.05.](image)

Comparisons between trials found that in the TCG there were no changes in KE coactivation pre to post intervention \( [F = 3.07, \text{df} = (1, 34), p = 0.089] \). However within the KF there was a significant decrease in the level of coactivity \( [F = 7.54, \text{df} = (1, 34), p = 0.010] \). Within the CG there was no change in KE coactivity from pre to post \( [F = 2.14, \text{df} = (1, 34), p = 0.153] \), however KF coactivation significantly increased post the intervention period \( [F = 10.96, \text{df} = (1, 34), p = 0.002] \) (Figure 6-7).

![Figure 6-4. Comparisons of KE and KF coactivity levels pre and post intervention during maximal voluntary contractions for both the TCG and CG groups. *: p ≤ 0.05.](image)
6.2.5.2  Dorsiflexor Plantarplexor Coactivation

The two factor repeated measures GLM (group × trial) for the AP revealed no main effect of either group \( [F = 0.01, \text{df} = (1, 35), p = 0.907] \) or trial \( [F = 0.02, \text{df} = (1, 35), p = 0.901] \) and no significant interaction for group × trial \( [F = 0.12, \text{df} = (1, 35), p = 0.745] \). The two factor repeated measures GLM (group × trial) for the AD revealed no main effect of trial \( [F = 0.37, \text{df} = (1, 34), p = 0.548] \) or group \( [F = 0.32, \text{df} = (1, 34), p = 0.575] \) and no significant interaction for group × trial \( [F = 0.06, \text{df} = (1, 34), p = 0.804] \).
6.2.6 Postural Control Traditional Parameters

6.2.6.1 Mean Distance Measures

The observed means and standard deviations of the mean distance measures during the four sensory conditions for the TCG and CG are presented in Table 6-5.

Table 6-5. Mean distance measures (Mean Dist, Mean Dist AnPo and Mean Dist MeLa) (mm) of the Tai Chi and Control participants COP during the four SOT conditions for both pre and post intervention tests.

<table>
<thead>
<tr>
<th></th>
<th>Pre</th>
<th></th>
<th></th>
<th>Post</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Dist</td>
<td>Mean Dist AnPo</td>
<td>Mean Dist MeLa</td>
<td>Mean Dist</td>
<td>Mean Dist AnPo</td>
<td>Mean Dist MeLa</td>
</tr>
<tr>
<td>SOT1</td>
<td>5.82 (1.78)</td>
<td>4.73 (1.70)</td>
<td>2.55 (0.73)</td>
<td>5.26 (1.50)</td>
<td>4.28 (1.44)</td>
<td>2.24 (0.79)</td>
</tr>
<tr>
<td>(mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT2</td>
<td>5.84 (1.55)</td>
<td>4.43 (1.22)</td>
<td>2.92 (0.99)</td>
<td>5.62 (1.53)</td>
<td>4.41 (1.32)</td>
<td>2.61 (0.99)</td>
</tr>
<tr>
<td>(mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT3</td>
<td>7.15 (2.14)</td>
<td>5.61 (2.02)</td>
<td>3.37 (0.85)</td>
<td>6.64 (2.06)</td>
<td>5.05 (1.87)</td>
<td>3.34 (0.98)</td>
</tr>
<tr>
<td>(mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT4</td>
<td>8.17 (2.47)</td>
<td>6.00 (2.04)</td>
<td>4.36 (1.36)</td>
<td>8.04 (2.02)</td>
<td>5.88 (1.62)</td>
<td>4.23 (1.31)</td>
</tr>
<tr>
<td>(mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For each of the three mean distance measures (Mean Dist, Mean Dist AnPo and Mean Dist MeLa) a two factor repeated measures GLM (group × trial) was conducted and repeated for each of the four SOT conditions. This was followed by an analysis of group × trial interactions. Table 6-6 presents the group and trial main effect analysis for each of the mean distance measures as well as the group × trial interactions.
It can be seen within table 6-6 that for all three Mean Dist measures across all four SOT conditions there were no significant main effects of group or trial and there were also no significant group × trial interactions.

Table 6-6. F statistics, degrees of freedom (df) and significance level for the main effect of group and trial and group × trial interaction of the mean distance measures (Mean Dist, Mean Dist AnPo and Mean Dist MeLa).

<table>
<thead>
<tr>
<th></th>
<th>Mean Dist</th>
<th>Mean Dist AnPo</th>
<th>Mean Dist MeLa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SOT1   SOT2  SOT3  SOT4</td>
<td>SOT1  SOT2  SOT3  SOT4</td>
<td>SOT1  SOT2  SOT3  SOT4</td>
</tr>
<tr>
<td>Group</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>0.44   0.38  0.02  0.01</td>
<td>0.43  0.95  0.01  0.01</td>
<td>0.10  0.03  0.50  0.01</td>
</tr>
<tr>
<td>df</td>
<td>1,35   1,35  1,35  1,35</td>
<td>1,35  1,35  1,35  1,35</td>
<td>1,35  1,35  1,35  1,35</td>
</tr>
<tr>
<td>Sig</td>
<td>0.514  0.543  0.883  0.922</td>
<td>0.516  0.337  0.932  0.942</td>
<td>0.752  0.864  0.485  0.941</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trial</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>1.21   0.04  0.002  0.09</td>
<td>0.51  0.07  0.03  0.04</td>
<td>2.36  0.37  0.39  1.26</td>
</tr>
<tr>
<td>df</td>
<td>1,35   1,35  1,35  1,35</td>
<td>1,35  1,35  1,35  1,35</td>
<td>1,35  1,35  1,35  1,35</td>
</tr>
<tr>
<td>Sig</td>
<td>0.279  0.853  0.962  0.770</td>
<td>0.479  0.796  0.863  0.849</td>
<td>0.134  0.546  0.535  0.270</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group × Trial</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>1.59   0.32  3.73  0.17</td>
<td>1.56  0.10  3.56  0.55</td>
<td>1.29  0.74  0.63  0.11</td>
</tr>
<tr>
<td>df</td>
<td>1,35   1,35  1,35  1,35</td>
<td>1,35  1,35  1,35  1,35</td>
<td>1,35  1,35  1,35  1,35</td>
</tr>
<tr>
<td>Sig</td>
<td>0.215  0.577  0.062  0.683</td>
<td>0.219  0.755  0.068  0.465</td>
<td>0.263  0.394  0.434  0.740</td>
</tr>
</tbody>
</table>

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### Mean Velocity Measures

The observed means and standard deviations of the mean velocity measures during the four sensory conditions for the TCG and CG are presented in Table 6-7.

#### Table 6-7. Mean Velocity measures (Mean Vel, Mean Vel AnPo and Mean Vel MeLa) (mm/s) of the Tai Chi and Control participants COP during the four SOT conditions for both pre and post intervention measurements.

<table>
<thead>
<tr>
<th></th>
<th>Pre</th>
<th></th>
<th></th>
<th>Post</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Vel</td>
<td>Mean Vel AnPo</td>
<td>Mean Vel MeLa</td>
<td>Mean Vel</td>
<td>Mean Vel AnPo</td>
<td>Mean Vel MeLa</td>
</tr>
<tr>
<td>SOT1</td>
<td>13.05 (3.04)</td>
<td>10.01 (2.36)</td>
<td>6.28 (2.00)</td>
<td>12.13 (2.85)</td>
<td>9.61 (2.25)</td>
<td>5.45 (1.87)</td>
</tr>
<tr>
<td>(mm/s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT2</td>
<td>18.12 (6.41)</td>
<td>14.30 (4.80)</td>
<td>8.19 (4.10)</td>
<td>16.54 (6.09)</td>
<td>13.39 (4.56)</td>
<td>6.98 (3.70)</td>
</tr>
<tr>
<td>(mm/s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT3</td>
<td>16.72 (3.66)</td>
<td>13.10 (3.06)</td>
<td>7.73 (2.37)</td>
<td>15.53 (3.50)</td>
<td>12.34 (2.75)</td>
<td>6.95 (2.18)</td>
</tr>
<tr>
<td>(mm/s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT4</td>
<td>25.47 (7.41)</td>
<td>25.47 (7.41)</td>
<td>11.25 (4.81)</td>
<td>24.24 (7.22)</td>
<td>24.24 (7.22)</td>
<td>10.64 (4.81)</td>
</tr>
<tr>
<td>(mm/s)</td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td></td>
<td>Tai Chi</td>
<td></td>
<td></td>
<td>Control</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT1</td>
<td>11.74 (4.39)</td>
<td>9.24 (3.34)</td>
<td>5.43 (2.48)</td>
<td>11.31 (3.53)</td>
<td>8.95 (2.76)</td>
<td>5.15 (1.82)</td>
</tr>
<tr>
<td>(mm/s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT2</td>
<td>16.44 (7.81)</td>
<td>13.47 (6.05)</td>
<td>6.83 (4.00)</td>
<td>15.52 (5.71)</td>
<td>12.88 (4.65)</td>
<td>6.26 (2.64)</td>
</tr>
<tr>
<td>(mm/s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT3</td>
<td>15.42 (4.85)</td>
<td>12.08 (3.57)</td>
<td>7.22 (2.80)</td>
<td>15.64 (4.62)</td>
<td>12.27 (3.69)</td>
<td>7.22 (2.50)</td>
</tr>
<tr>
<td>(mm/s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT4</td>
<td>24.82 (9.07)</td>
<td>24.82 (9.07)</td>
<td>11.45 (5.26)</td>
<td>24.46 (8.08)</td>
<td>24.46 (8.08)</td>
<td>11.06 (4.87)</td>
</tr>
<tr>
<td>(mm/s)</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Values in the table are Mean (SD)

For each of the three mean velocity measures (Mean Vel, Mean Vel AnPo and Mean Vel MeLa) a two factor repeated measures GLM (group × trial) was conducted and repeated for each of the four SOT conditions. This was followed by an analysis of group × trial interactions. Table 6-8 presents the group and trial main effect analysis for each of the mean velocity measures as well as the group × trial interactions.
It can be seen within table 6-8 that for all three Mean Dist measures across all four SOT conditions there were no significant main effects of group or group × trial interactions. In relation to the main effects of trial there were significant effects within Mean Vel in SOT2 and Mean Vel MeLa SOT1 and SOT2. This trial main effect indicated that the Mean Vel measures decreased from pre to post intervention. All other Mean Vel measures showed no significant main effects of trial.

**Table 6-8. F statistics, degrees of freedom (df) and significance level for the main effect of group and trial and group × trial interaction for the mean velocity measures (Mean Vel, Mean Vel AnPo and Mean Vel MeLa).**

<table>
<thead>
<tr>
<th></th>
<th>Mean Vel</th>
<th>Mean Vel AnPo</th>
<th>Mean Vel MeLa</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SOT1</td>
<td>SOT2</td>
<td>SOT3</td>
</tr>
<tr>
<td><strong>Group</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>0.96</td>
<td>0.42</td>
<td>0.21</td>
</tr>
<tr>
<td>df</td>
<td>1, 35</td>
<td>1, 35</td>
<td>1, 35</td>
</tr>
<tr>
<td>Sig</td>
<td>0.334</td>
<td>0.523</td>
<td>0.650</td>
</tr>
<tr>
<td><strong>Trial</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>3.78</td>
<td>4.57</td>
<td>1.13</td>
</tr>
<tr>
<td>df</td>
<td>1, 35</td>
<td>1, 35</td>
<td>1, 35</td>
</tr>
<tr>
<td>Sig</td>
<td>0.060</td>
<td><strong>0.040</strong></td>
<td>0.295</td>
</tr>
<tr>
<td><strong>Group × Trial</strong></td>
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</tr>
<tr>
<td>F</td>
<td>0.51</td>
<td>0.33</td>
<td>2.38</td>
</tr>
<tr>
<td>df</td>
<td>1, 35</td>
<td>1, 35</td>
<td>1, 35</td>
</tr>
<tr>
<td>Sig</td>
<td>0.480</td>
<td>0.572</td>
<td>0.132</td>
</tr>
</tbody>
</table>
6.2.6.3 Area Measures

The observed means and standard deviations of the area measures (95% CCA and Sway Area) during the four sensory conditions for the TCG and CG are presented in Table 6-9.

Table 6-9. Sway Area measures (95% CCA and Sway Area) of the Tai Chi and Control participants during the four SOT conditions for both pre and post intervention measurements.

<table>
<thead>
<tr>
<th></th>
<th>95% CCA (mm/s)</th>
<th>Sway Area (mm²/s)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tai Chi</td>
<td>Control</td>
<td>Tai Chi</td>
<td>Control</td>
<td>Tai Chi</td>
<td>Control</td>
</tr>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
<td>Pre</td>
<td>Post</td>
<td>Pre</td>
<td>Post</td>
</tr>
<tr>
<td>SOT1</td>
<td>428.55(239.84)</td>
<td>379.75(224.00)</td>
<td>350.46(150.25)</td>
<td>371.34(167.62)</td>
<td>22.73(9.42)</td>
<td>18.80(8.96)</td>
</tr>
<tr>
<td></td>
<td>379.75(224.00)</td>
<td>350.46(150.25)</td>
<td>371.34(167.62)</td>
<td>22.73(9.42)</td>
<td>18.80(8.96)</td>
<td>18.26(9.14)</td>
</tr>
<tr>
<td>SOT2</td>
<td>452.39(238.86)</td>
<td>406.45(209.50)</td>
<td>461.98(197.22)</td>
<td>516.92(342.88)</td>
<td>33.67(20.68)</td>
<td>28.99(17.92)</td>
</tr>
<tr>
<td></td>
<td>406.45(209.50)</td>
<td>461.98(197.22)</td>
<td>516.92(342.88)</td>
<td>33.67(20.68)</td>
<td>28.99(17.92)</td>
<td>29.86(21.97)</td>
</tr>
<tr>
<td>SOT3</td>
<td>643.19(378.18)</td>
<td>559.95(383.46)</td>
<td>531.08(211.79)</td>
<td>611.27(320.10)</td>
<td>36.21(15.84)</td>
<td>31.01(12.83)</td>
</tr>
<tr>
<td></td>
<td>559.95(383.46)</td>
<td>531.08(211.79)</td>
<td>611.27(320.10)</td>
<td>36.21(15.84)</td>
<td>31.01(12.83)</td>
<td>30.43(12.73)</td>
</tr>
<tr>
<td>SOT4</td>
<td>884.83(581.05)</td>
<td>817.70(401.30)</td>
<td>865.29(519.95)</td>
<td>880.89(659.49)</td>
<td>66.89(36.81)</td>
<td>62.97(29.91)</td>
</tr>
<tr>
<td></td>
<td>817.70(401.30)</td>
<td>865.29(519.95)</td>
<td>880.89(659.49)</td>
<td>66.89(36.81)</td>
<td>62.97(29.91)</td>
<td>68.62(42.46)</td>
</tr>
</tbody>
</table>

Values in the table are Mean (SD)

For each of the two area measures (95% CCA and Sway Area) a two factor repeated measures GLM (group × trial) was conducted and repeated for each of the four SOT conditions. This was followed by an analysis of group × trial interactions. Table 6-10 presents the group and trial main effect analysis for each of the area measures as well as the group × trial interactions.

It can be seen within table 6-10 that for both area measures across all four SOT conditions there were no significant main effects of group or trial. In relation to the group × trial interactions the only interaction found was within SOT3 of Sway Area while all other SOT conditions exhibited non-significant interactions.
Table 6-10. F statistics, degrees of freedom (df) and significance level for the main effect of group and trial and group × trial interaction for the sway area measures (95% CCA and Sway Area).

<table>
<thead>
<tr>
<th></th>
<th>Group</th>
<th></th>
<th>Sway Area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>95% CCA</td>
<td>SOT1</td>
<td>SOT2</td>
</tr>
<tr>
<td><strong>F</strong></td>
<td>0.53</td>
<td>0.77</td>
<td>0.09</td>
</tr>
<tr>
<td><strong>df</strong></td>
<td>1, 35</td>
<td>1, 35</td>
<td>1, 35</td>
</tr>
<tr>
<td><strong>Sig</strong></td>
<td>0.474</td>
<td>0.385</td>
<td>0.769</td>
</tr>
<tr>
<td><strong>F</strong></td>
<td>0.16</td>
<td>0.01</td>
<td>0.001</td>
</tr>
<tr>
<td><strong>df</strong></td>
<td>1, 35</td>
<td>1, 35</td>
<td>1, 35</td>
</tr>
<tr>
<td><strong>Sig</strong></td>
<td>0.689</td>
<td>0.925</td>
<td>0.976</td>
</tr>
<tr>
<td><strong>F</strong></td>
<td>1.02</td>
<td>1.14</td>
<td>2.65</td>
</tr>
<tr>
<td><strong>df</strong></td>
<td>1, 35</td>
<td>1, 35</td>
<td>1, 35</td>
</tr>
<tr>
<td><strong>Sig</strong></td>
<td>0.320</td>
<td>0.294</td>
<td>0.113</td>
</tr>
</tbody>
</table>

Post hoc interaction analysis found that when considering Sway Area SOT3 there was a significant decrease from pre to post intervention within the TCG [F = 5.42, df = (1, 35), p = 0.026] while the CG showed no change [F = 1.01, df = (1, 35), p = 0.323]. However, there were no significant differences between the TCG or CG at either pre [F = 1.39, df = (1, 35), p = 0.247] or post [F = 0.22, df = (1, 35), p = 0.643] intervention.
6.2.7 Postural Control Diffusion Parameters

6.2.7.1 Critical Point Measures

The observed means and standard deviations of the critical point measures during the four sensory conditions for the TCG and CG are presented in Table 6-11.

