Physiology and Pathophysiology of Low Back Pain in Ballet Dancers

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BPhy, MPhtySt(Manip)

A thesis submitted for the degree of Doctor of Philosophy at
The University of Queensland in 2015
School of Health and Rehabilitation Sciences
Abstract

Classical ballet dancers combine artistry and physical skills to perform graceful and exciting movements. Lengthy, exacting dance training potentially promotes unique adaptation of motor control to; execute these movements; maintain optimal physiological function, and provide stability to avoid injury and pain. Yet low back pain (LBP) is common in dancers. Differences in motor control are frequently observed between non-dancers with and without LBP. This often involves reduced and delayed activity of deep trunk muscles and augmented activity of superficial muscles. These changes are proposed to affect the control of movement and stiffness of the trunk. LBP is also associated with deficits in postural control, an aspect of motor control, which depends on control of the trunk. Some features of adaptation in motor control are relatively common; but there are some features that are specific to individuals or different populations. It is essential to understand how motor control is adapted in elite classical ballet dancers with LBP as less optimal motor control has potential to impair performance and limit the capacity to dance. The overall objective of this thesis was to investigate aspects of motor control in dancers with and without LBP, with specific attention to trunk muscle morphology and to postural stability. Studies I and II investigated trunk muscle size, symmetry and function, in dancers with and without LBP, at rest and during simple manoeuvres, with magnetic resonance imaging (MRI). Reduced size of the multifidus muscle was observed in dancers with LBP and dancers with both back and hip/pelvic region pain. This finding is similar to that for non-dancers. Study II provided preliminary evidence of a behavioural change in transversus abdominis (the deepest abdominal muscle); expressed as reduced length change of this muscle measured with MRI, in dancers with LBP. Thickness of transversus abdominis, obliquus internus abdominis and multifidus muscles were asymmetrical in dancers but this was not related to LBP. This may be related to repetitive performance of asymmetrical movements. Studies III and IV investigated postural control. In Study III, the trunk was perturbed in order to measure the dynamic properties of stiffness, damping and mass as an indication of control of the trunk. Dancers with LBP had less damping (control of velocity) than dancers without LBP, but this could be changed with motor imagery in the dancers with LBP. Study IV used linear and non-linear measures of centre of pressure trajectories to investigate standing balance in dancers with and without LBP and non-dancers. Balance was measured with the feet in parallel and the dance-specific turned out 'first' position; which increases the dependence on trunk motion for balance in the anteroposterior direction. Dancers without LBP used more movement to control balance.
than non-dancers. These findings suggest that “less” movement does not define optimal 
balance in dancers. Dancers with a history of LBP used strategies that were more similar 
to non-dancers than to their LBP-free counterparts. This compromised balance in dancers 
with LBP has potential to impact on performance. Each of these studies has identified 
differences in aspects of motor control between dancers with and without LBP and, in the 
case of balance, between non-dancers and the dancers’ groups. These changes in motor 
control associated with LBP are potentially modifiable and may provide a basis for the 
development of prevention or treatment programs to reduce the morbidity related to LBP in 
professional classical ballet dancers.
Declaration by author

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

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Gildea JE, van den Hoorn W, Hides JA, Hodges PW. Balance strategies of professional ballet dancers with a history of low back pain are more similar to non-dancers than dancers without low back pain. Submitted to journal March 2015.


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Contributions by others to the thesis

Warren Stanton assisted with the data analysis and statistics of the MRI studies.
Wolbert van den Hoorn assisted with data analysis and statistics of the dynamic properties and balance studies.
Henry Tsao assisted with data analysis of the balance studies.
Steve Wilson conducted medical assessments of the dancers prior to the MRI studies.
Mark Strudwick provided the technical assistance and operated the MRI.
Leanne Hall assisted with data collection for the dynamic properties and balance studies.
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Sue Mayes and Paula Baird provided technical advice for the design of the studies from a dance perspective and together with Stuart Buzza and other staff of The Australian Ballet assisted with recruitment of dancers for the studies.

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<td>ANOVA</td>
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<td>AP</td>
<td>Anteroposterior</td>
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<td>CoP</td>
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<tr>
<td>TrA</td>
<td>Transversus abdominis</td>
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<tr>
<td>IO</td>
<td>Obliquus internus abdominis</td>
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Picture 1 Carolyn Rappel, with kind permission from her daughter Sasha Webb.
Dance has been a prominent expression of culture, emotion and communication for people of all ages and race across the centuries. In classical ballet this form of expression is taken to a level of extreme physical and emotional demand. The physical skills of dancers which enable them to perform seemingly effortless leaps and spins come at a cost to the body. Musculoskeletal injuries are common, notably professional ballet dancers report a mean of 6.8 injuries per dancer per year or 4.4 injuries per 1000 hours. This has substantial impact on training and performance (Allen et al. 2012) (Table 1-1). In Australia, 89% of professional dancers reported a history of injury which affected their dancing (Crookshanks 1999). The prevalence of injury is also similar amongst professional dancers in other countries, e.g. 84% in the United Kingdom (Bowling 1989) and 90% in Sweden (Ramel et al. 1999). Spinal pain, in particular, is prominent in terms of prevalence and impact. For instance, in Australian professional dancers, prevalence of chronic low back pain (LBP) of 33% and acute LBP of 11% has been reported. In terms of injury location, back pain is second only to ankle/foot pain (53% chronic, 37% acute) (Crookshanks 1999). Furthermore, injury or pain in this area appears to be recalcitrant to intervention as results show the spine was nominated as the most common site of primary chronic injury in 1990 (34%) (Geeves 1990) and in a follow-up survey in 1999 (29%) (Crookshanks 1999). The prevalence of spinal pain was similar in these two studies despite a reduction in the total chronic injury prevalence (15%); and the implementation of education programs (in the intervening 10 years) which targeted injury prevention and management (Crookshanks 1999). Likewise in Swedish professional dancers, spinal pain was reported to have a prevalence of 70% in 1989 and 82% in a follow up study (6 years later); again despite the introduction of education programs (Ramel et al. 1999). The high prevalence of back pain and poor impact of intervention observed in these epidemiological studies emphasizes the need for further investigation of LBP in professional dancers in order to identify potentially modifiable causes of onset or persistence.