Table 6-11. Critical point measures (Crit Point R, Crit Point Y, & Crit Point X) of the Tai Chi and Control participants during the four SOT conditions for both pre and post intervention measurements.

<table>
<thead>
<tr>
<th></th>
<th>Pre</th>
<th></th>
<th></th>
<th>Post</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Crit Point R</td>
<td>Crit Point Y</td>
<td>Crit Point X</td>
<td>Crit Point R</td>
<td>Crit Point Y</td>
<td>Crit Point X</td>
</tr>
<tr>
<td>Tai Chi</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT1</td>
<td>1.08</td>
<td>1.10</td>
<td>1.19</td>
<td>1.08</td>
<td>1.11</td>
<td>1.17</td>
</tr>
<tr>
<td>(s)</td>
<td>(0.36)</td>
<td>(0.44)</td>
<td>(0.43)</td>
<td>(0.30)</td>
<td>(0.32)</td>
<td>(0.35)</td>
</tr>
<tr>
<td>SOT2</td>
<td>1.10</td>
<td>1.07</td>
<td>1.17</td>
<td>1.06</td>
<td>1.05</td>
<td>1.24</td>
</tr>
<tr>
<td>(s)</td>
<td>(0.35)</td>
<td>(0.34)</td>
<td>(0.38)</td>
<td>(0.36)</td>
<td>(0.37)</td>
<td>(0.46)</td>
</tr>
<tr>
<td>SOT3</td>
<td>1.29</td>
<td>1.38</td>
<td>1.38</td>
<td>1.28</td>
<td>1.34</td>
<td>1.61</td>
</tr>
<tr>
<td>(s)</td>
<td>(0.39)</td>
<td>(0.49)</td>
<td>(0.49)</td>
<td>(0.33)</td>
<td>(0.38)</td>
<td>(0.50)</td>
</tr>
<tr>
<td>SOT4</td>
<td>1.04</td>
<td>1.07</td>
<td>1.67</td>
<td>1.22</td>
<td>1.17</td>
<td>1.58</td>
</tr>
<tr>
<td>(s)</td>
<td>(0.20)</td>
<td>(0.21)</td>
<td>(0.52)</td>
<td>(0.41)</td>
<td>(0.40)</td>
<td>(0.58)</td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT1</td>
<td>1.11</td>
<td>1.27</td>
<td>1.29</td>
<td>1.14</td>
<td>1.35</td>
<td>1.14</td>
</tr>
<tr>
<td>(s)</td>
<td>(0.24)</td>
<td>(0.44)</td>
<td>(0.45)</td>
<td>(0.38)</td>
<td>(0.57)</td>
<td>(0.35)</td>
</tr>
<tr>
<td>SOT2</td>
<td>1.15</td>
<td>1.17</td>
<td>1.24</td>
<td>1.17</td>
<td>1.15</td>
<td>1.20</td>
</tr>
<tr>
<td>(s)</td>
<td>(0.49)</td>
<td>(0.50)</td>
<td>(0.37)</td>
<td>(0.42)</td>
<td>(0.38)</td>
<td>(0.38)</td>
</tr>
<tr>
<td>SOT3</td>
<td>1.36</td>
<td>1.37</td>
<td>1.46</td>
<td>1.41</td>
<td>1.49</td>
<td>1.17</td>
</tr>
<tr>
<td>(s)</td>
<td>(0.45)</td>
<td>(0.43)</td>
<td>(0.53)</td>
<td>(0.48)</td>
<td>(0.49)</td>
<td>(0.30)</td>
</tr>
<tr>
<td>SOT4</td>
<td>1.04</td>
<td>1.05</td>
<td>1.55</td>
<td>1.14</td>
<td>1.16</td>
<td>1.59</td>
</tr>
<tr>
<td>(s)</td>
<td>(0.35)</td>
<td>(0.35)</td>
<td>(0.56)</td>
<td>(0.34)</td>
<td>(0.46)</td>
<td>(0.54)</td>
</tr>
</tbody>
</table>

Values in the table are Mean (SD)

For each of the three critical point measures (Crit Point R, Crit Point Y, & Crit Point X) a two factor repeated measures GLM (group × trial) was conducted and repeated for each of the four SOT conditions. This was followed by an analysis of group × trial interactions. Table 6-12 presents the group and trial main effect analysis for each of the critical point measures as well as the group × trial interactions.
As seen in table 6-12 the Crit Point measures across all four SOT conditions exhibited no significant main effects of group. Crit Point R in SOT4 did exhibit a significant trial main effect which indicated a significant increase from pre to post intervention, however no other SOT condition in all other Crit Point measures showed a trial main effect. In relation to the group × trial interactions the only interaction found was within SOT3 of Crit Point X while all other SOT conditions exhibited non-significant interactions.

Table 6-12. F statistics, degrees of freedom (df) and significance level for the main effect of group and trial and group × trial interaction for the critical point measures (Crit Point R, Crit Point Y, & Crit Point X).

<table>
<thead>
<tr>
<th></th>
<th>Crit Point R</th>
<th>Crit Point Y</th>
<th>Crit Point X</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SOT1 SOT2 SOT3 SOT4</td>
<td>SOT1 SOT2 SOT3 SOT4</td>
<td>SOT1 SOT2 SOT3 SOT4</td>
</tr>
<tr>
<td>Group</td>
<td>F 0.23 0.41 0.74 0.25</td>
<td>2.68 0.84 0.28 0.04</td>
<td>0.10 0.02 1.59 0.12</td>
</tr>
<tr>
<td></td>
<td>df 1, 35 1, 35 1, 35 1, 35</td>
<td>1, 35 1, 35 1, 35 1, 35</td>
<td>1, 35 1, 35 1, 35 1, 35</td>
</tr>
<tr>
<td></td>
<td>Sig 0.633 0.524 0.396 0.620</td>
<td>0.110 0.367 0.602 0.835</td>
<td>0.752 0.897 0.215 0.735</td>
</tr>
<tr>
<td>Trial</td>
<td>F 0.05 0.02 0.06 4.62</td>
<td>0.35 0.07 0.24 1.96</td>
<td>1.36 0.08 0.19 0.12</td>
</tr>
<tr>
<td></td>
<td>df 1, 35 1, 35 1, 35 1, 35</td>
<td>1, 35 1, 35 1, 35 1, 35</td>
<td>1, 35 1, 35 1, 35 1, 35</td>
</tr>
<tr>
<td></td>
<td>Sig 0.826 0.889 0.805 0.039*</td>
<td>0.561 0.794 0.630 0.171</td>
<td>0.251 0.783 0.665 0.747</td>
</tr>
<tr>
<td>Group × Trial</td>
<td>F 0.06 0.20 0.11 0.33</td>
<td>0.17 0.001 0.86 0.004</td>
<td>0.70 0.71 14.69 0.54</td>
</tr>
<tr>
<td></td>
<td>df 1, 35 1, 35 1, 35 1, 35</td>
<td>1, 35 1, 35 1, 35 1, 35</td>
<td>1, 35 1, 35 1, 35 1, 35</td>
</tr>
<tr>
<td></td>
<td>Sig 0.803 0.659 0.741 0.567</td>
<td>0.683 0.974 0.361 0.953</td>
<td>0.408 0.406 0.001* 0.466</td>
</tr>
</tbody>
</table>

Post hoc analysis of the group × trial interaction in SOT3 of Crit Point X found that there was a significant increase from pre to post intervention in the TCG [F = 7.11, df = (1, 35), p = 0.012], however over the same time period there was a significant decline in the CG [F = 7.67, df = (1, 35), p = 0.009]. Comparison between groups showed that there was no significant difference pre intervention [F = 0.22, df = (1, 35), p = 0.642], however after the 12 weeks of TC it was found that the TCG exhibited significantly higher Crit Point X on average [F = 9.16, df = (1, 35), p = 0.005].
6.2.7.2 Critical Point Coordinate Measures

The observed means and standard deviations of the critical point coordinate measures during the four sensory conditions for the TCG and CG are presented in Table 6-13.

Table 6-13. Critical point coordinate measures (Crit Point Coord R, Crit Point Coord Y, & Crit Point Coord X) (mm²) of the Tai Chi and Control participants COP during the four SOT conditions for both pre and post intervention measurements.

<table>
<thead>
<tr>
<th></th>
<th>Pre</th>
<th>Post</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Crit Point Coord R</td>
<td>Crit Point Coord Y</td>
<td>Crit Point Coord X</td>
<td>Crit Point Coord R</td>
<td>Crit Point Coord Y</td>
</tr>
<tr>
<td>SOT1</td>
<td>(mm²)</td>
<td>(mm²)</td>
<td>(mm²)</td>
<td>(mm²)</td>
<td>(mm²)</td>
</tr>
<tr>
<td>Tai Chi</td>
<td>34.79 (20.29)</td>
<td>24.33 (16.57)</td>
<td>11.21 (7.52)</td>
<td>34.58 (23.66)</td>
<td>25.68 (19.75)</td>
</tr>
<tr>
<td>SOT2</td>
<td>(mm²)</td>
<td>(mm²)</td>
<td>(mm²)</td>
<td>(mm²)</td>
<td>(mm²)</td>
</tr>
<tr>
<td></td>
<td>52.91 (31.92)</td>
<td>35.56 (22.66)</td>
<td>17.01 (12.54)</td>
<td>45.43 (23.11)</td>
<td>32.24 (16.67)</td>
</tr>
<tr>
<td>SOT3</td>
<td>(mm²)</td>
<td>(mm²)</td>
<td>(mm²)</td>
<td>(mm²)</td>
<td>(mm²)</td>
</tr>
<tr>
<td></td>
<td>73.98 (54.88)</td>
<td>51.78 (35.21)</td>
<td>24.66 (23.23)</td>
<td>67.31 (47.37)</td>
<td>49.32 (37.99)</td>
</tr>
<tr>
<td>SOT4</td>
<td>(mm²)</td>
<td>(mm²)</td>
<td>(mm²)</td>
<td>(mm²)</td>
<td>(mm²)</td>
</tr>
<tr>
<td></td>
<td>124.26 (91.78)</td>
<td>82.56 (62.36)</td>
<td>56.28 (42.29)</td>
<td>120.08 (64.13)</td>
<td>74.12 (39.56)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Pre</th>
<th>Post</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Crit Point Coord R</td>
<td>Crit Point Coord Y</td>
<td>Crit Point Coord X</td>
<td>Crit Point Coord R</td>
<td>Crit Point Coord Y</td>
</tr>
<tr>
<td>Control</td>
<td>37.17 (14.97)</td>
<td>27.73 (11.38)</td>
<td>12.16 (7.75)</td>
<td>36.37 (14.58)</td>
<td>31.13 (17.99)</td>
</tr>
<tr>
<td></td>
<td>(mm²)</td>
<td>(mm²)</td>
<td>(mm²)</td>
<td>(mm²)</td>
<td>(mm²)</td>
</tr>
<tr>
<td>SOT2</td>
<td>(mm²)</td>
<td>(mm²)</td>
<td>(mm²)</td>
<td>(mm²)</td>
<td>(mm²)</td>
</tr>
<tr>
<td></td>
<td>53.57 (29.30)</td>
<td>39.95 (19.41)</td>
<td>15.87 (11.63)</td>
<td>62.62 (41.88)</td>
<td>47.41 (30.96)</td>
</tr>
<tr>
<td>SOT3</td>
<td>(mm²)</td>
<td>(mm²)</td>
<td>(mm²)</td>
<td>(mm²)</td>
<td>(mm²)</td>
</tr>
<tr>
<td></td>
<td>74.64 (32.87)</td>
<td>53.37 (23.77)</td>
<td>22.45 (11.13)</td>
<td>83.41 (57.36)</td>
<td>62.37 (43.68)</td>
</tr>
<tr>
<td>SOT4</td>
<td>(mm²)</td>
<td>(mm²)</td>
<td>(mm²)</td>
<td>(mm²)</td>
<td>(mm²)</td>
</tr>
<tr>
<td></td>
<td>117.38 (52.28)</td>
<td>75.27 (32.71)</td>
<td>53.13 (41.63)</td>
<td>130.65 (80.21)</td>
<td>86.88 (59.67)</td>
</tr>
</tbody>
</table>

Values in the table are Mean (SD)

For each of the three critical point coordinate measures (Crit Point Coord R, Crit Point Coord Y, & Crit Point Coord X) a two factor repeated measures GLM (group × trial) was conducted and was repeated for each of the four SOT conditions. This was followed by an analysis of group × trial interactions. Table 6-14 presents the group and trial main effect analysis for each of the critical point coordinate measures as well as the group × trial interactions.
Table 6-14 shows that for all three Crit Point Coord measures across all four SOT conditions there were no significant main effects of group or group × trial interactions. In relation to the main effects of trial there were no significant effects accept for Crit Point Coord X in SOT1 condition. This trial main effect indicated that the mean Crit Point Coord X decreased from pre to post intervention.

Table 6-14. F statistics, degrees of freedom (df) and significance level for the main effect of group and trial and group × trial interaction for the critical point coordinate measures (Crit Point Coord R, Crit Point Coord Y, & Crit Point Coord X).

<table>
<thead>
<tr>
<th></th>
<th>Crit Point Coord R</th>
<th></th>
<th>Crit Point Coord Y</th>
<th></th>
<th>Crit Point Coord X</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SOT1</td>
<td>SOT2</td>
<td>SOT3</td>
<td>SOT4</td>
<td>SOT1</td>
<td>SOT2</td>
</tr>
<tr>
<td><strong>Group</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>F</strong></td>
<td>0.12</td>
<td>0.92</td>
<td>0.29</td>
<td>0.01</td>
<td>0.78</td>
<td>2.11</td>
</tr>
<tr>
<td><strong>df</strong></td>
<td>1, 35</td>
<td>1, 35</td>
<td>1, 35</td>
<td>1, 35</td>
<td>1, 35</td>
<td>1, 35</td>
</tr>
<tr>
<td><strong>Sig</strong></td>
<td>0.729</td>
<td>0.343</td>
<td>0.596</td>
<td>0.937</td>
<td>0.385</td>
<td>0.155</td>
</tr>
<tr>
<td><strong>Trial</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>F</strong></td>
<td>0.04</td>
<td>0.03</td>
<td>0.04</td>
<td>0.21</td>
<td>0.78</td>
<td>0.38</td>
</tr>
<tr>
<td><strong>df</strong></td>
<td>1, 35</td>
<td>1, 35</td>
<td>1, 35</td>
<td>1, 35</td>
<td>1, 35</td>
<td>1, 35</td>
</tr>
<tr>
<td><strong>Sig</strong></td>
<td>0.847</td>
<td>0.875</td>
<td>0.849</td>
<td>0.648</td>
<td>0.384</td>
<td>0.540</td>
</tr>
<tr>
<td><strong>Group × Trial</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>F</strong></td>
<td>0.01</td>
<td>2.77</td>
<td>1.99</td>
<td>0.78</td>
<td>0.14</td>
<td>2.60</td>
</tr>
<tr>
<td><strong>df</strong></td>
<td>1, 35</td>
<td>1, 35</td>
<td>1, 35</td>
<td>1, 35</td>
<td>1, 35</td>
<td>1, 35</td>
</tr>
<tr>
<td><strong>Sig</strong></td>
<td>0.912</td>
<td>0.105</td>
<td>0.167</td>
<td>0.382</td>
<td>0.707</td>
<td>0.116</td>
</tr>
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</table>
6.2.7.3 Diffusion Coefficient Short Term Measures

The observed means and standard deviations of the diffusion coefficient short term measures during the four sensory conditions for the TCG and CG are presented in Table 6-15.

Table 6-15. Diffusion Coefficient short term measures (Diff Co st R, Diff Co st Y and Diff Co st X) (mm$^2$/s) of the Tai Chi and Control participants COP during the four SOT conditions for both pre and post intervention.

<table>
<thead>
<tr>
<th></th>
<th>Pre</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Diff Co st R</td>
<td>Diff Co st Y</td>
<td>Diff Co st X</td>
<td>Diff Co st R</td>
<td>Diff Co st Y</td>
<td>Diff Co st X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tai Chi</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT1 (mm$^2$/s)</td>
<td>23.54 (11.65)</td>
<td>15.88 (6.96)</td>
<td>7.72 (5.58)</td>
<td>22.76 (11.66)</td>
<td>16.29 (8.96)</td>
<td>6.50 (4.59)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT2 (mm$^2$/s)</td>
<td>40.99 (29.80)</td>
<td>28.24 (18.00)</td>
<td>12.87 (14.49)</td>
<td>35.52 (22.15)</td>
<td>25.99 (14.34)</td>
<td>9.60 (9.65)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT3 (mm$^2$/s)</td>
<td>36.43 (17.68)</td>
<td>24.70 (11.81)</td>
<td>11.88 (7.79)</td>
<td>33.18 (16.50)</td>
<td>23.54 (12.59)</td>
<td>9.70 (5.38)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT4 (mm$^2$/s)</td>
<td>82.19 (47.47)</td>
<td>57.87 (34.56)</td>
<td>24.61 (19.91)</td>
<td>72.33 (37.64)</td>
<td>50.30 (27.09)</td>
<td>22.27 (15.92)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT1 (mm$^2$/s)</td>
<td>24.00 (12.70)</td>
<td>16.99 (9.98)</td>
<td>7.05 (4.67)</td>
<td>22.96 (10.07)</td>
<td>16.72 (7.67)</td>
<td>6.29 (3.15)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT2 (mm$^2$/s)</td>
<td>40.87 (28.63)</td>
<td>30.61 (18.68)</td>
<td>10.31 (11.51)</td>
<td>38.78 (22.53)</td>
<td>29.67 (16.81)</td>
<td>9.16 (6.45)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT3 (mm$^2$/s)</td>
<td>37.53 (21.76)</td>
<td>25.95 (13.49)</td>
<td>11.69 (9.05)</td>
<td>38.02 (18.31)</td>
<td>25.71 (11.80)</td>
<td>12.35 (7.95)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT4 (mm$^2$/s)</td>
<td>91.79 (58.56)</td>
<td>63.21 (45.56)</td>
<td>28.68 (21.08)</td>
<td>83.64 (47.07)</td>
<td>57.23 (30.15)</td>
<td>26.60 (19.74)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Values in the table are Mean (SD)

For each of the three diffusion coefficient short term measures (Diff Co st R, Diff Co st Y and Diff Co st X) a two factor repeated measures GLM (group × trial) was conducted and was repeated for each of the four SOT conditions. This was followed by an analysis of group × trial interactions. Table 6-16 presents the group and trial main effect analysis for each of the diffusion coefficient short term measures as well as the group × trial interactions.
Table 6-16 shows that for all three Diff Co st measures across all four SOT conditions there were no significant main effects of group or trial and there were also no significant group × trial interactions.

Table 6-16. F statistics, degrees of freedom (df) and significance level for the main effect of group and trial and group × trial interaction diffusion coefficient short term measures (Diff Co st R, Diff Co st Y and Diff Co st X).

<table>
<thead>
<tr>
<th></th>
<th>Diff Co st R</th>
<th></th>
<th>Diff Co st Y</th>
<th></th>
<th>Diff Co st X</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SOT1 SOT2 SOT3 SOT4</td>
<td>SOT1 SOT2 SOT3 SOT4</td>
<td>SOT1 SOT2 SOT3 SOT4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Group</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>0.01 0.04 0.26 0.52</td>
<td>0.10 0.32 0.20 0.35</td>
<td>0.09 0.19 0.28 0.52</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>df</td>
<td>1, 35 1, 35 1, 35 1, 35</td>
<td>1, 35 1, 35 1, 35 1, 35</td>
<td>1, 35 1, 35 1, 35 1, 35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sig</td>
<td>0.926 0.852 0.614 0.477</td>
<td>0.755 0.575 0.660 0.558</td>
<td>0.769 0.667 0.603 0.475</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Trial</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>0.32 1.92 0.51 2.12</td>
<td>0.003 0.73 0.21 1.87</td>
<td>3.94 2.17 0.73 0.71</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>df</td>
<td>1, 35 1, 35 1, 35 1, 35</td>
<td>1, 35 1, 35 1, 35 1, 35</td>
<td>1, 35 1, 35 1, 35 1, 35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sig</td>
<td>0.578 0.175 0.480 0.154</td>
<td>0.960 0.397 0.650 0.180</td>
<td>0.055 0.149 0.399 0.404</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Group × Trial</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>0.01 0.38 0.93 0.02</td>
<td>0.07 0.13 0.09 0.03</td>
<td>0.21 0.50 2.59 0.003</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>df</td>
<td>1, 35 1, 35 1, 35 1, 35</td>
<td>1, 35 1, 35 1, 35 1, 35</td>
<td>1, 35 1, 35 1, 35 1, 35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sig</td>
<td>0.936 0.540 0.341 0.890</td>
<td>0.800 0.725 0.767 0.873</td>
<td>0.649 0.485 0.117 0.960</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
6.2.7.4  Diffusion Coefficient Long Term Measures

The observed means and standard deviations of the diffusion coefficient long term measures during the four sensory conditions for the TCG and CG are presented in Table 6-17.

Table 6-17. Diffusion Coefficient long term measures (Diff Co lt R, Diff Co lt Y and Diff Co lt X) (mm\(^2\)/s) of the Tai Chi and Control participants during the four SOT conditions for both pre and post intervention period.

<table>
<thead>
<tr>
<th></th>
<th>Pre Diff Co lt R</th>
<th>Pre Diff Co lt Y</th>
<th>Pre Diff Co lt X</th>
<th>Post Diff Co lt R</th>
<th>Post Diff Co lt Y</th>
<th>Post Diff Co lt X</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tai Chi</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT1</td>
<td>4.02 (3.27)</td>
<td>3.19 (2.93)</td>
<td>0.80 (0.50)</td>
<td>3.32 (2.31)</td>
<td>2.80 (2.22)</td>
<td>0.53 (0.50)</td>
</tr>
<tr>
<td>SOT2</td>
<td>2.81 (1.78)</td>
<td>1.89 (1.55)</td>
<td>0.96 (0.84)</td>
<td>2.34 (2.28)</td>
<td>1.77 (2.11)</td>
<td>0.58 (0.76)</td>
</tr>
<tr>
<td>SOT3</td>
<td>5.28 (4.31)</td>
<td>4.29 (3.80)</td>
<td>1.15 (1.00)</td>
<td>4.75 (4.18)</td>
<td>3.42 (3.37)</td>
<td>1.12 (1.11)</td>
</tr>
<tr>
<td>SOT4</td>
<td>3.66 (4.93)</td>
<td>3.00 (4.51)</td>
<td>0.65 (2.57)</td>
<td>4.17 (3.22)</td>
<td>2.73 (2.77)</td>
<td>1.34 (1.21)</td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT1</td>
<td>2.68 (1.30)</td>
<td>2.16 (1.19)</td>
<td>0.65 (0.54)</td>
<td>3.12 (2.39)</td>
<td>2.22 (1.68)</td>
<td>0.76 (0.97)</td>
</tr>
<tr>
<td>SOT2</td>
<td>3.02 (2.61)</td>
<td>2.21 (2.15)</td>
<td>0.81 (1.27)</td>
<td>2.69 (2.35)</td>
<td>1.87 (1.52)</td>
<td>0.84 (1.10)</td>
</tr>
<tr>
<td>SOT3</td>
<td>3.23 (1.87)</td>
<td>2.57 (1.62)</td>
<td>0.72 (0.72)</td>
<td>4.39 (2.54)</td>
<td>3.14 (2.11)</td>
<td>1.21 (1.53)</td>
</tr>
<tr>
<td>SOT4</td>
<td>4.94 (6.41)</td>
<td>2.85 (3.03)</td>
<td>2.01 (3.47)</td>
<td>3.93 (6.65)</td>
<td>2.41 (4.70)</td>
<td>1.35 (2.38)</td>
</tr>
</tbody>
</table>

Values in the table are Mean (SD)

For each of the three diffusion coefficient long term measures (Diff Co lt R, Diff Co lt Y and Diff Co lt X) a two factor repeated measures GLM (group × trial) was conducted and was repeated for each of the four SOT conditions. This was followed by an analysis of group × trial interactions. Table 6-18 presents the group and trial main effect analysis for each of the diffusion coefficient long term measures as well as the group × trial interactions.
Table 6-18 shows that for all three Diff Co lt measures across all four SOT conditions there were no significant main effects of group or trial and there were also no significant group × trial interactions.

<table>
<thead>
<tr>
<th></th>
<th>Diff Co lt R</th>
<th>Diff Co lt Y</th>
<th>Diff Co lt X</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SOT1</td>
<td>SOT2</td>
<td>SOT3</td>
</tr>
<tr>
<td>Group</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>1.22</td>
<td>0.23</td>
<td>1.50</td>
</tr>
<tr>
<td>df</td>
<td>1,35</td>
<td>1,35</td>
<td>1,35</td>
</tr>
<tr>
<td>Sig</td>
<td>0.276</td>
<td>0.636</td>
<td>0.230</td>
</tr>
<tr>
<td>Trial</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>0.08</td>
<td>0.73</td>
<td>0.22</td>
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<tr>
<td>df</td>
<td>1,35</td>
<td>1,35</td>
<td>1,35</td>
</tr>
<tr>
<td>Sig</td>
<td>0.782</td>
<td>0.399</td>
<td>0.641</td>
</tr>
<tr>
<td>Group × Trial</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>1.45</td>
<td>0.03</td>
<td>1.54</td>
</tr>
<tr>
<td>df</td>
<td>1,35</td>
<td>1,35</td>
<td>1,35</td>
</tr>
<tr>
<td>Sig</td>
<td>0.237</td>
<td>0.874</td>
<td>0.223</td>
</tr>
</tbody>
</table>
6.2.7.5  Scaling Exponent Short Term Measures

The observed means and standard deviations of the scaling exponent short term measures during the four sensory conditions for the TCG and CG are presented in Table 6-19.

Table 6-19. Scaling Exponent short term measures (Scal Ex st R, Scal Ex st Y and Scal Ex st X) of the Tai Chi and Control participants during the four SOT conditions for both pre and post intervention measurements.

<table>
<thead>
<tr>
<th></th>
<th>Pre</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Scal Ex st R</td>
<td>Scal Ex st Y</td>
<td>Scal Ex st X</td>
<td>Scal Ex st R</td>
<td>Scal Ex st Y</td>
<td>Scal Ex st X</td>
</tr>
<tr>
<td>Tai Chi</td>
<td>0.82</td>
<td>0.81</td>
<td>0.85</td>
<td>0.83</td>
<td>0.82</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>(0.05)</td>
<td>(0.06)</td>
<td>(0.05)</td>
<td>(0.05)</td>
<td>(0.05)</td>
<td>(0.07)</td>
</tr>
<tr>
<td>SOT2</td>
<td>0.84</td>
<td>0.85</td>
<td>0.84</td>
<td>0.85</td>
<td>0.85</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>(0.05)</td>
<td>(0.05)</td>
<td>(0.06)</td>
<td>(0.05)</td>
<td>(0.06)</td>
<td>(0.07)</td>
</tr>
<tr>
<td>SOT3</td>
<td>0.82</td>
<td>0.81</td>
<td>0.84</td>
<td>0.82</td>
<td>0.82</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td>(0.05)</td>
<td>(0.06)</td>
<td>(0.05)</td>
<td>(0.05)</td>
<td>(0.05)</td>
<td>(0.05)</td>
</tr>
<tr>
<td>SOT4</td>
<td>0.85</td>
<td>0.86</td>
<td>0.84</td>
<td>0.85</td>
<td>0.85</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>(0.04)</td>
<td>(0.05)</td>
<td>(0.05)</td>
<td>(0.05)</td>
<td>(0.05)</td>
<td>(0.05)</td>
</tr>
<tr>
<td>Control</td>
<td>0.83</td>
<td>0.83</td>
<td>0.84</td>
<td>0.82</td>
<td>0.82</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>(0.05)</td>
<td>(0.05)</td>
<td>(0.05)</td>
<td>(0.05)</td>
<td>(0.05)</td>
<td>(0.07)</td>
</tr>
<tr>
<td>SOT2</td>
<td>0.85</td>
<td>0.85</td>
<td>0.85</td>
<td>0.85</td>
<td>0.85</td>
<td>0.86</td>
</tr>
<tr>
<td></td>
<td>(0.05)</td>
<td>(0.05)</td>
<td>(0.05)</td>
<td>(0.04)</td>
<td>(0.04)</td>
<td>(0.07)</td>
</tr>
<tr>
<td>SOT3</td>
<td>0.85</td>
<td>0.84</td>
<td>0.86</td>
<td>0.84</td>
<td>0.83</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>(0.03)</td>
<td>(0.04)</td>
<td>(0.05)</td>
<td>(0.03)</td>
<td>(0.04)</td>
<td>(0.04)</td>
</tr>
<tr>
<td>SOT4</td>
<td>0.89</td>
<td>0.89</td>
<td>0.88</td>
<td>0.87</td>
<td>0.88</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td>(0.04)</td>
<td>(0.04)</td>
<td>(0.06)</td>
<td>(0.04)</td>
<td>(0.04)</td>
<td>(0.06)</td>
</tr>
</tbody>
</table>

Values in the table are Mean (SD)

For each of the three scaling exponent short term measures (Scal Ex st R, Scal Ex st Y and Scal Ex st X) a two factor repeated measures GLM (group × trial) was conducted and repeated for each of the four SOT conditions. This was followed by an analysis of group × trial interactions. Table 6-20 presents the group and trial main effect analysis for each of the scaling exponent short term measures as well as the group × trial interactions.
Table 6-20 shows that for all three Crit Point Coord measures across all four SOT conditions there were no significant main effects of trial or group × trial interactions. In relation to the main effects of group there were no significant effects accept for Scal Ex st R and Scal Ex st Y in SOT4 condition. This group main effect indicated that the average Scal Ex st was significantly lower in the TCG when compared to the CG.

Table 6-20. F statistics, degrees of freedom (df) and significance level for the main effect of group and trial and group × trial interaction for the scaling exponent short term measures (Scal Ex st R, Scal Ex st Y and Scal Ex st X).

<table>
<thead>
<tr>
<th></th>
<th>Scal Ex st R</th>
<th></th>
<th></th>
<th></th>
<th>Scal Ex st Y</th>
<th></th>
<th></th>
<th></th>
<th>Scal Ex st X</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SOT1</td>
<td>SOT2</td>
<td>SOT3</td>
<td>SOT4</td>
<td>SOT1</td>
<td>SOT2</td>
<td>SOT3</td>
<td>SOT4</td>
<td>SOT1</td>
<td>SOT2</td>
<td>SOT3</td>
<td>SOT4</td>
</tr>
<tr>
<td><strong>Group</strong></td>
<td>F</td>
<td>0.03</td>
<td>0.12</td>
<td>3.27</td>
<td>6.53</td>
<td>0.20</td>
<td>0.20</td>
<td>2.39</td>
<td>5.43</td>
<td>0.09</td>
<td>0.08</td>
<td>2.22</td>
</tr>
<tr>
<td></td>
<td>Df</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
</tr>
<tr>
<td></td>
<td>Sig</td>
<td>0.866</td>
<td>0.727</td>
<td>0.079</td>
<td>0.015*</td>
<td>0.655</td>
<td>0.657</td>
<td>0.131</td>
<td>0.026*</td>
<td>0.771</td>
<td>0.779</td>
<td>0.146</td>
</tr>
<tr>
<td><strong>Trial</strong></td>
<td>F</td>
<td>0.01</td>
<td>0.04</td>
<td>0.01</td>
<td>1.00</td>
<td>0.07</td>
<td>0.01</td>
<td>0.08</td>
<td>0.70</td>
<td>0.78</td>
<td>0.52</td>
<td>1.80</td>
</tr>
<tr>
<td></td>
<td>Df</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
</tr>
<tr>
<td></td>
<td>Sig</td>
<td>0.917</td>
<td>0.847</td>
<td>0.926</td>
<td>0.323</td>
<td>0.790</td>
<td>0.909</td>
<td>0.774</td>
<td>0.410</td>
<td>0.383</td>
<td>0.478</td>
<td>0.188</td>
</tr>
<tr>
<td><strong>Group × Trial</strong></td>
<td>F</td>
<td>0.59</td>
<td>0.16</td>
<td>1.20</td>
<td>0.34</td>
<td>1.88</td>
<td>0.09</td>
<td>2.01</td>
<td>0.01</td>
<td>0.001</td>
<td>0.43</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Df</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
<td>1.35</td>
</tr>
<tr>
<td></td>
<td>Sig</td>
<td>0.449</td>
<td>0.694</td>
<td>0.281</td>
<td>0.564</td>
<td>0.179</td>
<td>0.771</td>
<td>0.165</td>
<td>0.920</td>
<td>0.970</td>
<td>0.514</td>
<td>0.910</td>
</tr>
</tbody>
</table>
6.2.7.6 Scaling Exponent Long Term Measures

The observed means and standard deviations of the scaling exponent long term measures during the four sensory conditions for the TCG and CG are presented in Table 6-21.

### Table 6-21. Scaling Exponent long term measures (Scal Ex lt R, Scal Ex lt Y and Scal Ex lt X) of the Tai Chi and Control participants COP during the four SOT conditions for both pre and post intervention.