The findings of surveys of Australian professional dancers suggest that a substantial percentage of the chronic injuries occur early in the dancer’s career (Crookshanks 1999), even before the commencement of professional training. By the age of 18 years, 36% of the chronic injuries have occurred and this figure increases to 87% by 25 years of age (Crookshanks 1999). In a survey of dance students aged between 16 and 19.5 years, 80.6% had sustained an injury with 18.4% nominating the site as the lumbar spine (Purnell et al. 2003). Compared with age-matched controls,
young pre-professional dancers (aged 12-27 years) experience significantly more back pain (McMeeken et al. 2002). In addition, adolescent dancers with a history of LBP are markedly more susceptible (56%) to future injury (Gamboa et al. 2008). The high rate of spinal injury reported in pre-professional dancers indicates there is a need to identify dancers at risk of developing injury. Preventative measures could then be implemented into the training programs of these dancers. Preventative intervention is based on knowledge of normal function and impairments associated with pain and injury. Investigation of dancers and dancers with LBP is necessary to provide this knowledge which has potential to identify dancers at risk of back injury or guide prevention programs with the aim of reducing injury occurrence.

The causes of spinal pain in dancers are multi-factorial (Micheli et al. 1999). Factors which have been cited as contributing to dancers’ low back injury and pain include; excessive compressive load (Alderson et al. 2009) and volume of activity (Kadel et al. 1992, McMeeken et al. 2001, Purnell et al. 2003); excessive range of movement or hypermobility (Klemp et al. 1984); presence of scoliosis (Hakim and Grahame 2003, Hamilton et al. 1992, Liederbach et al. 1997); posture (Solomon et al. 2000); low (Benson et al. 1989) and relatively high Body Mass Index (McMeeken et al. 2002); limited range of lower limb external rotation compared to other dancers (Bachrach 1986, Kelly 1987, Micheli 1983, Solomon et al. 2000); and inadequate muscle strength, control (Gelabert 1986, Kelly 1987, Micheli 1983, Solomon et al. 2000) and endurance (Swain and Redding 2014). The relative contribution of each of these factors to LBP in dancers is yet to be identified. Studies of professional dancers with LBP to date have included measurements of torque production (Cale-Benzoor et al. 1992) and range of movement (Feipel et al. 2004), however, none have shown an association between these factors and pain. Suboptimal motor control of the spine has been proposed by many authors as an important factor in LBP in dancers (Gelabert 1986, Kelly 1987, Micheli 1983, Rickman et al. 2012, Smith 2009, Solomon et al. 2000). These authors also emphasize that motor control training is an essential component in rehabilitation of back injuries. A first step that is required to justify and design an evidenced-based program targeted at motor control to prevent LBP or facilitate recovery from LBP is to establish whether differences exist in motor control between dancers with back pain and those with no back pain. A major impediment to designing a program is that despite the proposed importance of motor control issues in dancers there are very few studies that have specifically investigated the motor control system in professional dancers and how it might change when dancers have LBP.
Table 1-1 Epidemiology studies investigating dance injuries (including lumbar spine).