<table>
<thead>
<tr>
<th></th>
<th>Pre Scal Ex lt R</th>
<th>Pre Scal Ex lt Y</th>
<th>Pre Scal Ex lt X</th>
<th>Post Scal Ex lt R</th>
<th>Post Scal Ex lt Y</th>
<th>Post Scal Ex lt X</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tai Chi</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT1</td>
<td>0.25 (0.11)</td>
<td>0.26 (0.12)</td>
<td>0.21 (0.10)</td>
<td>0.22 (0.07)</td>
<td>0.24 (0.09)</td>
<td>0.17 (0.10)</td>
</tr>
<tr>
<td>SOT2</td>
<td>0.16 (0.10)</td>
<td>0.15 (0.10)</td>
<td>0.16 (0.10)</td>
<td>0.14 (0.10)</td>
<td>0.14 (0.11)</td>
<td>0.12 (0.13)</td>
</tr>
<tr>
<td>SOT3</td>
<td>0.20 (0.11)</td>
<td>0.21 (0.12)</td>
<td>0.18 (0.13)</td>
<td>0.19 (0.08)</td>
<td>0.20 (0.10)</td>
<td>0.17 (0.12)</td>
</tr>
<tr>
<td>SOT4</td>
<td>0.10 (0.08)</td>
<td>0.11 (0.10)</td>
<td>0.10 (0.12)</td>
<td>0.11 (0.06)</td>
<td>0.11 (0.09)</td>
<td>0.11 (0.06)</td>
</tr>
<tr>
<td>Control</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT1</td>
<td>0.19 (0.05)</td>
<td>0.20 (0.06)</td>
<td>0.17 (0.08)</td>
<td>0.20 (0.10)</td>
<td>0.19 (0.11)</td>
<td>0.18 (0.12)</td>
</tr>
<tr>
<td>SOT2</td>
<td>0.15 (0.12)</td>
<td>0.15 (0.13)</td>
<td>0.12 (0.11)</td>
<td>0.12 (0.07)</td>
<td>0.12 (0.07)</td>
<td>0.14 (0.10)</td>
</tr>
<tr>
<td>SOT3</td>
<td>0.15 (0.07)</td>
<td>0.16 (0.07)</td>
<td>0.12 (0.10)</td>
<td>0.19 (0.08)</td>
<td>0.19 (0.09)</td>
<td>0.18 (0.11)</td>
</tr>
<tr>
<td>SOT4</td>
<td>0.10 (0.08)</td>
<td>0.10 (0.09)</td>
<td>0.11 (0.10)</td>
<td>0.08 (0.07)</td>
<td>0.07 (0.09)</td>
<td>0.09 (0.10)</td>
</tr>
</tbody>
</table>

Values in the table are Mean (SD)

For each of the three scaling exponent long term measures (Scal Ex lt R, Scal Ex lt Y and Scal Ex lt X) a two factor repeated measures GLM (group × trial) was conducted and repeated for each of the four SOT conditions. This was followed by an analysis of group × trial interactions. Table 6-22 presents the group and trial main effect analysis for each of the scaling exponent long term measures as well as the group × trial interactions.
As shown in table 6-22 all three Scal Ex lt measures across all four SOT conditions exhibited no significant main effects of group or trial as well as no significant group × trial interactions.

Table 6-22. F statistics, degrees of freedom (df) and significance level for the main effect of group and trial and group × trial interaction for the scaling exponent long term measures (Scal Ex lt R, Scal Ex lt Y and Scal Ex lt X).

<table>
<thead>
<tr>
<th></th>
<th>Scal Ex lt R</th>
<th>Scal Ex lt Y</th>
<th>Scal Ex lt X</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SOT1  SOT2  SOT3  SOT4</td>
<td>SOT1  SOT2  SOT3  SOT4</td>
<td>SOT1  SOT2  SOT3  SOT4</td>
</tr>
<tr>
<td><strong>Group</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>3.32  0.23  1.38  0.54</td>
<td>4.02  0.27  1.53  0.96</td>
<td>0.39  0.17  0.81  0.01</td>
</tr>
<tr>
<td>df</td>
<td>1,35  1,35  1,35  1,35</td>
<td>1,35  1,35  1,35  1,35</td>
<td>1,35  1,35  1,35  1,35</td>
</tr>
<tr>
<td>Sig</td>
<td>0.077  0.633  0.248  0.467</td>
<td>0.053  0.604  0.224  0.334</td>
<td>0.535  0.682  0.376  0.931</td>
</tr>
<tr>
<td><strong>Trial</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>0.06  0.94  1.25  0.13</td>
<td>0.40  1.03  0.09  0.94</td>
<td>0.44  0.16  0.85  0.001</td>
</tr>
<tr>
<td>df</td>
<td>1,35  1,35  1,35  1,35</td>
<td>1,35  1,35  1,35  1,35</td>
<td>1,35  1,35  1,35  1,35</td>
</tr>
<tr>
<td>Sig</td>
<td>0.807  0.338  0.272  0.726</td>
<td>0.533  0.318  0.766  0.339</td>
<td>0.510  0.694  0.362  0.978</td>
</tr>
<tr>
<td><strong>Group × Trial</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>0.83  0.04  2.17  1.32</td>
<td>0.04  0.17  1.08  0.35</td>
<td>1.10  1.51  1.58  0.44</td>
</tr>
<tr>
<td>df</td>
<td>1,35  1,35  1,35  1,35</td>
<td>1,35  1,35  1,35  1,35</td>
<td>1,35  1,35  1,35  1,35</td>
</tr>
<tr>
<td>Sig</td>
<td>0.368  0.850  0.150  0.258</td>
<td>0.838  0.684  0.307  0.561</td>
<td>0.301  0.228  0.217  0.512</td>
</tr>
</tbody>
</table>
6.2.8 Postural Control Coactivation

The observed means and standard deviations of the postural control SEMG coactivation measures during the four sensory conditions for the TCG and CG are presented in Table 6-23.

Table 6-23. KF/KE and AD/AP Coactivation measures during the four SOT conditions of the Tai Chi and Control participants COP during the four SOT conditions for both pre and post intervention measurements.

<table>
<thead>
<tr>
<th></th>
<th>Pre</th>
<th></th>
<th></th>
<th>Post</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tai Chi</td>
<td>Control</td>
<td>Tai Chi</td>
<td>Control</td>
<td></td>
</tr>
<tr>
<td>KF/KE Coactivation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT1</td>
<td>1.18 (0.97)</td>
<td>1.68 (2.19)</td>
<td>1.77 (1.92)</td>
<td>1.65 (1.56)</td>
<td></td>
</tr>
<tr>
<td>SOT2</td>
<td>1.24 (1.02)</td>
<td>1.49 (1.81)</td>
<td>2.21 (2.57)</td>
<td>1.74 (1.74)</td>
<td></td>
</tr>
<tr>
<td>SOT3</td>
<td>1.33 (1.10)</td>
<td>2.76 (5.54)</td>
<td>1.58 (2.10)</td>
<td>2.09 (2.72)</td>
<td></td>
</tr>
<tr>
<td>SOT4</td>
<td>1.78 (2.41)</td>
<td>0.83 (0.77)</td>
<td>2.55 (3.15)</td>
<td>4.16 (7.70)</td>
<td></td>
</tr>
<tr>
<td>AD/AP Coactivation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SOT1</td>
<td>1.28 (1.61)</td>
<td>4.65 (5.73)</td>
<td>2.92 (4.06)</td>
<td>9.39 (16.21)</td>
<td></td>
</tr>
<tr>
<td>SOT2</td>
<td>1.32 (1.65)</td>
<td>4.94 (5.33)</td>
<td>3.09 (4.52)</td>
<td>8.56 (14.88)</td>
<td></td>
</tr>
<tr>
<td>SOT3</td>
<td>1.15 (1.13)</td>
<td>3.03 (3.42)</td>
<td>4.49 (5.27)</td>
<td>3.14 (3.98)</td>
<td></td>
</tr>
<tr>
<td>SOT4</td>
<td>2.86 (6.82)</td>
<td>3.46 (4.01)</td>
<td>7.81 (10.22)</td>
<td>7.48 (8.96)</td>
<td></td>
</tr>
</tbody>
</table>

Values in the table are Mean (SD)

For each of the coactivation measures (KF/KE and AD/AP) a two factor repeated measures GLM (group × trial) was conducted and was repeated for each of the four SOT conditions. This was followed by an analysis of group × trial interactions. Table 6-24 presents the group and trial main effect analysis for each of the postural coactivation measures as well as the group × trial interactions.
Examination of table 6-24 shows that for all three KF/KE Coactivation measures across all four SOT conditions there were no significant main effects of group or group × trial interactions. In relation to the main effects of trial there were no significant effects accept for SOT4 condition. This trial main effect indicated that the average KF/KE Coactivation level was significantly higher in post intervention period when compared to pre intervention.

In relation to the AD/AP Coactivation levels main effects of group were found for SOT1 and SOT2 but not for SOT3 or SOT4. This group main effect indicated that the CG exhibited significantly higher coactivation then the TCG. Trial main effects analysis revealed that there were no effects in SOT1 and SOT2 conditions however there were trial effects in SOT3 and SOT4. The trial main effect analysis revealed that in SOT3 and SOT4 there were significant increases in coactivation of the AD/AP from pre to post intervention. There was no significant group × trial interactions found for any of the four SOT conditions.

**Table 6-24. F statistics, degrees of freedom (df) and significance level for the main effect of group and trial and group × trial interaction for the KF/KE and AD/AP Coactivation measures.**

<table>
<thead>
<tr>
<th></th>
<th>KF/KE Coactivation</th>
<th>AD/AP Coactivation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SOT1</td>
<td>SOT2</td>
</tr>
<tr>
<td>Group</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>0.22</td>
<td>0.05</td>
</tr>
<tr>
<td>df</td>
<td>1, 32</td>
<td>1, 32</td>
</tr>
<tr>
<td>Sig</td>
<td>0.640</td>
<td>0.829</td>
</tr>
<tr>
<td>Trial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>0.44</td>
<td>1.87</td>
</tr>
<tr>
<td>df</td>
<td>1, 32</td>
<td>1, 32</td>
</tr>
<tr>
<td>Sig</td>
<td>0.511</td>
<td>0.182</td>
</tr>
<tr>
<td>Group × Trial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>0.55</td>
<td>0.66</td>
</tr>
<tr>
<td>df</td>
<td>1, 32</td>
<td>1, 32</td>
</tr>
<tr>
<td>Sig</td>
<td>0.465</td>
<td>0.424</td>
</tr>
</tbody>
</table>
6.3 Discussion:

There were three major findings of study three. Firstly, TC exercise resulted in significant improvements in maximal strength in the KE and KF of the TCG. This was not coupled with significant increases in muscle activation for the KE and KF of the TCG. However, TC exercise did not result in strength differences between groups. Secondly, the HQR and DPR did not change for either group from pre to post intervention. Thirdly, TC exercise improved only Sway Area and Crit Point X in SOT3 condition and did not result in any changes in postural agonist/antagonist coactivation.

6.3.1 Effects of Tai Chi on MVC, Strength task Coactivation and Strength Ratio

Muscular strength is fundamental to the successful and efficient performance of functional tasks such as walking, raising from a chair or postural control. With ageing however, there is a reduction in the force production capacity of most muscle groups which leads to a decrement in activities of daily living (Carroll et al., 2001). Therefore, there is an increased demand to investigate the most efficient and effective training modes that slow or even reverse the functional performance deficits associated with ageing.

Many types of training such as resistance training have been explored and found to significantly improve muscular strength and functional performance, and more importantly has been repeatedly found to be an effective countermeasure to the age related decline in strength (Gabriel et al., 2006; Latham et al., 2004). Tai Chi has gained popularity in the past two decades. This popularity is in part due to TC having beneficial effects on muscular strength of the lower limb muscle groups and also functional tasks such as postural control (Xu et al., 2008).
6.3.1.1 MVC, Muscle Activation & Coactivation

In the current study KE and KF muscle groups of the lower limb in the TCG showed significant improvements in maximal strength. Previous studies have also found strength improvements in isolated muscle groups (Jacobson et al., 1997; Lan et al., 1998; Wu et al., 2002; Xu et al., 2008) or in multiple muscle groups (Choi et al., 2005; Li et al., 2009; Li & Manor, 2010; Tsang & Hui-Chan, 2005). It was also found that at either pre or post intervention there were no significant differences between the TCG and the CG within any of the muscle groups. This indicates that although TC exercise was beneficial in producing strength improvements in a group of older adults, it possibly was not of a sufficient intensity that strength was improved above people of the same age range.

Intervention studies have consistently shown TC to be efficacious in the improvement of lower limb muscular strength (Choi et al., 2005; Jacobson et al., 1997; Lan et al., 1998; Li et al., 2009; Li & Manor, 2010). In one such intervention study, Lan et al. (1998) a group of older adults completed 12 months of TC exercise. Post intervention it was found that muscle strength was enhanced in both the KE (20.3% improvement) and KF (15.9% improvement) of the exercise group. This was similar to the findings of Li et al. (2009), who found that even after a much shorter training period of 16 weeks TC exercise resulted in a 19.9% improvement in KF MVC. The participants of the present study had similar age and recruitment criteria as that of Lan et al. (1998) and Li et al. (2009) but with a lower exercise intensity and shorter intervention time. However, there were similar muscular strength improvements across the lower limb muscle groups (KE 11.39% and KF 17.32%). This indicates that even a relatively short training period of 12 weeks with three one hour sessions per week was effective in improving muscular strength of the KE and KF muscle groups in older adults. The reason for the improved muscular strength of the proximal lower limbs is thought to be due to the movement patterns associated with TC exercise. Tai Chi is performed
in a semi-squat posture which can place very large loads on the lower extremity muscle groups which can be similar to common body weight resistance exercises such as lunges and squats (Jacobson et al., 1997). Many of the movement patterns of TC require guided movements of the ankle, knee and hip joints with the muscle crossing those joints contracting either concentrically, eccentrically or isometrically. These movements and contractions place significant loads on the lower limb muscle groups and appear to be of sufficient intensity to cause positive adaptations in muscular strength. However, in the current study there were no changes in maximal strength of the distal lower limb muscles which is similar to the findings of Li et al. (2009) who found no change in the AP and AD strength after 16 weeks of TC exercise. Therefore, it appears that 12 to 16 weeks of TC exercise may not be long enough to positively affect the strength of AP or AD within older adults. Another possibility is that the intensity of the exercise was not sufficient to cause positive adaptations in these muscle groups or that the movement patterns within TC are more demanding of the proximal lower limb muscles compared to the distal muscle groups.

With muscular strength improvements there is often a concomitant increase in the neural drive to the trained muscle or muscle group, especially when considering resistance exercise (Hakkinen, Kallinen, et al., 1998; Scaglioni et al., 2002; Simoneau et al., 2006). Due to the relatively high intensity weight bearing nature of TC exercise it is plausible that there may also be an increase in the muscle activation of the lower limb muscle groups post intervention. To the author’s knowledge this is the first study to examine the effects of TC exercise on the SEMG amplitude of the lower limb muscle groups. A previous study that examined the muscle latency patterns of the four lower limb muscle groups (Li et al., 2009) found that the TC group had significantly shorter latency in the semitendinosus post intervention but no change in latency for the rectus femoris, gastrocnemius, or tibialis anterior. This highlights that TC exercise may have a potential positive effect not only at the muscular level but at the neural level. In the current study there were no significant main effects of group or trial and
no significant group × trial interaction when considering the KE, KF, AD or AP muscle activation levels. Therefore it appears that TC exercise may not have a positive effect on specific lower limb muscle groups in relation to neural drive.

Another possible mechanism for the increase of maximal strength is an associated decrease in antagonist muscle coactivation. Previous studies have investigated the effects of resistance exercise on the adaptations in antagonist coactivation patterns with authors reporting either a reduction in coactivation (Hakkinen, Kallinen, et al., 1998; Hakkinen, Newton, et al., 1998; Patten & Kamen, 2000), no change in coactivation level (Ochala, Lambertz, Hoecke, & Pousson, 2005; Reeves, Maganaris, & Narici, 2005) or a significant increase in coactivation level (de Boer et al., 2007; Simoneau et al., 2006). However, no investigation has ever focussed on changes in agonist/antagonist coactivation after a TC intervention specifically. Because of the repetitive squatting nature of TC, relatively large loads can be placed on the lower limb muscle group and are quite similar to the loads experienced during body weight squats and lunges (Jacobson et al., 1997). Therefore it is possible that the resistance type of activities experienced in TC may cause alteration in the behaviour of agonist/antagonist muscle groups of the lower limb. The findings of this study however indicate that during maximal isometric strength assessment there were very few changes in coactivation levels from pre to post intervention. The only muscle group that showed a decreased coactivation level post intervention was the KF of the TCG with no change found in the other muscles (significant interaction for group × trial). However what was also found was a significant increase in the CG’s KF coactivation level from pre to post. This finding may suggest that the reproducibility of coactivation measure using SEMG may be questionable and may need to be investigated as a valid measure of coactivation. Therefore it suggests that TC exercise, which requires muscular contractions at intensities that are much less than the maximum may not alter the level of antagonistic muscle activity within older adults.
It is concluded that although TC exercise had a significant positive effect on the strength of the proximal lower limb muscles, this improvement was not associated with improvements in either neuromuscular drive (as measured by maximal SEMG amplitude) or alterations in antagonist coactivation. However, it needs to be highlighted that this study is the first to investigate the effects of TC on muscular strength, muscle activation and coactivation levels in older adults. It is suggested by the author that future studies employing similar methods as the current study should consider the possible limitation of SEMG and the efficacy of the coactivation calculations used in this study. It may also be valuable to investigate these measures when using dynamic maximal strength due to the dynamic nature of TC exercise.

6.3.1.2 Strength Ratios

Investigation into the effects of TC exercise on lower limb strength ratio is currently lacking. The only previous research article found by the author relating to the effects of TC exercise on HQR values was conducted by Tsang and Hui-Chan (2005). Within the current study it was found that the HQR did not change from pre to post intervention. This indicates that although TC exercise had positive effects on the strength of the proximal lower limb muscle groups of the TCG, the relative improvement across agonist/antagonist pairs were similar (KF 17.32% stronger and KE 11.39% stronger). These findings were similar to the findings of Tsang and Hui-Chan (2005) who found that TC practitioners had similar agonist/antagonist strength ratios in both the concentric and eccentric contractions as those of healthy control subjects.

In relation to the effects of TC exercise on the DPR levels of older individuals there are no previous reports in the literature. In the current study there were no significant changes in DPR values from pre to post (a decrease of 6.5%) intervention. This finding was expected as there were no changes in maximal strength of the AP and AD between testing session for either group.
The finding of a group main effect within the DPR revealed that the TCG was significantly lower than the CG. This significantly lower DPR may be the result of the CG exhibiting slightly stronger AD (pre = 15.6%, post = 2.4%) and weaker AP (pre = 10.8%, post = 8.5%) compared to the TCG which would lead to elevated DPR values within the CG.

As a result of these findings it may be suggested that future studies employ longer and more intense TC exercise in order to elicit maximal strength changes in lower limb muscles. This may help to elucidate whether there is any difference in the rate of muscle strength improvement between agonist/antagonist pairs and if this then influences the resultant strength ratios of the lower limbs.

6.3.2 Effects of Tai Chi training on Postural Control and Postural Task Coactivation

The loss of strength, decreasing aerobic capacity and increased risk of falls are well-known consequences associated with the ageing process (Lord et al., 1991c; Lord & Ward, 1994). The development and implementation of cost-efficient and effective exercise interventions for the improvement of postural control and prevention of falls is of utmost importance to the ageing population. Some modes of training that older adults have shown positive responses and enhancements in functional abilities include resistance exercises (Ferri et al., 2003; Hess & Woollacott, 2005), Tai Chi (Choi et al., 2005), electromyostimulation (Amiridis et al., 2005), balance exercises (Nagy et al., 2007) and walking exercises (Melzer et al., 2003).

As a traditional exercise in China, TC was originally developed as a form of martial arts, however now it has become popular among many older populations as a form of exercise to improve health and physical wellbeing. Tai Chi involves smooth, continuously linked movements that incorporate postural muscle strengthening, balance and postural alignment (Wolf et al., 1997). Tai Chi is an exercise that is performed in a semi-squat posture that often
places large torque loads on the muscles of the lower extremities such as the hip, knee and ankle joint muscles (Xu et al., 2008). Previous reports have demonstrated that TC can significantly improve the functioning of the neuromuscular and somatosensory systems which has been shown to be important in the performance of postural control and is an effective intervention in the areas of falls prevention and healthy ageing (Li et al., 2001; Wong & Lan, 2008; Wu, 2002).

**6.3.2.1  Effects of Tai Chi Training on Postural Control**

To the Author’s knowledge this study is the first to analyse a comprehensive list of both traditional and diffusion measures to investigate the efficacy of TC exercise on laboratory based postural control assessment. Previous investigations have employed a vast array of differing outcome measures ranging from self-report (questionnaire), single-leg stance, Romberg stance, walking velocity, postural platform measures, lateral stability (laterally tilting board kept horizontal for 1 minute) and direct measure of fall number (Wu, 2002). Of the studies that have employed postural platform measures various variables have been used including COP displacement, centre of gravity displacement, body sway and functional base of support. Within these measurement variables many testing conditions have been assessed including quiet stance with or without eyes open, with or without change in visual field and with or without change in support base or a combination of these (Wu, 2002).

In the current study it was found that the only two measures that exhibited significant improvements post TC intervention was Sway Area and Crit Point X. The improvements in Sway Area and Crit Point X were only seen in SOT3 conditions. All other traditional measures and all of the diffusion measures showed no significant change from pre to post intervention. These findings are in conflict with several previous reports that have shown TC exercise to have multiple benefits on physical functioning such as balance control and or falls reduction (Lan, Chen, & Lai, 2008; Li et al., 2001; Liu & Frank, 2010; Tsang & Hui-Chan,
2003, 2004a, 2004b, 2005; Tsang et al., 2004; Voukelatos et al., 2007; Wong & Lan, 2008; Wong, Lin, Chou, Tang, & Wong, 2001; Wu, 2002; Wu et al., 2002) especially when the testing conditions were based on dynamic stability, stability limits and/or single leg stance. However, of these studies some have found no improvement in postural stability when the postural assessment was done under static double-leg stance (Nnodim et al., 2006; Tsang & Hui-Chan, 2003, 2005; Wong et al., 2001). This raises the question as to the appropriateness of using non-challenging postural assessments such as double-leg stance and whether future studies should utilise more dynamic postural assessments, especially when relating to dynamic exercise interventions such as TC.

In a study by Voukelatos et al. (2007) a longitudinal design was adopted with the aim of assessing the efficacy of TC exercise on community dwelling older adults (60 years and older). It was found that after 24 weeks of TC exercise (1 hour per week) there was an improvement in five out of six balance variables compared with the CG: sway on floor, sway on foam mat, lateral stability, coordinated stability and choice stepping reaction time. In relation to the sway measures of the Voukelatos et al. (2007)’s study similar results were reported with the TCG exhibiting significant improvements in sway area on compliant surfaces with the eyes open (SOT3). Another longitudinal intervention study (Tsang & Hui-Chan, 2004a) investigated whether 4 and/or 8 weeks of intensive (1.5 hours, 6 times per week) TC practice could improve balance control in healthy older adults. The results revealed that there were no differences between the Tai Chi group and control group in the simpler test conditions (i.e. somatosensory and visual alterations). The only improvements observed in the Tai Chi group were during the most difficult testing conditions (i.e. vestibular ratio: reflection of the relative reduction in stability when absent visual and inaccurate somatosensory inputs occurred simultaneously to force subjects to rely primarily on vestibular input for balance control). These findings are similar to those of the current study that showed no significant improvement in most postural measures which may be due to the simplicity of the postural
tasks assessed. However, direct comparison between the findings of the current study and previous research findings should be done with care. A number of factors may also account for the lack of effect in the current study, such as differences in TC style, individual health status and the duration and intensity of the TC intervention. For example, it has been shown that the stylistic differences between types of TC have significantly different intensities and movement styles (Liu & Frank, 2010; Sheng et al., 2006). This potentially could contribute to significantly different physiological adaptations, and hence conclusions, between studies using different types of TC styles. Many previous studies have investigated the effects of long term TC practice on postural control (Tsang & Hui-Chan, 2003, 2004b, 2005; Tsang et al., 2004; Wong et al., 2001; Wu et al., 2002). In two studies conducted by Tsang and Hui-Chan, comparisons were made between long term TC participants (minimum of 1.5 hours per week for at least 3 years’ experience) and control subjects (Tsang & Hui-Chan, 2003, 2005). In both of these studies the researchers compared experienced TC participants with healthy older control subjects. It was found that there were no differences between groups when measuring postural control variables such as mean normalized and mean maximal AnPo and MeLa sway during static conditions. However, when analysing dynamic postural control it was found that during tasks involving forward or backward platform translations long term TC participants had significantly lower maximum AnPo sway angles compared with the control subjects. It was hypothesised that the continuous squatting posture and slow controlled movements of TC resulted in specific adaptations in dynamic postural conditions compared with static posture (Tsang & Hui-Chan, 2003, 2005). However, conclusion drawn from these studies should be done with caution as they are either non-randomised or cross-sectional designs which did not control for confounding variables such as lifestyle characteristics. It is therefore suggested that future research into the efficacy of long term TC exercise utilise randomised controlled research designs, in an effort to clarify whether TC does indeed improve postural control and physical function.
After examination of the above studies and the results of the current study, it seems that TC exercise generally results in specific adaptations of the postural control system. It appears that TC exercise does not result in improvements in static postural control but does however result in significant improvements in dynamic postural control such as perturbed stance, perturbed single-leg stance and limited stability tasks. This may be due to the specificity of motor behaviour adaptations that directly relate to the dynamic nature of TC exercise such as dynamic single leg stance and weight transfer (Tsang & Hui-Chan, 2003, 2005). Therefore it is suggested that future studies that aim to investigate the effects of TC exercise on postural control should focus on dynamic postural assessment that are directly related to the specific movement patterns of TC.

Another consideration to in future investigation regarding the efficacy of TC is the role it has on falls prevention. Many past studies have investigated and found improvements in a multitude of clinical balance/stability measures after exercise interventions such as TC. Importantly however, very few of these investigations have either monitored or investigated the potential to reduce falls number. Consequently it is suggested that future investigations into the benefit of TC should not only include measurement of clinical balance/stability measures, but also include falls as an outcome measure.

### 6.3.2.2 Effects of Tai Chi Training on Postural Task Coactivation

It has previously been speculated that older people adopt a strategy of coactivation at the ankle joint in an effort to stiffen the joint which may help to reduce excessive movements and thus decreasing postural sway (Melzer et al., 2001). It has also been shown that during postural tasks and tasks that involve stepping, the level of coactivation at the ankle joint is significantly increased in older people especially when there are restrictions on visual feedback, a narrow base of support, or are required to undertake dual cognitive tasks while maintaining posture (Benjuya et al., 2004; Hortobagyi & DeVita, 2000; Melzer et al., 2001).
Although there previously has not been an investigation into the effects of TC on muscle agonist/antagonist coactivation during postural tasks there have been investigations into the learning effects on muscle modes and multi-mode postural synergies (Asaka, Wang, Fukushima, & Latash, 2008). Asaka et al. (2008) investigated the effects of practice on the composition of muscle modes (M-modes) and multi-M-mode synergies stabilizing the location of the COP. Muscle modes within this context were defined as muscle groups which muscle activation levels scale in parallel with variations of task characteristics. Within the training period participants practiced loads release tasks for five days while standing on a narrow support surface. The participants M-modes and indices of multi-M-mode synergies were computed during standing on a stable surface and also during standing on an unstable board before practice, in the middle of practice and at the end of practice. The authors reported that the practice led to better task performance which was reflected in fewer incidences of impaired balance. This was accompanied by a drop in the occurrence of co-contraction M-modes and the emergence of multi-mode synergies stabilizing the COP location. This finding highlights the adaptability, due to practice, of the human central nervous system to alter the adopted strategy in the control of posture. This leads to the hypothesis that TC exercise, due to its postural nature, may lead to alterations in the level of agonist/antagonist coactivation during postural tasks.

In the current investigation it was shown that there were very few alterations in agonist/antagonist coactivation during postural tasks. Analysis of pre to post differences in KF/KE coactivation showed that there were no changes in the TCG with the only difference found in the CG being in SOT4 (significantly higher post intervention). In relation to the AD/AP coactivation levels there were no differences seen within the CG and within the TCG the only significant difference was an increased level of coactivation post intervention during SOT3 postural conditions. Therefore it appears that 12 weeks of TC exercise had very little effect on the level of coactivation and hence the strategy utilized by the nervous system to
control static upright posture. This may be a result of the static nature of the postural tasks assessed in the current study as opposed to the study by Asaka et al. (2008) which assessed under dynamic conditions and found that there were adaptations in muscle activation patterns. Therefore future studies should consider applying dynamic postural assessment techniques when assessing the effects of TC on coactivation levels.

When analysing the KF/KE coactivation differences between the CG and TCG it was found that the level was similar between groups at pre and post intervention. Within the AD/AP coactivation measures it was seen that the CG exhibited significantly greater coactivation levels pre intervention in SOT1, SOT2 and SOT3. However post intervention there were no differences between groups in relation to AD/AP coactivation levels. The elevated level of coactivation seen in the CG during pre-testing may have been the result of the participants being unfamiliar with the testing conditions. It has been shown that during strength tasks when subjects are untrained in the task they experience significantly higher levels of coactivation between agonist/antagonist pairs (Sale, 1987; Sale et al., 1992). Therefore, perhaps the unusual postural tests involving having the feet relatively close together, having the eyes closed and/or having a compliant surface under the feet may have lead the participants in the CG to adopt a postural control strategy that involved heightened coactivation of the ankle musculature (Benjuya et al., 2004; Melzer et al., 2001). However, further examination of this potential postural control strategy needs to be conducted especially during more difficult postural situations such as perturbed or single leg stance.
6.4 Conclusions

The results of this study indicated that 12 weeks of TC exercise significantly improved strength of the proximal lower limb muscle groups in a group of older individuals. Therefore the null hypothesis one of Study Three can be partially rejected in relation to lower limb muscle strength as there were significant improvements from pre to post intervention in the KE and KF. The significant improvement in muscular strength of the KE and KF muscle groups however, did not result in alterations from pre to post intervention of the HQR. This was due to relatively similar improvements in strength between the agonist/antagonist pairs. Similar to those findings there were relatively few alterations in the level of agonist/antagonist coactivation from pre to post intervention. Therefore, in relation to the strength ratios and coactivation level the second null hypothesis of this study can be accepted as TC exercise had no effect on these tested variables.

Of the 26 measured postural variables only two were found to show significant improvements in the TCG from pre to post intervention. The two postural variables that showed improvement were Sway Area and Crit Point X. It can consequently be concluded that TC exercise as prescribed in this study had little to no effect on quiet stance postural control in older individuals. The lack of significant improvement in postural control may be due to the dynamic nature of the TC exercise which may have caused specific adaptations in dynamic stability rather than in quiet stance. There were also few changes in agonist/antagonist coactivation levels during postural control tasks from pre to post intervention. Therefore, the null hypothesis that TC exercise would not cause changes in postural control or postural control coactivation levels can be accepted.
Chapter 7: Conclusions, Implications and Limitations
7.1 Thesis Conclusions

The research presented in this thesis investigated the effects of ageing, gender and Tai Chi exercise on the HQR, DPR, postural control and coactivation levels of participants during both strength and postural tasks. The conclusions that can be drawn from this series of investigations are listed below.

1. The strength ratios of the lower limb muscles were found to be similar between males and females. In both young and older individuals the differences in relative strength between agonist/antagonist pairs were similar between genders as shown in Studies One and Two. There was a significant difference in the maximal strength between males and females. Males were found to be significantly stronger than females in either young or older adult groups, which may be explained by the findings that males exhibited significantly higher agonist muscle activations while females showed significantly higher antagonist coactivation.

2. Alteration of joint angle had a significant effect on lower limb muscle strength ratios. The alteration in HQR and DPR with knee and ankle joint changes respectively was due to the relatively larger changes in maximal torque of the KE and AP compared with the KF and AD. The changes in maximal strength of each muscle group between joint angles could not be explained by either changes in agonist activation or antagonist coactivation. This suggests that mechanical factors such as the torque-angle relationship may be responsible for the torque changes across joint angles.

3. Moderate positive correlations were found between maximal strength and certain postural parameters. This suggests a possible “relaxation” of the postural control system in young adults who have sufficient muscular strength to counteract gravitational forces. There
were very few relationships found between strength ratios of the lower limb and postural control measures and it was concluded that the relative strength between agonist/antagonist pairs may not be an influencing factor in the maintenance of a quiet stance.

4. The ageing process appeared to have a negative effect on muscular strength and this age-related decline can be somewhat reversed with the application of 12 weeks of TC exercise. The older individuals were found to have significantly lower muscle strength than young adults which were speculated to be related to the significantly lower agonist activation levels and higher antagonist coactivation seen in the older group. After the TC intervention the strength of older adults was improved, however it was not associated with either increases in agonist activation or decreases in antagonist coactivation. Strength ratios of the lower limb muscles were also affected by age with the HQR being significantly higher in the younger participants while the DPR was higher in the older individuals. The significant decline in HQR with ageing is suggested to be caused by the greater decline in KF strength compared with the KE. The significant increase in DPR with ageing is purported to be due to the greater decrease in AP strength in comparison to the AD. The HQR and DPR were not significantly altered with TC exercise as the relative improvement in agonist/antagonist pairs was similar.

5. Ageing had a negative impact on postural control. However, 12 weeks of TC exercise did not significantly affect the postural control variables in the present study. Interestingly, it was revealed that older males experienced a significantly greater decline in postural control compared to older females. This may have been related to the differences in anthropometric measures between the genders in the older group. Older males were found to be significantly taller, weigh more and have significantly higher BMI values. The TC
intervention did not result in significant improvements in postural control in older adults. The lack of improvement in postural control might be due to the dynamic nature of TC which was dissimilar to the static stance that was utilized to assess posture in Study Three. Some other potential contributing factors to the lack of TC effect may be the type of TC utilised as stylistic differences can have a significant effect on the intensity of exercise and/or the duration of the TC intervention.
### 7.2 Implications and Future Research

The following implications and future research directions were drawn from the results and conclusions of the three studies presented in this thesis.

- Females of both Study One and Study Two exhibited significantly higher levels of coactivation during strength tasks. It was also found in Study Two that females exhibited significantly lower agonist activations. In relation to clinical implications these findings indicates that the strength difference between genders may be the result of lower agonist activation or heightened antagonist activity during strength tasks. However the potential neuromuscular mechanism for this phenomenon needs to be elucidated.

- The HQR and DPR were shown to be the highest at an extended knee joint ($30^\circ$) and neutral ankle joint respectively in Study One. These joint angles showed the strongest correlation with postural measures. Future studies and clinicians should carefully consider the joint angle at which strength is assessed especially when relating lower limb maximal strength with postural measures.

- The moderate positive correlations found between strength and postural measures in Study One suggest that maximal strength may not be a major determinant of reduced postural sway. Future studies should investigate the relative strength of lower limb muscles and the potential relation with postural control. A clinical implication of this finding is that interventions aimed at improving functional performance should focus on coordinative exercises rather than specifically focusing on strength development.

- The ageing process was shown to differentially affect the HQR and DPR. This was due to greater age-related reductions in KF and AP torque, respectively. Future clinical interventions aimed at muscular strength and/or functional performance improvement in older individuals may benefit from targeted exercise programs of the KF and AP. This
may help to clarify if the maintenance of relative strength between agonist/antagonist pairs is important in improving daily functioning.