<table>
<thead>
<tr>
<th>Study</th>
<th>Location</th>
<th>Group</th>
<th>Age (years)</th>
<th>Number In Study</th>
<th>Injury Prevalence</th>
<th>Injury Prevalence Spine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geeves 1990</td>
<td>Australia</td>
<td>Prof</td>
<td>86% &lt; 30</td>
<td>172</td>
<td>89%</td>
<td>34% chronic</td>
</tr>
<tr>
<td>Crookshanks 1999</td>
<td>Australia</td>
<td>Prof</td>
<td>79% &lt;30</td>
<td>139</td>
<td>89%</td>
<td>33% chronic, 11% recent</td>
</tr>
<tr>
<td>McMeekan et al 2002</td>
<td>Australia</td>
<td>Pre-prof / non-dancers</td>
<td>10-25</td>
<td>120</td>
<td>Not reported</td>
<td>37% pre-prof, 18% non-dancers</td>
</tr>
<tr>
<td>Negus et al 2005</td>
<td>Australia</td>
<td>Pre-prof</td>
<td>15-22</td>
<td>29</td>
<td>100% in 2 years</td>
<td>93% current, 41% trauma, 93% non-trauma</td>
</tr>
<tr>
<td>Bowling 1989</td>
<td>UK</td>
<td>Prof</td>
<td>18-37</td>
<td>141</td>
<td>84%</td>
<td>29% chronic, 26% recent</td>
</tr>
<tr>
<td>Ramel et al 1994</td>
<td>Sweden</td>
<td>Prof</td>
<td>17-47</td>
<td>128</td>
<td>95%</td>
<td>70%</td>
</tr>
<tr>
<td>Ramel et al 1999</td>
<td>Sweden</td>
<td>Prof</td>
<td>22-37</td>
<td>51</td>
<td>90% recurring</td>
<td>31% new injury</td>
</tr>
<tr>
<td>Feipel et al 2004</td>
<td>Germany</td>
<td>Prof, semi-prof</td>
<td>21 + 4</td>
<td>25</td>
<td>100% Hx pain/ injury</td>
<td>43%</td>
</tr>
<tr>
<td>Allen et al 2012</td>
<td>UK</td>
<td>Prof</td>
<td>18-31</td>
<td>52</td>
<td>6.8/dancer/year</td>
<td>16% females, 12% males</td>
</tr>
<tr>
<td>Hincapié et al 2008</td>
<td>Systematic review</td>
<td>Prof</td>
<td>&lt;13-47</td>
<td>Total 1457</td>
<td>3-95%</td>
<td>24-75%</td>
</tr>
<tr>
<td>Jacobs et al 2012</td>
<td>Systematic review</td>
<td>Mixed</td>
<td>14-42</td>
<td>Total 802</td>
<td>37-87%</td>
<td>12-16%</td>
</tr>
</tbody>
</table>

Abbreviations: Prof, professional dancers. Hx, history of injury.

Optimal motor control is ideal for dancers as the human body is a collection of extremely complex systems which not only have vital independent roles but also have to integrate to enable the body to function. As the trunk is positioned at the centre of the body and houses the major components of most systems, it is involved in most physiological functions as well as having a major role in maintaining equilibrium and movement. The spine, as the mechanical pillar of the trunk, has multiple roles including providing load bearing, allowing movement and protecting nervous tissue and organs (Panjabi 1992). As the spine is inherently unstable, a complex system is required to maintain its stability without compromising other functions (Crisco et al. 1992). Along
with passive structures, the stabilising system is comprised of an active component i.e. trunk muscles, which are controlled by the central nervous system (CNS) (Panjabi 1992). One aspect of motor control is the integration of these interdependent components (the active, passive and neural structures) to control movement and stiffness (Shumway-Cook and Woollacott 2012). Classical ballet challenges many aspects of both movement and stiffness. There are repetitive high loads on the spine often at the limit of range (Alderson et al. 2009, Feipel et al. 2004) whilst dancers are simultaneously maintaining equilibrium on a small base of support along with addressing challenges of other functions like maintaining respiration and continence. Success in coping with these diverse requirements suggests that dance training mediates adaptation of motor control. There is some evidence that dance training modifies motor control. For instance, in a task involving lateral weight shift and leg elevation, dancers used a more sophisticated and efficient motor program which involved feedforward counter-rotation of the trunk around the hip joint to maintain the vertical alignment of the trunk axis compared with naïve participants (Mouchnino et al. 1991, Mouchnino et al. 1992). Comparisons of balance ability in dancers of different ages and non-dancers also revealed more proficient control in older dancers. This was reported to reflect a more developed motor program (Golomer et al. 1997). Furthermore, electromyography (EMG) and kinematic data of a dance step demonstrated decreased variability between trials of an expert dancer compared with a novice dancer (Chatfield 2003), which was interpreted as refinement of motor control. These findings indicate that the challenges to spinal stability inherent in the movements of ballet may be met by adaptation of motor control and result in parameters which are quantifiably different in dancers compared to non-dancers.

When investigating motor control it is also important to consider how motor control and stability of the spine changes when the body is challenged by injury. Although there is substantial redundancy in the stability system even a relatively discrete insult such as temporarily inducing pain in the paraspinal muscles, results in alteration to motor control which resembles the changes that have been associated with LBP (Hodges et al. 2003b). In addition, motor control changes remain despite removal of the painful stimulus; suggesting that recovery may not be automatic (Moseley et al. 2004) and that a non-optimal control strategy may persist (Hodges 2011). Changes which have been identified in relation to LBP include, but are not limited to; reduction in muscle size (Hides et al. 1996) and volume of contractile tissue (Mengardi et al. 2006); asymmetry of muscle size (Hides et al. 2006a); alteration of muscle activation (Hodges and Richardson 1998, MacDonald et al. 2009) and recruitment patterns (Cholewicki et al. 2002, Radebold et al. 2000); delayed muscle response times (Radebold et al. 2000); reduced proprioceptive input (Brumagne et al. 2004); changes in stiffness and damping (Hodges et al. 2009); and changes in strategies used to maintain postural equilibrium (Mok et al. 2004). These wide ranging changes associated with LBP
necessitate corresponding alteration in motor control in order to preserve spinal functions including stability. As this evidence of change associated with LBP has been found in non-dancers it is important to investigate if these changes also occur in dancers with LBP as extrapolating data to this specific population may be misleading.