- There was an age related decline in postural control which appeared to affect older males to a greater degree than older females. This however may have been the result of higher BMI values in the older males. It is therefore suggested that future investigations recruit anthropometrically matched males and females to help elucidate whether anthropometric or neuromuscular variables are the causal factor in the gender differences seen in the current study.

- Twelve weeks of TC exercise appeared to be inadequate in improving quiet postural control. The lack of improvement is speculated to be due to the specificity of the movements used in the TC exercise program. Tai Chi was a dynamic exercise while the postural assessment was static. It is therefore suggested that future investigations incorporate a dynamic postural assessment into their design to help explicate the efficacy of TC interventions. It appears that TC exercise interventions potentially need to be of a higher intensity and longer duration than 12 weeks of low to moderate intensity.

- The maximal strength of the proximal lower limb muscle groups was improved after the implementation of 12 weeks of TC exercise. However, the mechanism for this improvement in strength was not clear. Neither a significant increase in agonist activation nor a reduction in antagonist coactivation was observed post TC intervention. Therefore the issue of what mechanisms, whether morphological or neurological, are responsible for the concomitant increase in muscular strength still needs to be clarified. Clinically it appears that TC exercise interventions of 12 weeks or less may not be warranted in situations in which the aim of the intervention is to improve neuromuscular functioning and/or muscular strength of the AP and AD.
There are several limitations within the current thesis that need to be considered when interpreting the results and discussion of each study.

Within all three studies the assessment of SEMG was only useful in measuring the magnitude of muscle activation. However previous findings have shown that many influencing factors may contribute to changes in SEMG amplitude such as the number of motor units recruited, the firing rate of motor units, the synchrony of motor unit firing, muscle mass, muscle fibre size and non-contractile structures such as fat and connective tissue. Therefore the results and conclusions drawn from the current investigations need to be treated with care as both gender and ageing have been shown to influence many of the above mentioned factors. This is therefore a major limitation to the findings of the current research.

The fact that all subjects were volunteers and therefore were not a random sample of the population being investigated is another limitation of the research. This may have led to selection bias within the groups especially in Study Two and Three which may mean that not all participants were equally balanced or objectively represented. Within Study Three the allocation of participants into either the control or TC groups was based on availability to participate in three sessions of TC per week for 12 weeks. This meant that randomisation into groups did not occur and may have potentially introduced selection bias, therefore the results may not be a reflection of the population.

The laboratory test was performed under specific conditions and did not reflect exactly the daily activities of the volunteers. For example, the use of static bipedal stance and isometric muscular contractions, which is very rarely utilised in everyday activities, may not be of functional relevance in the real world. Also the introduction of constraints such as having the feet much closer together than normally experienced and hands directly by their side, might
have led to postural behaviours that were not necessarily seen during more functional postural movements. Therefore the interpretation of the results may be limited to the task performed during laboratory testing and may explain why no improvement was seen after TC exercise.

Due to the fact that in Study Three cointervention and intention to treat analysis were not actively monitored/undertaken for either the control or TC group this may have led to the introduction of confounding variables which could erode the validity of the results of the trial and hence be perceived as a limitation of study three.
Chapter 8: References


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Tracy, B. L., & Enoka, R. M. (2002). Older adults are less steady during submaximal isometric contractions with the knee extensor muscles. *Journal of Applied Physiology, 92*(3), 1004-1012.


Chapter 9: Appendices
Appendix A: Call for Volunteers
Study One

CALL FOR VOLUNTEERS

FOR A RESEARCH ON POSTURAL CONTROL

School of Health and Human Sciences

Southern Cross University

Name of Project: The effects of joint angle on strength ratios and coactivation of the agonists and antagonists at the knee and ankle joints, and their correlations with postural control.

Purpose: This study aims to examine the relationship between postural control and lower limb muscle strength at differing joint angles. The outcomes of the study will allow us to have a better understanding of the effects of strength and strength ratios between different muscle groups on postural control and may help us to find better ways in improving control of balance and preventing falls, particularly for older populations.

Volunteers invited: healthy participants in the age range of 18 to 50 are invited to participate.

What will be involved: Each participant is required to visit the exercise science laboratory, in P Block, Lismore Campus, Southern Cross University, twice. The first visit is for familiarization of experimental procedures and the second visit is for the formal experimental trials. Each testing session will require approximately 2 hours to complete. During each session participants will perform strength tasks of the leg musculature as well as balance assessment tasks.

Further information: If you are interested in participating in this project and would like to know more about it, there is an information sheet and you are welcome to contact the researchers who will provide you with this further information.

Zac Crowley, phone (02) 66203759 or e-mail to z.crowley.10@scu.edu.au

or Dr Shi Zhou, phone (02) 66203991 or email to shi.zhou@scu.edu.au

or Yung Sheng Chen, phone (02) 66203759 or e-mail to y.chen.33@scu.edu.au
Study Two

CALL FOR VOLUNTEERS

FOR A RESEARCH ON POSTURAL CONTROL

School of Health and Human Sciences

Southern Cross University

Name of Project: An investigation of the effects of age and gender on lower limb strength ratios, strength task coactivation, postural control and postural task coactivation.

Purpose: To investigate the influence of altered sensory conditions on postural control and the possible role that strength ratios between different muscle groups of the lower limb may contribute to postural maintenance. The outcomes of the study will allow us to have a better understanding of the effect of ageing on postural control and may help us to find better ways in improving control of balance and preventing falls, particularly for older populations.

Volunteers invited: healthy participants in two age groups: young, 18 to 40 years of age; and older, 65 to 80 years of age.

What will be involved: Each participant is required to visit the exercise science laboratory, in P Block, Lismore Campus, Southern Cross University, twice. The first visit is for familiarization of experimental procedures and the second visit is for the formal experimental trials. Each testing session will require approximately 2 hours to complete. During each session participants will perform strength tasks of the leg musculature as well as balance assessment tasks.

Further information: If you are interested in participating in this project and would like to know more about it, there is an information sheet and you are welcome to contact the researchers who will provide you with this further information.

Zac Crowley, phone (02) 66203759 or e-mail to z.crowley.10@scu.edu.au

or Dr Shi Zhou, phone (02) 66203991 or email to shi.zhou@scu.edu.au

or Yung Sheng Chen, phone (02) 66203759 or e-mail to y.chen.33@scu.edu.au
Study Three

CALL FOR VOLUNTEERS

FOR A RESEARCH ON POSTURAL CONTROL

School of Health and Human Sciences

Southern Cross University

Name of Project: Effects of Tai Chi training on postural control, coactivation, and lower limb muscle strength ratio modulation.

Purpose: This study aims to determine whether Tai Chi practice can improve postural stability and strength ratios between different muscle groups of the lower limbs in older adults. The outcomes of the study will allow us to have a better understanding of the effect of aging on postural control and may help us to find better ways in improving balance and preventing falls, particularly for older populations.

Volunteers invited: Healthy participants aged 65 to 80 years are required. The training group will be given 12 weeks of Tai Chi exercise programme with 3 sessions per week. The control group will continue with normal daily activities without specific exercise or other structured physical activity programs during the 12 weeks. They should have no prior previous experience of Tai Chi training.

What will be involved: Each participant is required to visit the exercise science laboratory, in P Block, Lismore Campus, Southern Cross University, twice. The first visit is for familiarization of experimental procedures and the second visit is for the formal experimental trials. Each testing session will require approximately 1 hour to complete. During each session participants will perform strength tasks of the leg musculature as well as balance assessment tasks. The same tests will be repeated after 12 weeks.

Further information: If you are interested in participating in this project and would like to know more about it, there is an information sheet and you are welcome to contact the researchers who will provide you with this further information.

Zac Crowley, office phone (02) 66203759 or e-mail to z.crowley.10@scu.edu.au

or Dr Shi Zhou, phone (02) 66203991 or email to shi.zhou@scu.edu.au

or Yung Sheng Chen, phone (02) 66203759 or e-mail to y.chen.33@scu.edu.au
Appendix B: Information Sheets
Study One

INFORMATION SHEET

Name of Project: **The effects of joint angle on strength ratios and coactivation of the agonists and antagonists at the knee and ankle joints, and their correlations with postural control.**

My name is Zac Crowley and you are invited to participate in a research project that is part of my PhD studies. This research aims to examine the relationship between postural control and lower limb strength ratios at different joint angles. The research requires 15 males and 15 females whose age is between 18 and 50 years. Both male and female, who are not currently undertaking regular resistance training, may participate in the study. If you meet these criteria and are interested in participating in this project, or want to know more about it before making the decision, please contact me or other researchers in the team (see contact details below).

The research will be conducted by researchers in the exercise science laboratory at the Department of Exercise Science and Sport Management, Southern Cross University, Lismore Campus.

What the research is about:

Postural control is the ability to maintain the body in an upright position during standing which involves integration of sensory information from the vestibular (a sensory organ in the inner ear), visual and tactile-proprioceptive (from muscles and joints) receptors which results in muscular responses to maintain balance. Muscle strength plays a pivotal role in the maintenance of posture however little information is available on the effects of muscle strength from different muscle groups in the lower limb on postural control. This study will investigate the influence of altered joint angles on strength ratios between different muscle groups of the lower limb and the possible role that these strength ratios may contribute to postural maintenance. We hope to gain a better understanding of the mechanisms in postural control, which in turn may help us to develop better exercise programs for the prevention of falls in older populations.

What will be involved:

Participants are invited to visit the laboratory twice. The first visit will be a familiarization trial and the second visit is for a formal experimental trial. Prior to participation, we would like to know whether there is any contraindication to participation in muscle strength and postural control testing. The researcher will interview the potential participants about their health status. Participants who show no contraindication will be given a familiarization trial during which the detailed experimental procedure will be explained.
During the formal experiment trial, participants’ muscle strength at the knee and ankle joints will be assessed at three different joint angles. Each participant will be required to sit in a testing chair and perform several maximal voluntary contractions for each muscle group.

Postural control tasks require the participant to stand upright on a forceplate with hands by their side looking straight ahead, and body sway will be monitored by the sensors in the forceplate. Each postural test will be performed three times with each test lasting 30 seconds.

Each testing session would require approximately 2 hours to complete. Prior to each testing session, it would be appreciated if participants do not smoke, or take caffeine-containing drinks or food within 2 hours, and do not participate in strenuous exercise within 24 hours.

Possible Discomforts and Risks:

Performing muscle contractions with maximal effort may have some potential risks, including injuries to muscle/tendon, and increased blood pressure.

Responsibilities of the Researcher:

The researchers will take all necessary measures in an attempt to minimise the above-mentioned potential risks. At all times you will be monitored and if at any time you experience any of the above mentioned discomforts or risks it will be the researchers responsibility to cease testing. In respect of privacy, any information that is obtained in connection with this study and that can be identified with the participants will remain confidential, and will be disclosed only with their permission. The original data collected will have to be retained for at least seven years by the researcher as required by the University. The data with personal identity will then be destroyed in a way that the privacy of the participants is protected.

Responsibilities of the Participant:

It is important that the participant discloses all current health conditions that may be considered as contraindications to perform maximal muscle contractions, or medicine that may affect the ability to maintain posture, and discuss with the researcher if there is any concern.

Freedom of Consent:

Your participation in this research is totally voluntary. It is your decision whether or not to participate. If you decide to participate, you are free to withdraw your consent and to discontinue participation at any time with no negative consequence to you. However, we would appreciate you letting us know your decision.
Inquiries:

If you have any questions, please ask us. If you have any additional questions at any time please talk to the researchers, Dr Shi Zhou (Supervisor), Mr. Zac Crowley (researcher), or Mr. Yung Sheng Chen (researcher) who will be happy to answer the queries you may have.

Dr Shi Zhou, Mr. Zac Crowley, Mr. Yung Sheng Chen

School of Health and Human Sciences
Southern Cross University

P.O. Box 157, Lismore, NSW 2480

Work phone number: (02) 66203991 (Dr Zhou), (02) 66203759 (Mr. Crowley and Mr. Chen)

Email: shi.zhou@scu.edu.au, z.crowley.10@scu.edu.au, y.chen.33@scu.edu.au

The ethical aspects of this study have been approved by the Southern Cross University Human Research Ethics Committee (HREC). The Approval Number will be confirmed. If you have any complaints or reservations about any ethical aspect of your participation in this research, you may contact the Committee through the Ethics Complaints Officer:

Ms Sue Kelly

Ethics Complaints Officer and Secretary

HREC
Southern Cross University

PO Box 157
Lismore, NSW, 2480

Telephone (02) 6626-9139 or fax (02) 6626-9145

Email: sue.kelly@scu.edu.au

All complaints, in the first instance, should be in writing to the above address. All complaints are investigated fully and according to due process under National Statement on Ethical Conduct in Research Involving Humans and this University. Any complaint you make will be treated in confidence and investigated, and you will be informed of the outcome.
Study Two

INFORMATION SHEET

Name of Project: An investigation of the effects of age and gender on lower limb strength ratios, strength task coactivation, postural control and postural task coactivation.

My name is Zac Crowley and you are invited to participate in a research project that is part of my PhD studies. You are invited to participate in a research project that will examine the relationship between postural control and lower limb strength ratios in young and old individuals under altered sensory feedback conditions. The research requires two groups of healthy volunteers: young adult group (18 to 40 years of age) and older adult group (65 to 80 years of age). Both male and female, who are not currently undertaking regular resistance training, may participate in the study. If you meet these criteria and are interested in participating in this project, or want to know more about it before making the decision, please contact me or other researchers in the team (see contact details below).

The research will be conducted by researchers in the exercise science laboratory at the Department of Exercise Science and Sport Management, Southern Cross University, Lismore Campus.

What the research is about:

Postural control is the ability to maintain the body in an upright position during standing which involves integration of sensory information from the vestibular (a sensory organ in the inner ear), visual and tactile-proprioceptive (from muscles and joints) receptors which results in muscular responses to maintain balance. Muscle strength plays a pivotal role in the maintenance of posture however little information is available on the effects of muscle strength ratios of the lower limb and its effect on postural control. This study will investigate the influence of altered sensory conditions on postural control and the possible role that strength ratios between muscle groups of the lower limb may contribute to postural maintenance. We hope to gain a better understanding of the effect of ageing on postural control and other neuromuscular functions such as the strength ratios, which in turn my help us to develop better exercise programs for the prevention of falls in older populations.

What will be involved:

Participants are invited to visit the laboratory twice. The first visit will be a familiarization trial and the second visit is for a formal experimental trial. Prior to participation, we would like to know whether there is any contraindication to participation in muscle strength and postural control testing. The researcher will interview the potential participants about their health status. Participants who show no contraindications will be given a familiarization trial during which the detailed experimental procedure will be explained.
During the formal experiment trial, participants’ muscle strength at the knee and ankle joints will be assessed. Each participant will be required to sit in a testing chair and perform several maximal voluntary contractions for each muscle group.

Postural control tasks require the participant to stand upright on a forceplate with hands by their side looking straight ahead, and body sway will be monitored by the sensors in the forceplate, under four conditions: 1) eyes-open on firm surface, 2) eyes-closed on firm surface, 3) eyes-open on compliant surface, and 4) eyes-closed on compliant surface. Each condition will be performed three times with each test lasting 30 seconds.

Each testing session would require approximately two hours to complete. Prior to each testing session, it would be appreciated if participants do not smoke, or take caffeine-containing drinks or food within 2 hours, and do not participate in strenuous exercise within 24 hours.

Possible Discomforts and Risks:

Performing muscle contractions with maximal effort may have some potential risks, including injuries to muscle/tendon, and increased blood pressure.

Responsibilities of the Researcher:

The researchers will take all necessary measures in an attempt to minimise the above-mentioned potential risks. At all times you will be monitored and if at any time you experience any of the above mentioned discomforts or risks it will be the researchers responsibility to cease testing. In respect of privacy, any information that is obtained in connection with this study and that can be identified with the participants will remain confidential and will be disclosed only with their permission. The original data collected will have to be retained for at least seven years by the researcher as required by the University. The data with personal identity will then be destroyed in a way that the privacy of the participants is protected.

Responsibilities of the Participant:

It is important that the participants disclose all current health conditions that may be considered as contraindications to perform maximal muscle contractions, or medicine that may affect the ability in maintain posture, and discuss with the researcher if there is any concern.

Freedom of Consent:

Your participation in this research is totally voluntary. It is your decision whether or not to participate. If you decide to participate, you are free to withdraw your consent and to discontinue participation at any time with no negative consequence to you. However, we would appreciate you letting us know your decision.
Inquiries:

If you have any questions, please ask us. If you have any additional questions at any time please talk to the researchers, Dr Shi Zhou (Supervisor), Mr. Zac Crowley (researcher), or Mr. Yung Sheng Chen (researcher) who will be happy to answer any queries you may have.

Dr Shi Zhou, Mr. Zac Crowley, Mr. Yung Sheng Chen

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Southern Cross University

P.O. Box 157, Lismore, NSW 2480

Work phone number: (02) 66203991 (Dr Zhou), (02) 66203759 (Mr. Crowley and Mr. Chen)

Email: shi.zhou@scu.edu.au, z.crowley.10@scu.edu.au, y.chen.33@scu.edu.au

The ethical aspects of this study have been approved by the Southern Cross University Human Research Ethics Committee (HREC). The Approval Number will be confirmed. If you have any complaints or reservations about any ethical aspect of your participation in this research, you may contact the Committee through the Ethics Complaints Officer:

Ms Sue Kelly

Ethics Complaints Officer and Secretary

HREC

Southern Cross University

PO Box 157

Lismore, NSW, 2480

Telephone (02) 6626-9139 or fax (02) 6626-9145

Email: sue.kelly@scu.edu.au

All complaints, in the first instance, should be in writing to the above address. All complaints are investigated fully and according to due process under National Statement on Ethical Conduct in Research Involving Humans and this University. Any complaint you make will be treated in confidence and investigated, and you will be informed of the outcome.
Name of Project: Effects of Tai Chi training on postural control, coactivation, and lower limb muscle strength ratio modulation.