In non-dancers, one extensively investigated aspect of change in motor control associated with LBP is altered behaviour of trunk muscles in people with LBP or with a history of LBP (Hodges and Moseley 2003, van Dieën et al. 2003). The common findings included reduced or delayed activation of the deeper trunk muscles (Hodges 2013) and contrasting co-contraction and prolonged contraction of more superficial trunk muscles (van Dieën et al. 2003). For instance, in people with chronic LBP (Hodges and Richardson 1996, Hodges and Richardson 1998) and in healthy people with induced lumbar pain (Hodges et al. 2001c) activation of the transversus abdominis (the deepest abdominal muscle) is delayed in association with rapid limb movements. Even elite athletes with LBP demonstrate reduced ability to draw in the abdominal wall (Hides et al. 2008a, Hides et al. 2010b) and asymmetrical contraction of transversus abdominis muscle in response to loading, in contrast to the symmetrical contraction of healthy athletes (Hides 2006). Changes in activation have also been demonstrated in the deep paraspinal muscles e.g. during rapid arm movement, the onset of activation of the short fibres of multifidus muscles are delayed in people with LBP compared with healthy participants (MacDonald et al. 2009). In people with LBP, compared with healthy individuals, activity in the deep multifidus muscle (short fibres) is reduced in response to a predictable load and activity in both the short and long fibres of the multifidus muscle is decreased in response to an unpredictable load (MacDonald et al. 2010). Consistent with the compromised activity of the deep muscles demonstrated in studies of motor behaviour (Hodges and Moseley 2003), changes in muscle morphology have also been associated with LBP. These include reduced cross-sectional area (CSA) of multifidus muscles in people with acute (Hides et al. 1994), subacute (Hides et al. 1996) and chronic LBP (Barker et al. 2004, Beneck and Kulig 2012, Danneels et al. 2000). In those with unilateral back pain, atrophy is correlated with the duration of symptoms (Barker et al. 2004), the side of pain (Barker et al. 2004, Hides et al. 1994) and the level of pain (Hides et al. 1994). Animal studies show that lesions to the intervertebral disc or nerve root can cause rapid atrophy of the multifidus muscles, fatty replacement of muscle tissue and an increase in connective tissue (Hodges et al. 2006). It follows that multifidus muscle atrophy may account for the reduced CSA of multifidus muscles reported in people with LBP (Hides et al. 1994). Evidence from biomechanical modelling studies (Bergmark 1989) suggests that compromised behaviour and structure of the deep muscles may reduce their ability to ‘fine-tune’ intervertebral motion which results in altered spinal function and may render the spine vulnerable to injury or re-injury (Hodges et al. 2003a).
In contrast to the consistent compromised activity demonstrated in the deep muscles in people with LBP (Hodges and Moseley 2003), activation of the more superficial muscles is more variable but often augmented (Arendt-Nielsen et al. 1996, Cholewicki et al. 2002, Hodges and Richardson 1996, Radebold et al. 2000). Compared with healthy individuals, recordings from surface electromyography (EMG) show increased co-contraction of trunk muscles in response to a quick load release in people with chronic LBP (Radebold et al. 2000) and athletes with acute pain (Cholewicki et al. 2002). Augmented co-activation of the superficial muscles increases the compressive load on the spine, (Gardner-Morse and Stokes 1998) spinal stiffness, (Hodges et al. 2009) energy expenditure (Lamoth et al. 2002) and may compromise movement (Hodges et al. 1999). Support for the association between the changes in motor control and LBP comes from studies that show treatment modalities that target motor control issues are effective in reducing pain and disability associated with LBP (Hides et al. 2008b, O’Sullivan et al. 1997); reducing recurrence of pain (Hides et al. 2001); restoring muscle recruitment (Tsao et al. 2010a, Tsao and Hodges 2008); restoring organisation of the motor cortex of the brain (Tsao et al. 2010b); restoring muscle size, symmetry and control in athletes with LBP (Hides et al. 2008b, Hides et al. 2009) and decreasing games missed and severe lower limb injury in footballers (Hides and Stanton 2014, Hides et al. 2012). Evidence from these studies suggests that investigation of trunk muscle behaviour and morphology in dancers and dancers with LBP is likely to provide important information about the association between LBP and motor control in dancers.

Altered recruitment and morphology of trunk muscles is thought to underlie the changes in the mechanical behaviour of the trunk that have been identified in people with recurring episodes of LBP (Hodges et al. 2009). The mechanical behaviour of the trunk depends primarily on its inertia, damping and stiffness properties which can be estimated from the response to small perturbations (Gardner-Morse and Stokes 2001, Moorhouse and Granata 2007). Stiffness is the resistance to trunk displacement (Moorhouse and Granata 2005) whereas damping is resistance to trunk velocity (Bazrgari et al. 2011). Damping reduces oscillations in a system and absorbs energy which has potential to affect the qualitative behaviour of the system. Greater trunk stiffness and less damping has been observed in people with recurrent LBP (Hodges et al. 2009). These findings support the investigation of dynamic properties of the trunk in dancers and dancers with LBP.