My name is Zac Crowley and you are invited to participate in a research project that is part of my PhD studies. You are invited to participate in a research project that aims to examine the effects of 12 to 24 weeks Tai Chi training on postural stability and strength ratios of the lower limb in older individuals. The research requires participation of healthy individuals, both male and female, who are in the age range of 65 to 80 years, and have no previously experience of undertaking Tai Chi training. If you meet these criteria and are interested in participating in this project, or want to know more about it before making the decision, please contact me or other researchers in the team (see contact details below).

What the research is about:

Ageing may affect individuals’ ability in control of balance and increase may the chance of fall injuries because of the degradation of sensory and motor systems. These changes are related to the compromised postural control strategy during standing. It has been shown that Tai Chi exercise has beneficial effects in improving sensory-motor function and balance control in older adults. However, whether the improvements are related to the strength ratios between different muscle groups of the lower limb is unknown. The first aim of this study is to investigate whether Tai Chi training would improve postural stability in older adults. The second aim is to evaluate the effects of Tai Chi training on strength ratios and control of posture. The outcomes of the study will allow us to have a better understanding of the effects of ageing on our neuromuscular system and help us to find better ways in improving balance and preventing falls in older populations.

What will be involved:

Forty volunteers, in the age range of 65-80 years, both males and females, will be randomly allocated into a control and a Tai Chi training group. The control group will maintain their normal daily activities for 12 weeks, while the Tai Chi group will participate in training at a Tai Chi club. Training will be run for 24 weeks. After the first 12 weeks, the control group will also participate in the Tai Chi training, together with the other group for the next 12 weeks.

Prior to the training, participants will attend a familiarization trial followed by a pre training testing trial to establish the baseline data. The same tests will be repeated after 12 weeks and 24 weeks of training and/or control period. During the first visit, the researcher will interview the potential participants to find out if there is any contraindication to participation of both muscle strength and postural control testing. Participants who show no
contraindications will be given a familiarization trial during which the detailed experimental procedure will be explained.

During the formal experiment trial, participants’ muscle strength at the knee and ankle joints will be assessed. Each participant will sit in a testing chair and perform several maximal voluntary contractions for each muscle group.

Postural control tasks require the participant to stand upright on a forceplate with hands by their side looking straight ahead, during which body sway will be monitored by the sensors in the forceplate, under four conditions: 1) eyes-open on firm surface, 2) eyes-closed on firm surface, 3) eyes-open on compliant surface, and 4) eyes-closed on compliant surface. Each condition will be performed three times with each test lasting 30 seconds.

Each testing session would require approximately two hours to complete. Prior to each testing session, it would be appreciated if participants do not smoke, or take caffeine-containing drinks or food within 2 hours, and do not participate in strenuous exercise within 24 hours.

Possible Discomforts and Risks

Performing muscle contractions with maximal effort may have some potential risks, including injuries to muscle/tendon, and increased blood pressure.

Responsibilities of the Researcher

The researchers will take all necessary measures in an attempt to minimise the above-mentioned potential risks. At all times you will be monitored and if at any time you experience any of the above mentioned discomforts or risks it will be the researchers responsibility to cease testing. In respect of privacy, any information that is obtained in connection with this study and that can be identified with the participants will remain confidential and will be disclosed only with their permission. The original data collected will have to be retained for at least seven years by the researcher as required by the University. The data with personal identity will then be destroyed in a way that the privacy of the participants is protected.

Responsibilities of the Participant

It is important that the participants disclose all current conditions that may be considered as contraindications to perform such maximal muscle contractions, or medicine that may affect control of balance, and discuss with the researcher if there is any concern.

Freedom of Consent

Your participation in this research is totally voluntary. It is your decision whether or not to participate. If you decide to participate, you are free to withdraw your consent and to
discontinue participation at any time with no negative consequence to you. However, we would appreciate you letting us know your decision.

Inquiries

If you have any questions, please ask us. If you have any additional questions at any time please talk to the researchers, Dr Shi Zhou (supervisor), Mr. Zac Crowley (researcher) or Mr. Yung Sheng Chen (researcher) who will be happy to answer any queries you may have.

Dr Shi Zhou, Mr. Zac Crowley, Mr. Yung Sheng Chen

School of Health and Human Sciences

Southern Cross University

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Appendix C: Consent Forms
Study One

CONSENT FORM

**Title of research project:** The effects of joint angle on strength ratios and coactivation of the agonists and antagonists at the knee and ankle joints, and their correlations with postural control.

**NOTE:** This consent form will remain with the Southern Cross University researcher for their records.

**Tick the box that applies, sign and date and give to the researcher**

I agree to take part in the Southern Cross University research project specified above.

Yes □ No □

I have been provided with information at my level of comprehension about the purpose, methods, demands, risks, inconveniences and possible outcomes of this research. I understand this information.

Yes □ No □

I understand that my participation is voluntary.

Yes □ No □

I can choose not to participate in part or all of this research at any time, without consequence.

Yes □ No □

I understand that any information that may identify me, will be de-identified at the time of analysis of any data. Therefore, I, or any information I have provided cannot be linked to my person/company. (*Privacy Act 1988 Cth*)

Yes □ No □

I understand that neither my name nor any identifying information will be disclosed or published, except with my permission.

Yes □ No □

**OR**

I give permission for identifying information to be published or disclosed.

Yes □ No □
I understand that all information gathered in this research is confidential. It is kept securely and confidentially for 7 years at the University (unless there are special circumstances, that have been explained to me).

I am aware that I can contact the Supervisor or other researchers at any time with any queries.

I understand that the ethical aspects of this research have been approved by the SCU Human Research Ethics Committee.

If I have concerns about the ethical conduct of this research, I understand that I can contact the SCU Ethics Complaints Officer. All inquiries are confidential and should be in writing, in the first instance, to the following:

Ethics Complaints Officer
Southern Cross University
PO Box 157
Lismore NSW 2480
Email: sue.kelly@scu.edu.au

Participants name: ____________________________________________________________

Participants signature: _______________________________________________________

Date: ______________________________________________________________________

Contact: Tel: __________________________________________________________________

Email: _____________________________________________________________________
Study Two

CONSENT FORM

Title of research project: An investigation of the effects of age and gender on lower limb strength ratios, strength task coactivation, postural control and postural task coactivation.

NOTE: This consent form will remain with the Southern Cross University researcher for their records.

Tick the box that applies, sign and date and give to the researcher

I agree to take part in the Southern Cross University research project specified above. Yes ☐ No ☐

I have been provided with information at my level of comprehension about the purpose, methods, demands, risks, inconveniences and possible outcomes of this research. I understand this information. Yes ☐ No ☐

I understand that my participation is voluntary. Yes ☐ No ☐

I can choose not to participate in part or all of this research at any time, without consequence. Yes ☐ No ☐

I understand that any information that may identify me, will be de-identified at the time of analysis of any data. Therefore, I, or any information I have provided cannot be linked to my person/company. (Privacy Act 1988 Cth) Yes ☐ No ☐

I understand that neither my name nor any identifying information will be disclosed or published, except with my permission. Yes ☐ No ☐

OR

I give permission for identifying information to be published or disclosed. Yes ☐ No ☐
I understand that all information gathered in this research is confidential. It is kept securely and confidentially for 7 years at the University (unless there are special circumstances, that have been explained to me).  

Yes ☐  No ☐

I am aware that I can contact the Supervisor or other researchers at any time with any queries.  

Yes ☐  No ☐

I understand that the ethical aspects of this research have been approved by the SCU Human Research Ethics Committee.  

Yes ☐  No ☐

If I have concerns about the ethical conduct of this research, I understand that I can contact the SCU Ethics Complaints Officer. All inquiries are confidential and should be in writing, in the first instance, to the following:  

Yes ☐  No ☐

Ethics Complaints Officer  
Southern Cross University  
PO Box 157  
Lismore NSW 2480  
Email: sue.kelly@scu.edu.au

Participants name: __________________________________________________________

Participants signature: _______________________________________________________

Date: ______________________________________________________________________

Contact: Tel: __________________________________________________________________

Email: ______________________________________________________________________
Study Three

CONSENT FORM

Title of research project: Effects of Tai Chi training on postural control, coactivation, and lower limb muscle strength ratio modulation.

NOTE: This consent form will remain with the Southern Cross University researcher for their records.

Tick the box that applies, sign and date and give to the researcher

I agree to take part in the Southern Cross University research project specified above. Yes □ No □

I have been provided with information at my level of comprehension about the purpose, methods, demands, risks, inconveniences and possible outcomes of this research. I understand this information. Yes □ No □

I understand that my participation is voluntary. Yes □ No □

I can choose not to participate in part or all of this research at any time, without consequence. Yes □ No □

I understand that any information that may identify me, will be de-identified at the time of analysis of any data. Therefore, I, or any information I have provided cannot be linked to my person/company. (Privacy Act 1988 Cth) Yes □ No □

I understand that neither my name nor any identifying information will be disclosed or published, except with my permission. Yes □ No □

OR

I give permission for identifying information to be published or disclosed. Yes □ No □
I understand that all information gathered in this research is confidential. It is kept securely and confidentially for 7 years at the University (unless there are special circumstances, that have been explained to me).  

Yes ☐ No ☐

I am aware that I can contact the Supervisor or other researchers at any time with any queries.  

Yes ☐ No ☐

I understand that the ethical aspects of this research have been approved by the SCU Human Research Ethics Committee.  

Yes ☐ No ☐

If I have concerns about the ethical conduct of this research, I understand that I can contact the SCU Ethics Complaints Officer. All inquiries are confidential and should be in writing, in the first instance, to the following:  

Yes ☐ No ☐

Ethics Complaints Officer
Southern Cross University
PO Box 157
Lismore NSW 2480
Email: sue.kelly@scu.edu.au

Participants name: ____________________________________________________________

Participants signature: _________________________________________________________

Date: ________________________________________________________________________

Contact: Tel: __________________________________________________________________

Email: _______________________________________________________________________
Appendix D: Health Screen Questionnaire
HEALTH STATUS ASSESSMENT PRIOR TO EXERCISE TESTING

(Adapted from ASMF)

School of Health and Human Sciences

Southern Cross University

This form is used as a pre-participation health and risk factor screening device and should be completed prior to the commencement of an exercise test or exercise program.

The information obtained in this screening will be kept as CONFIDENTIAL. Only the responsible staff member and the medical practitioner may access to the information.

Sections (1) to (9) should be completed by the client before seeing a medical practitioner.

Section (10) should be completed by the staff.

Sections (11) and (12) should be completed by a medical practitioner.

___________________________________________________________________________

Client’s Surname (Mr., Mrs., Ms.): _____________________________________________

Given Names: _______________________________________________________________

Date of Birth: _______________________________________________________________

Address: ___________________________________________________________________

___________________________________________________________________________ Postcode: _________________

Contact Telephone: (Home)____________________ (Work/Mobile) __________________

Reasons for participating in exercise testing or training:

___________________________________________________________________________

___________________________________________________________________________
(I) FAMILY MEDICAL HISTORY.

Has any near relative brother (B), sister (S), father (F), mother (M), grandparents (GP) suffered:

Please tick the appropriate column

<table>
<thead>
<tr>
<th></th>
<th>No</th>
<th>Yes</th>
<th>Relation</th>
<th>Age</th>
<th>Remarks/Details</th>
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<tbody>
<tr>
<td>Apoplexy (stroke)</td>
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<td>Congenital heart trouble</td>
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<td>Rheumatic heart disease</td>
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<td>Heart operation</td>
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<td>Angina</td>
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<td>Heart attack</td>
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<tr>
<td>Sudden death</td>
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<tr>
<td>High blood pressure</td>
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<tr>
<td>High cholesterol</td>
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<tr>
<td>'Hardening of arteries'</td>
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<tr>
<td>Asthma</td>
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<tr>
<td>Lung disorder</td>
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<tr>
<td>Bronchitis, emphysema</td>
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<tr>
<td>Hay fever</td>
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<tr>
<td>Diabetes</td>
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<tr>
<td>Gout</td>
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<tr>
<td>Arthritis</td>
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<tr>
<td>Epilepsy</td>
<td></td>
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</tbody>
</table>
(2) PAST MEDICAL HISTORY

Have you suffered any of the following conditions at any time:

(Please tick the appropriate column)

<table>
<thead>
<tr>
<th>Condition</th>
<th>No</th>
<th>Yes</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rheumatic or scarlet fever</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Heart trouble or murmur</td>
<td></td>
<td></td>
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<tr>
<td>Heart palpitation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High blood pressure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heart attack</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Chest pain/Angina</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stroke</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Disease of arteries or veins</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Undue limiting shortness of breath with exercise</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fainting or blackout</td>
<td></td>
<td></td>
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<tr>
<td>Loss of consciousness or fainting with exercise</td>
<td></td>
<td></td>
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<tr>
<td>Epilepsy</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Lung or bronchial disease</td>
<td></td>
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<tr>
<td>Asthma</td>
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<td></td>
<td></td>
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<tr>
<td>Hay fever</td>
<td></td>
<td></td>
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<tr>
<td>Anaemia</td>
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<td></td>
<td></td>
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<tr>
<td>Diabetes</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Thyroid disease</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Arthritis, rheumatism or gout spondylitis, disc trouble or back injury</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Serious accident or injury</td>
<td></td>
<td></td>
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<tr>
<td>Surgical operation</td>
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<td></td>
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<tr>
<td>Congenital abnormality</td>
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<tr>
<td>Other serious illness (or conditions that may affect exercise)</td>
<td></td>
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<tr>
<td>For female only:</td>
<td></td>
<td></td>
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<tr>
<td>Having normal/regular periods</td>
<td></td>
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</tbody>
</table>
(3) SOCIAL HISTORY

Marital Status: _________________________ Number of Children: _________________

Occupation: ______________________________________________________________

(4) HABITS

Please tick and fill in your usual habit of consumption of the following substances:

Alcoholic beverage:

( ) Nil

( ) Every day: number of drinks per day: _________________

( ) Irregular: number of drinks per week: _________________

Smoking:

( ) Never smoked

( ) Gave up ______ years ago

( ) Now smoke  Cigarettes: ______________ per day

Pipe: ______________ per day

Cigars: ______________ per day

(5) The poliovirus eradication campaign is almost complete but risks exist for people who have been to West Africa, Central Africa, Ethiopia, India, Pakistan, Afghanistan and Eastern Turkey. Have you been to any of the listed areas in the previous 6 months?

___________________________________________________________________________
(6) DIETARY SUPPLEMENTS

Please tick if you regularly take any of the following:

( ) Vitamins:   Type: ____________________________________________________
( ) Minerals:   Type: ____________________________________________________
( ) Iron:   Type: ____________________________________________________
( ) Other compounds: _________________________________________________________

(7) PRESENT MEDICAL CONDITIONS

This section should be completed at the INITIAL EXAMINATION and also at examination IMMEDIATELY PRIOR TO THE EXERCISE TEST.

Are you currently suffering or have you in the recent past suffered any of the following conditions (Please tick the appropriate column):

<table>
<thead>
<tr>
<th>Condition</th>
<th>Initial Exam</th>
<th>Second Exam</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Cough</td>
<td></td>
<td></td>
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<tr>
<td>Stuffy nose or sore throat</td>
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<tr>
<td>Tonsillitis, glandular fever</td>
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<tr>
<td>Hepatitis</td>
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<tr>
<td>Diarrhoea/vomiting</td>
<td></td>
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<tr>
<td>Headaches</td>
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<tr>
<td>Shortness of breath</td>
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<tr>
<td>Pain in chest, left arm or neck at rest, or during physical activities</td>
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<tr>
<td>Heart palpitations</td>
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<td>Cramp in legs</td>
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<td>Abnormal loss of blood</td>
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<td>Insomnia</td>
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<td>Indigestion or constipation</td>
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<td>Swollen, stiff or painful joints</td>
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<tr>
<td>Backache</td>
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<tr>
<td><strong>Sports injury or other injury</strong></td>
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<tr>
<td><strong>Other symptom or illness, or surgery</strong></td>
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<td><strong>Any deterioration in training or competitive performance</strong></td>
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<tr>
<td><strong>Any other conditions that may contraindicate to exercise or affect exercise capacity</strong></td>
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<td><strong>For female only:</strong></td>
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<td><strong>Currently in pregnancy</strong></td>
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<td><strong>If yes, provide details</strong></td>
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(8) CURRENT MEDICATION

This section should also be checked **IMMEDIATELY PRIOR TO THE EXERCISE TEST**.

State the name and dosage of any drugs or medicines that you are taking regularly:

<table>
<thead>
<tr>
<th>Drug</th>
<th>Dose</th>
<th>Time of last dose</th>
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(9) EXERCISE OR PHYSICAL ACTIVITY HISTORY

Present exercise and/or physical activities (activities may include walking to work, gardening, bike riding, swimming, weights training, and sports):

<table>
<thead>
<tr>
<th>Type of activity</th>
<th>Intensity (rate 1-5 gentle to intense)</th>
<th>Hours per day</th>
<th>Days per week</th>
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</table>

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I attest that the information provided by me in completing this form is to the best of my knowledge a true and accurate reflection of my current health status. In the event that I display symptoms of illness at any point during my participation in this exercise test I will advise the testing staff immediately.