In addition to the potential role of trunk control in LBP, as the trunk contributes 70% to body mass it follows that dancers with LBP may have balance disorders. Alterations in balance capabilities and strategies have been observed in non-dancers with LBP. For example, in static balance tests, people with LBP demonstrate increased or reduced centre of pressure (CoP) motion (Mientjes and Frank 1999), are less successful in maintaining quiet stance on a short base (Mok et al. 2004) and less able to use a hip strategy to maintain balance than people without LBP (Mok et
Balance is a critical element of classical ballet and there have been several studies on postural control in dancers which suggest that dancers are better able to maintain balance in challenging conditions (Crotts et al. 1996) and are more stable than non-dancers (Golomer et al. 1999a, Golomer and Dupui 2000, Stins et al. 2009), although some authors report that difference in postural control between dancers and non-dancers is task dependant (Hugel et al. 1999, Pérez et al. 2014, Perrin et al. 2002, Simmons 2005b). Despite the importance of balance skills in classical ballet and the association between LBP and altered balance control there is limited information about the effect of LBP on balance in dancers and contradictory observations about the difference between dancers and non-dancers. These factors highlight the need to study and compare balance control in dancers with and without LBP and non-dancers.

The evidence of changes in muscle behaviour (Hodges and Moseley 2003), morphology (Hides et al. 1994, Hodges et al. 2006), mechanical properties (Hodges et al. 2009) and balance control (Mok et al. 2007) associated with LBP implicates alteration to the motor control system. This alteration in motor control has potential for wide reaching effects on the trunk and body which may persist after the resolution of pain and could contribute to persistence or recurrence of back pain (Hodges et al. 2006, Hodges 2011, MacDonald et al. 2009, MacDonald et al. 2010). Given the evidence of changes in trunk control in non-dancers (Hodges and Moseley 2003, van Dieën et al. 2003) it is likely that deficits in motor control exist in dancers with LBP and could have considerable implications for performance. For example, back pain may not only limit rehearsal time and performance participation it may also impact on quality of movement. As ballet dancers use movement to convey emotions and tell a story the quality of movement is as important as the physical execution of the movement (Krasnow and Chatfield 2009) i.e. how a dancer moves across the stage is just as important as how many seconds it takes. Dancers aspire for a perception of effortless movement despite the physical strain of performing precise actions at a variety of speeds and ranges. It is difficult to quantify quality or style of movement, however, this thesis focuses on utilising a research approach which considers the trunk as a dynamic structure e.g. measuring trunk muscle behaviour with Magnetic Resonance Imaging (MRI), the dynamic trunk properties of stiffness and damping and dynamic measures of balance, in order to gain information about movement control strategies in dancers with LBP.

Although there is emerging evidence in normally active individuals, there are limited data of physiology and pathophysiology of trunk muscle control in dancers, particularly those at an elite level. The overall objective of this thesis was to advance understanding of the motor control of professional classical ballet dancers with and without LBP to provide a foundation to understand the potential role of motor control of the trunk in dancers. This thesis addressed the issue of potentially modified trunk control from three perspectives.
The first perspective was to determine whether the changes in trunk muscle morphology and behaviour that have been identified in non-dancers with LBP are present in elite professional ballet dancers with LBP.

The second perspective was to investigate motor control by comparing the mechanical properties of the trunk in ballet dancers with and without a history of LBP.

As the trunk is essential for control of balance and optimal balance is fundamental to dance, the third perspective was to investigate if there are differences in the characteristics of balance control between ballet dancers with and without a history of LBP and non-dancers.

The ultimate objective was to find potentially modifiable factors that can be tested in prevention or treatment programs to optimise performance of dancers and dancers with LBP.
Picture 2 The Australian Ballet Etudes. Photographer Georges Antoni.
Chapter 2  Background

2.1  Introduction

Understanding motor control is essential for investigating the physiology and pathophysiology of trunk control in dancers, which is the basis of this thesis. Motor control is the multifaceted relationship between the interdependent subsystems that the body uses to manage movement and stiffness (Shumway-Cook and Woollacott 2012) or redefined more broadly with regard to trunk control; the combination of neurophysiological and biomechanical mechanisms that contribute to control of the spine and trunk (Hodges et al. 2013). Motor control of the spine and trunk is complex and if individual elements of the motor control system are considered in isolation it can lead to incomplete interpretation of the net effect (Hodges 2013). It is therefore essential to investigate several aspects of motor control in order to develop a comprehensive understanding of motor control in dancers and dancers with LBP. The muscle system is one of the essential components of motor control hence two studies in this thesis, examined morphology and behaviour of key trunk muscles in dancers with and without LBP. The first study focused on the CSA of relatively posteriorly located trunk muscles i.e. multifidus, erector spinae, psoas and quadratus lumborum (Study I [Chapter 3]). Measurement of the abdominal muscles; transversus abdominis and obliquus internus abdominis along with the total trunk cross-sectional, both at rest and with the muscles contracted was the emphasis in the second study (Study II [Chapter 4]). In the third study (Study III [Chapter 5]), the mechanical properties (stiffness, damping and mass) of the trunk, in dancers with and without a history of LBP, were estimated from small perturbations to the trunk. In the fourth study (Study IV [Chapter 6]) another aspect of motor control, the characteristics of balance control were investigated in dancers with and without a history of LBP and non-dancers. These studies provide a basis for developing an understanding of how the motor control system succeeds in meeting the challenges of movement and stiffness in a timely manner in dancers and the changes that may occur in this system in association with LBP in dancers.


2.2 Trunk control in elite dance

There are a number of demands on the trunk control of elite dancers. Aesthetic demand has a major impact on all aspects of movement, as classical ballet is an art-form that is concurrently traditional and evolving as well as an athletic activity. The overall aim is that the movement looks effortless whilst still providing ‘wow’ factor that derives from pushing the body to extremes. There is limited opportunity for individual movement strategy as positions and movements have to conform to many requirements including; the choreographer’s aesthetic ideals and the characterisation of the role; group or partner coordination for the majority of time; and compliance with the time constraints of the accompanying music. Other factors such as costumes, stage setting, stage props and variations in lighting also have an impact on movement. At times these aesthetic demands compete with the mechanical demands on the body and may precipitate compensation or injury.

Classical ballet places unique demands on the body which potentially impact on trunk stiffness and movement. Movements in ballet are a complex combination of dynamic motion and static holds performed at different speeds both within normal range and at the extreme limits of range. Although there is a much wider variety of postures and range of movements used than in activities of daily living, there is also considerable repetition of movement (Feipel et al. 2004). In particular, dancers use a large range of lumbar spine extension often in combination with end of range hip extension and pelvic rotation and tilt to achieve frequently used positions such as an arabesque (Smith 2009). Precise coordination of control of the multiple joints and muscles involved in such movements along with maintenance of postural equilibrium requires a highly efficient and effective motor control system.

The demands on trunk control of elite dancers also include coordination of multiple functions. As dance involves times of intense physical activity, homeostatic functions such as breathing and continence are challenged simultaneously with trunk control. Several trunk muscles have roles in spinal stability and breathing or continence (Hodges et al. 1997, Hodges et al. 2007). In this competitive environment the motor control system must cope with high mechanical loads, coordination of muscles with multiple roles and complex timing of events to maintain the function of all the components in the system and prevent injury. There is evidence that LBP may affect the motor control system causing a change in motor control strategy from an optimal to less optimal strategy in order to preserve homeostatic functions (Hodges 2013). For example, quiet breathing in relaxed standing disturbs posture in a cyclic manner which is partially compensated by movement of the lumbar spine and hips in healthy people, whereas people with LBP demonstrate impaired...
compensation (Grimstone and Hodges 2003). Any compromise in motor control strategy of dancers could have substantial impact on the function of the trunk and performance of dance movements.

2.3 Motor control of the trunk and spine

2.3.1 Development of motor control theory

Knowledge of motor control has expanded considerably over the last hundred years and a brief history of the development of motor control theories assists with comprehension of this complex system. Early theories about the control of movement proposed that movement occurred through the combined action of reflexes hierarchically controlled from the top down (Shumway-Cook and Woollacott 2012). Most current theories remain based on neuroanatomy. Contemporary research has confirmed the importance of reflex activity and its importance for control of the spine (Hodges et al. 2009, Moorhouse and Granata 2007) and the changes that may occur with LBP (Hodges and Richardson 1996) (see Section 2.3.4.2). The research evidence, however, extends the initial theories, outlining that reflexes are only one of the processes involved in the generation and control of movement and that there is also interaction in the nervous system (Shumway-Cook and Woollacott 2012, van Dieën et al. 2003). The concept of central pattern generation of motor programs that could be modulated by sensory stimuli but were not driven by reflexes or sensory input was developed in the 1960’s (Shumway-Cook and Woollacott 2012). Another dimension was added by the realisation that perception of the task and not just sensation is formative in guiding movement. Recognition that the body is also a mechanical system which has internal and external forces acting on it triggered further development (Turvey and Fonseca 2009). The introduction of the systems dynamic approach with engineering modelling has particularly increased an understanding of behavioural attributes such as stability, and mechanical properties like stiffness and damping (Reeves et al. 2007, Reeves et al. 2011) (see Section 2.3.4.1). The use of mathematical models to analyse and describe complex phenomena such as the centre of pressure time-evolutions used for measuring balance control provides further insight into motor control (Roerdink et al. 2006)(see Section 2.6). Furthermore, theory of motor control has also broadened to view movement as an emergent property which needs to be explained in terms of physical principles like ‘self organisation’, momentum and inertia (Shumway-Cook and Woollacott 2012, Turvey and Fonseca 2009).

Contemporary theory about motor control is that movement is not solely the result of specific motor programs or stereotyped reflexes but results from a dynamic interplay between perception, cognition and action systems so that the emergent movement is an interaction between the individual, the task and the environment in which the task is being carried (Gordon 1987,
Shumway-Cook and Woollacott 2012, Turvey and Fonseca 2009). This integrated theory of motor control is supported by research in spinal control which implicates high level central nervous system control which is context or task specific and embraces engineering and physical approaches (Cholewicki et al. 2003, Hodges and Moseley 2003, van Dieën et al. 2003).