Signed: ________________________________  Name: _________________________  
Date: ______________________________

(10) BODY MASS, HEIGHT AND BODY MASS INDEX (to be completed by the staff)

Body Mass (kg): ___________________________  Height (m): _____________________

Body Mass Index (kg/m$^2$) : ___________________________
(11) PHYSICAL EXAMINATION

This section should be completed by a medical practitioner.

___________________________________________________________________________

General appearance including glands, and lymph nodes

___________________________________________________________________________

(b) Cardiovascular system

(i) Peripheral vessel and pulses

(ii) Neck veins

(iii) Apex beat position

(iv) Heart sounds

(v) Resting heart rate

(vi) Blood Pressure: Lying: ___________ mmHg, Standing: ___________ mmHg

(vii) 12 leads ECG (a copy of resting ECG should be on file).

___________________________________________________________________________

(c) Respiratory system

___________________________________________________________________________

(d) Abdomen

___________________________________________________________________________

(e) Nervous system

___________________________________________________________________________

(f) Fundi

___________________________________________________________________________
(g) Locomotor system

___________________________________________________________________________

(h) Varicose veins

___________________________________________________________________________

(i) Urinalysis:

Protein: ______________________  Sugar: ______________________

Specific Gravity: _____________  Other results: _________________

___________________________________________________________________________

(j) Blood lipid profile:

TC: _________________________  LDL: _______________________

Triglyceride: _________________  Other results: _________________

___________________________________________________________________________

(k) Other examinations:

___________________________________________________________________________
(12) MEDICAL PRACTITIONER'S SUMMARY:

(a) Comments (detail any significant abnormalities or reservations):

___________________________________________________________________________
___________________________________________________________________________
___________________________________________________________________________

(b) Recommendations:

The medical practitioner should underline and initial the appropriate clause:

(i)  Fit to undergo maximal exercise tests.

(ii)  Not fit to undergo maximal exercise test, but may undergo submaximal test without special precautions.

(iii)  Not fit to undergo maximal exercise test but may undergo submaximal test with following precaution:

Precaution: ________________________________________________________________
_________________________________________________________________________

(iv)  Not fit to undergo any exercise test.

Signed: ________________________________  Name: ___________________________

Date: ________________________________

Contact Telephone Number:

(Work) ____________________ (A/H) ____________________
Appendix E: Postural COP Calculations
Computation of Traditional COP Measures

The proceeding description of the traditional stabilogram calculations are all taken from the work of Prieto et al. (1996).

The COP is a bivariate distribution, jointly defined by AnPo and MeLa coordinates. The $AnPo_o$ and $MeLa_o$ time series define the COP path relative to the origin of the force platform coordinate system. The mean COP is the position on the force platform defined by the arithmetic means of the AnPo and MeLa time series. In the following equations, all summations are from 1 to N, unless indicated otherwise; $N$, the number of data points included in the analysis, is 2000; and $T$, the period of time selected for analysis, is 20 seconds.

$$\overline{AnPo} = \frac{1}{N} \sum AnPo_o [n] \quad \overline{MeLa} = \frac{1}{N} \sum MeLa_o [n] \quad (1)$$

To simplify the following definitions, the AP and ML time series are referenced to the mean COP.

$$AnPo [n] = AnPo_o [n] - \overline{AnPo} \quad MeLa [n] = AnPo_o [n] - \overline{MeLa} \quad (2)$$

The COP coordinate time series, AnPo and MeLa, are commonly used to compute measures of postural steadiness, and characterize the static performance of the postural control system. In the strict sense, these axes are referenced to the force platform, not the subject.

Postural steadiness measures are also computed with another times series, which is derived from the COP but is not sensitive to the orientation of the base-of-support with respect to the force platform. The resultant distance (RD) time series is the vector distance from the mean COP to each pair of points in the $AnPo_o$ and $MeLa_o$ time series.
The following equation are for the composite measures computed using both the AP and ML time series, and those based on the AnPo time series. Every measure defined for the AnPo time series, is similarly defined for the MeLa time series. In these equations, it is assumed that the number of COP data points is large enough so that $N \approx N - 1$.

**Time-Domain “Distance” Measures:**

The measures described in this section are the most commonly used measures of postural steadiness. Time-domain distance measures estimate a parameter associated with either the displacement of the COP from the central point of the stabilogram, or the velocity of the COP. The mean distance ($Mean\ Dist$) is the mean of the RD time series, and represents the average distance from the mean COP.

\[
Mean\ Dist = \frac{1}{N} \sum RD\ [n]
\]  

(4)

The mean anterior-posterior distance ($Mean\ Dist \ AnPo$) is the mean absolute value of the AnPo time series and represents the average AnPo distance from the mean COP.

\[
Mean\ Dist\ AnPo = \frac{1}{N} \sum |AP[n]|.
\]  

(5)

The total excursion ($Total\ Ex$) is the total length of the COP path, and is approximated by the sum of the distances between consecutive points on the COP path.

\[
Total\ Ex = \sum_{n=1}^{N-1} [(AnPo[n+1] - AnPo[n])^2 + (MeLa[n+1] - MeLa[n])^2]^{1/2}
\]  

(6)
The anterior-posterior total excursion (Total Ex AnPo) is the total length of the COP path in the AnPo direction, and is approximated by the sum of the distances between consecutive points in the AnPo time series.

\[
    Total \ Ex \ AnPo = \sum_{n=1}^{N-1} |AnPo[n+1] - AnPo[n]|
\]  

(7)

The mean velocity (Mean Vel) is the average velocity of the COP. In effect, this normalizes the total excursions to the analysis interval.

\[
    Mean \ Vel = \frac{Total \ Ex}{T}
\]  

(8)

The mean anterior-posterior velocity (Mean Vel AnPo) is the average velocity of the COP in the AnPo direction.

\[
    Mean \ Vel \ AnPo = \frac{Total \ Ex \ AnPo}{T}
\]  

(9)

**Time-Domain “Area” Measures**

The 95% confidence circle area (AREA-CC) is the area of a circle with a radius equal to the one-sided 95% confidence limit of the RD time series. This models the area of the stabilogram with a circle that includes approximately 95% of the distances from the mean COP, assuming that the distances are normally distributed.

\[
    95\%CCA = \pi (Mean \ Dist + z_{0.05}s_{RD})^2
\]  

(10)

where \( z_{0.05} \), the \( z \) statistic at the 95% confidence level, is 1.645 and \( s_{RD} \) is the standard deviation of the RD time series.

\[
    s_{RD} = \left[ \frac{1}{N} \sum RD^2 \ [n] - Mean \ Dist^2 \right]^{1/2}
\]
Time-Domain “Hybrid” Measures

Hybrid time-domain measures model the stabilogram with a combination of distance measures. Sway Area estimates the area enclosed by the COP path per unit of time. This measure is approximated by summing the area of the triangles formed by two consecutive points on the COP path and the mean COP. Sway Area is dependent on the distance from the mean COP and the distance travelled by the COP, and can be conceptualized as proportional to the product of mean distance and mean velocity.

\[
Sway\ Area = \frac{1}{2T} \sum_{n=1}^{N-1} |AnPo[n+1] MeLa[n] - AnPo[n] MeLa[n+1]| \tag{12}
\]
Computation of Diffusion COP Measures

The proceeding description of stabilogram-diffusion calculations are all taken from the work of Collins and De Luca (Collins & De Luca, 1993, 1995a, 1995b; Collins et al., 1995).

The COP trajectories were studied as one-dimentional and two-dimentional random walks according to stability-diffusion analysis (Collins & De Luca, 1993). In stabilogram-diffusion analysis, the displacement analysis of COP trajectories is carried out by computing the square of the displacements between all pairs of points separated in time by a specified time interval $\Delta t$ (Figure E-1). The square displacements are then averaged over the number of $\Delta t$ making up the COP time series. This process is repeated for increasing values of $\Delta t$. A plot of mean square COP displacement (e.g., $\langle \Delta r^2 \rangle$) versus $\Delta t$ is known as a stabilogram-diffusion plot (Figure E-2).

A schematic representation of a typical resultant stabilogram-diffusion plot is shown in Figure F-2. In order to parameterize such plots, two regions are identified – a short-term region and a long-term region. These regions are separated by a critical period over which the slope of the stabilogram-diffusion plot changes considerably. From this analysis three posturographic parameters are calculated: diffusion coefficients, scaling exponents, and critical point coordinates.
Figure E-1. Diagram showing the method for calculating mean square planar displacements \(<\Delta r^2>\) as a function of time interval \(\Delta t\) for a COP trajectory made up of \(N\) data points \((x_1, y_1; x_2, y_2; \ldots; x_N, y_N)\). Similar techniques are also used to calculate \(<\Delta x^2>\) and \(<\Delta y^2>\) as functions of \(\Delta t\). In this case, \(\Delta t\) does not represent the sampling interval, instead \(\Delta t\) represents a moving time window spanning \(m\) data intervals. The summation for calculating mean square displacement for a given time interval is for \((N - m)\) computed displacements. Thus, the last displacement which can be and is considered in the random-walk analysis is that between the \((N - m)\)th point and the \(N\)th point of the time series.

Figure E-2. A schematic representation of a typical resultant planar stabilogram-diffusion plot (\(<\Delta r^2>\) vs \(\Delta t\)) generated from COP time series according to the method shown in Figure F-1. The effective diffusion coefficients \(D_{rs}\) and \(D_{rl}\) are computed from the slopes of the lines fitted to the short-term and long-term regions, respectively. The critical point, \((\Delta t_c, <\Delta r^2>_c)\), is defined by the intersection of the lines fitted to the two regions of the plot. The scaling exponents \(H_{rs}\) and \(H_{rl}\) are calculated from the slopes of the log-log plots of the short-term and long-term regions respectively (from Collins & De Luca 1993).
Diffusion coefficients reflect the level of stochastic activity and/or energy of the COP along the MeLa or AnPo axis. Diffusion coefficients $D_j$ are calculated from the slopes of the resultant linear-linear plots of mean square COP displacement versus $\Delta t$, according to the general expression

$$\langle \Delta j^2 \rangle = 2D_j \Delta t \quad (1)$$

Where the $\langle \Delta j^2 \rangle$ is the mean square COP displacement, and $j = x, y, or r$.

Scaling exponents, which can be any real number in the range $0 < H < 1$, quantify the correlation between the step increments making up an experimental time series. If $H_j = 0.5$, then the increments in displacement are statistically independent which is the result expected for classical Brownian motion. If $H > 0.5$, then past and future increments are positively correlated. In this case, a random walker moving in a particular direction for some $t_0$ will tend to continue in the same direction for $t > t_0$. In general, increasing (decreasing) trends in the past implies an increasing (decreasing) trend in the future. This type of behaviour is known as persistence. On the other hand, if $H < 0.5$, then the stochastic process is negatively correlated. In this case, an increasing (decreasing) trend in the past implies a decreasing (increasing) trend in the future. This type of stochastic behaviour is referred to as anti-persistence. Scaling exponents $H_j$ were calculated from the slopes of the resultant log-log plots of the mean square displacement versus $\Delta t$ curve, according to the generalized scaling law

$$\langle \Delta j^2 \rangle \sim \Delta t^{2H_j} \quad (2)$$

where the symbols correspond to those of Eq. (1) above. Diffusion coefficients and scaling exponents were each computed for both the short-term and long-term regions of resultant stabilogram-diffusion plots. In the present study, the respective slopes needed to calculate
these parameters were determined by utilizing the method of least squares to fit straight lines through defined portions of the aforementioned plots.

The critical point coordinates – the critical time interval $\Delta t_c$ and critical mean square displacement $\langle \Delta j^2 \rangle_c$ where $j = x, j, or x$ – approximates the transition region that separates the short-term and long-term regions. An estimate for each critical point was determined as the intersection point of the straight lines fitted to the two regions of the linear-linear version of each resultant stabilogram-diffusion plot (Figure F-2).

1 In the present study, $\{x_t\}$ and $\{y_t\}$ are the MeLa and AnPo COP time series, respectively, and $\langle \Delta r^2 \rangle = c\langle \Delta x^2 \rangle + \langle \Delta y^2 \rangle$. Thus $r$ designates planar COP measurements and displacements. The angled brackets $\langle \cdot \rangle$ denote an average over time or an ensemble average over a large number of samples.
Appendix F: Tai Chi Training Program
Warm-up exercises

1. Supporting the sky with both hands
2. Drawing a bow to each side
3. Holding up a single hand
4. Looking back like a cow
5. Lowering the head and hips
6. Touching the feet with both hands
7. Clenching the fists
8. Shaking the body
9. Open your hands and turn your head
10. Backstroke
11. Turn the wheel
12. Clean the mirror
13. Picking fruit
14. Swing your arms and turn your head
15. Twist your body and let your arms swing
16. Reaching down and leaning back
17. Turn to look at the moon
18. Interlace fingers behind your neck and squeeze your elbows together
19. Fingers exercises
20. Eyes exercises
21. Kicks
22. Massage

Table F-1. The schedule of the 12 week Tai Chi program

<table>
<thead>
<tr>
<th>Period</th>
<th>Yang style Tai Chi</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Learning Period</strong></td>
<td></td>
</tr>
</tbody>
</table>
| Week 1          | 1. Beginning of Tai Chi  
|                 | 2. Grasp bird’s tail                                    |
| Week 2          | 3. Single whip                                          |
|                 | 4. Raise hands and step up                              |
| Week 3          | 5. White stork displays its wings                       |
|                 | 6. Brush knee and twist left                            |
| Week 4          | 7. Play guitar                                          |
|                 | 8. Brush knee and twist - left, right and left           |
| Week 5          | 9. Play guitar                                          |
|                 | 10. Brush knee and twist left                           |
| Week 6          | 11. Deflect sideways, parry, step forward and punch     |
|                 | 12. Apparent counter and closure                        |
|                 | 13. Cross hands                                         |
| **Practice Period** |                                                      |
| Week 7-Week 12  | 14. Slow forms of Yang style Tai Chi                   |
Instructions of 13 slow forms

Next to the description heading of each movement pattern is the corresponding picture numbers that depict the movements performed.

1) **Beginning of Tai Chi (Pictures 1 – 2)**
   - Check your position.
   - Raise your hands to shoulder level.
   - Turn your palms and pull them down.

2) **Grasp Bird’s Tail (Pictures 3 – 14)**
   - Bend your knees.
   - Raise your right arm and turn your right foot.
   - Raise your left arm and step your left foot.
   - Right arm forms a circle and step your right foot.
   - Left arm follows right arm (like holding a football).
   - Turn your palms and pull them to the left.
   - Left hand forms a circle and touch your right wrist.
   - Press your hands forward, separate, pull back and push.

3) **Single Whip (Pictures 15 – 22)**
   - Turn your body and turn your right foot.
   - Keep your hands at eye level and pull them to the left
   - Put your hands down and pull them to the right.
   - Right hand forms a bird head and look to the right.
   - Step your left foot and turn your left palm out.

4) **Raise Hands and Step Up (Pictures 23 – 24)**
   - Open your right palm and raise your hands to the centre.
   - Raise your right foot to the centre (right heel touches the floor).

5) **White Stork Display Its Wings (Pictures 25 – 28)**
   - Turn your body to the left (left hand up, right hand down).
   - Step your right foot (right hand up, left hand down).
   - Point your left foot and turn your right palm up.

6) **Brush Knee and Twist Left (Pictures 29 – 33)**
   - Right hand forms a circle to the back of your right ear.
   - Left hand follows right hand and step your left foot.
• Left hand brushes left knee and right hand pushes to the front.

7) **Play Guitar (Pictures 34 – 35)**
• Step your back foot in and raise your hands to the centre (left heel touches the floor).

8) **Brush Knee and Twist: Left, Right, and Left (Pictures 29 – 33 and 36 – 43)**
• Right hand forms a circle to the back of your right ear.
• Left hand follows right hand and step your left foot.
• Left hand brushes left knee and right hand pushes to the front.
• Left hand forms a circle to the back of your left ear.
• Right hand follows left hand and step your right foot.
• Right hand brushes right knee and left hand pushes to the front.
• Right hand forms a circle to the back of your right ear.
• Left hand follows right hand and step your left foot.
• Left hand brushes left knee and right hand pushes to the front.

9) **Play Guitar (Pictures 34 – 35)**
• Step your back foot in and raise your hands to the centre (left heel touches the floor).

10) **Brush Knee and Twit Left (Pictures 29 – 33)**
• Right hand forms a circle to the back of your right ear.
• Left hand follows right hand and step your left foot.
• Left hand brushes left knee and right hand pushes to the front.

11) **Deflect Sideways, Parry, Step Forward and Punch (Pictures 44 – 49)**
• Right hand makes a fist and turn your left foot.
• Both hands form a circle and twist your right foot to the front.
• Step your left foot and withdraw your right fist to the right.
• Your right fist strikes out and your left palm goes under your right upper arm.

12) **Apparent Counter and Closure (Pictures 50 – 52)**
• Open your palm and withdraw to the right.
• Turn your palms and push.

13) **Cross Hands (Pictures 53 – 56)**
• Turn your body and turn your left foot.
• Both arms form a circle and cross hands (your right foot steps in).