2.3.2 Stability of the trunk and spine

An important aspect of motor control of the trunk and spine in activities of daily living and classical ballet is stability (Cholewicki et al. 1997). Stability is the ability to maintain a desired position or movement if perturbed and is a fundamental characteristic of the spine and pelvic region which enables it to function optimally and avoid injury (Reeves et al. 2007). Stability of the spinal system is necessary to allow movement between body parts while simultaneously providing: load bearing; protection of the spinal cord and nerve roots; and facilitating fundamental human functions such as respiration, digestion, and postural equilibrium (Panjabi 1992). The normal role of the stabilising system requires instantaneously matching the stability demands from changes in spinal posture during both static (Panjabi 1992) and dynamic loads (Reeves and Cholewicki 2010, Reeves et al. 2007) without unduly compromising basic functions like breathing. It is well accepted that the spinal stabilising system can be divided into 3 interconnected subsystems; the passive, active and neural control subsystems (Panjabi 1992, Panjabi 2003).

The passive subsystem is comprised of the vertebrae, facet articulations, intervertebral discs, ligaments, joint capsule, connective tissue and the passive properties of muscles. This subsystem contributes to spinal stability particularly towards the limits of range of movement as tension in the ligaments and other soft tissues resist spinal motion (Panjabi 1992). The integrity of these structures also determines the size of the neutral zone i.e. the component of the range of motion in which there is minimal resistance to intervertebral motion and relatively greater proportion of stability is provided by neuromuscular elements (Panjabi 2003). Biomechanical studies demonstrate that the osseo-ligamentous lumbar spine buckles at relatively low compressive loads, that is, less than 88 N of vertical forces (Crisco et al. 1992). In vivo, the compressive force on the spine can exceed 2600N (Nachemson 1966). This discrepancy in load bearing supports the theory that the osseo-ligamentous system (part of the passive subsystem) must be augmented by muscle activation to maintain spinal stability (Bergmark 1989, Crisco and Panjabi 1991).

The active subsystem constitutes all the muscles that can apply forces to the spinal column (Panjabi 1992). Although it is established that the activation and motor control of trunk muscles (Figure 2-1), play a key role in providing spinal stability (Cholewicki and McGill 1996, Panjabi 2003) there is debate about the relative contribution of individual muscles to stability in both healthy and injured spines (Cholewicki and Van Vliet 2002, Hodges and Moseley 2003, McGill et
Bergmark (1989) categorized the trunk muscles into ‘local’ and ‘global’ muscle systems based on their anatomical features and differing mechanical roles in stabilization. Bergmark (1989) proposed a biomechanical model which predicts that the deeper, ‘local’ muscles with attachments to individual vertebrae such as the paraspinal multifidus muscles, are capable of controlling stiffness and the intervertebral relationship of spinal segments. In contrast, the relatively more superficial, ‘global’ muscles, (e.g. obliquus internus abdominis, obliquus externus abdominis, rectus abdominis and portions of quadratus lumborum and erector spinae) attach from the ribs to the pelvis with no direct attachment to the spine and are involved in moving the spine and transferring the load between thoracic cage and pelvis (Bergmark 1989, Richardson et al. 1999). The primary function of this active system is to balance external loads so that the residual forces transferred to the spine can be kept to a minimum and managed by the local muscles. For optimal spinal function, a complex interplay between both deep and superficial muscles is necessary (Cholewicki and Van Vliet 2002, McGill et al. 2003). There is consistent evidence supporting differential roles in spinal stability for some muscles (Hodges and Richardson 1997a, Hodges and Richardson 1997b). For instance, the transversus abdominis muscle is the first trunk muscle to be recruited in healthy subjects in preparation for rapid leg or arm movement and the onset of activity is not influenced by the direction of limb movement (Hodges and Richardson 1997a, Hodges and Richardson 1997b). Contraction of the transversus abdominis muscle along with the diaphragm (in a porcine model), also plays a key role in controlling intervertebral spinal stiffness and reducing intervertebral displacement (Hodges et al. 2003a). Differential activation of deep and superficial components of the multifidus muscles with postural perturbations provides evidence that the deep multifidus fibres may control intervertebral shear and torsion whereas the superficial multifidus fibres control orientation of the lumbar lordosis (Moseley et al. 2002).

![Figure 2-1 Transverse section of the trunk at L3/4 disc. Adapted from the Visible Human Project.](image)

The neural subsystem is comprised of the central nervous system and the sensory elements from both the active and passive subsystems (e.g. mechanoreceptors situated in ligaments, tendons
and muscles). The sensory elements provide information about vertebral position and motion to the neural control subsystem via signals produced from the soft tissue. The neural control system monitors position and movement and plans strategies of muscle activity to meet demand (Panjabi 1992). The muscles are controlled by both reflex and higher order neural commands in order to ensure that the trunk and spine system meets the requirements for stability (described in Section 2.3.4). This results in complex demands on the CNS to simultaneously coordinate the muscle activity required for spinal stability and homeostatic functions (Hodges and Moseley 2003).

2.3.3 Anatomy and function of selected trunk muscles

Although it is recognised that all trunk muscles have a role in maintaining optimal function (see Section 2.3.2), the focus in this thesis are the trunk muscles which have been observed to change in association with LBP in non-dancers (see Section 2.3.7). The trunk muscles investigated in this thesis include; the lumbar multifidus and lumbar erector spinae; quadratus lumborum; psoas major; transversus abdominis; and obliquus internus abdominis. Trunk muscles have complex anatomical structure which reflects the complex mechanics of the spine. Many trunk muscles have multiple fascicles that attach multiple structures with variable alignments relative to the joint/joints that they cross. The muscles have often been considered to operate as a single, functional unit but newer investigative techniques such as fine-wire EMG, have demonstrated differential activation, which suggests different functions in discrete regions of muscles such as transversus abdominis and obliquus internus abdominis (Urquhart and Hodges 2005), lumbar multifidus (Moseley et al. 2002), psoas major, and quadratus lumborum (Park et al. 2013a, Park et al. 2012). The function of discrete anatomical regions of the trunk muscles is not considered in this thesis however, description of the anatomy and function of these muscles is included to facilitate understanding of their potential role in motor control of the trunk of dancers and dancers with LBP.

2.3.3.1 Lumbar multifidus muscles

The lumbar multifidus muscle is the largest muscle that spans the lumbosacral junction and is composed of five separate fascicles (Figure 2-2). Each fascicle arises from a lumbar spinous process (extending from the tip to vertebral lamina of L1-L5) and receives separate innervation from medial branches of the lumbar dorsal rami which issue below that vertebra (Macintosh et al. 1986). The fascicles span several vertebral segments (2-5) attaching caudally in a variety of patterns. Attachment areas include the mamillary processes of L3-S1, the zygapophysial joint capsules (Lewin et al. 1962), the deep aspect of the erector spinae aponeurosis and the dorsal surface of the sacrum, sacro-iliac ligament and iliac crest (Macintosh et al. 1986). Importantly, the orientation of the fascicles suggests that the principal action of multifidus is posterior sagittal rotation of the
vertebrae (extension of the spine without posterior translation) and that it has limited capacity to produce axial rotation (Macintosh and Bogduk 1986) (Figure 2-2). EMG recordings confirm the superficial fibres from the fascicles control orientation of the lumbar lordosis, whereas the deep fibres are more involved in control of intervertebral shear and torsion (Moseley et al. 2002). These actions are particularly relevant when considering the requirements for movement and stiffness of dancers.

![Image](202x443 to 429x661)

**Figure 2-2** Schematic illustration of the overlying structure of the lumbar multifidus. Each band is separated from its neighbouring bands by distinct cleavage planes. In transverse sections, the overlapping arrangement of successive bands is evident. Adapted and reprinted from Macintosh et al (1986) with permission from Elsevier.

### 2.3.3.2 Lumbar erector spinae muscles

The lumbar erector spinae is a large muscle mass which lies laterally to the multifidus muscle and has three components; the longissimus thoracis, the iliocostalis lumborum which each have thoracic and lumbar fascicles (Macintosh and Bogduk 1987) and the spinalis thoracis, which is mainly aponeurotic in the lumbar region (Bogduk 1980)(Figure 2-3). Innervation is reported to be by the lateral branches of the dorsal rami of spinal nerves(Scheunke et al. 2006). Systematic resection reveals that the longissimus thoracis pars thoracis arises from thoracic transverse processes and ribs and traverses to attach to lumbar and sacral spinous processes, the fourth sacral segment and the ilium. Iliocostalis lumborum pars thoracis arises from the ribs and attaches to the posterior superior iliac spine and the iliac crest. In the lumbar region, the muscle mass can be divided into a medial (longissimus thoracis pars lumborum) and lateral division (iliocostalis lumborum pars lumborum) separated by an aponeurotic envelope formed by the erector spinae aponeurosis and the lumbar intermuscular aponeurosis (Bogduk 1980, Macintosh and Bogduk
1987). The longissimus thoracis pars lumborum arises from the lumbar transverse and accessory processes and attaches to the posterior superior iliac spine. Iliocostalis lumborum pars lumborum arises from the lumbar transverse processes and middle layer of the thoracolumbar fascia and attaches to the iliac crest (Macintosh and Bogduk 1987). As a group the lumbar erector spinae are reported to extend the lumbar spine and exert large intervertebral compression forces (Bogduk et al. 1992a). Iliocostalis lumborum also contributes to trunk lateral flexion (Ng et al. 2002). This may be an oversimplification of the forces produced by these muscles as the anatomical findings suggest individual fascicles may have differing functions (Bogduk 1980).

Figure 2-3 Surface anatomy of the lumbar multifidus and lumbar erector spinae. The locations of the lumbar multifidus (M) and the four components of the lumbar erector spinae (ES). The myotendinous junction of iliocostalis lumborum pars thoracis (ILpT) is indicated by the line aa1. These fibres cover the iliocostalis lumborum pars lumborum (ILpL). The line cc1 marks the lowest fibres of longissimus thoracis pars thoracis (LTpT) that lie deep to the ES aponeurosis over the longissimus thoracis pars lumborum (LTpL) whose medial border is depicted by the line bb1. The line A marks the lateral margin of the M. Line B marks the dorsal edge of the lumbar intermuscular aponeurosis and therefore the junction between the ILpL and LTpL. Line C marks the lateral border of ES. Line D marks the lower limit of the thoracic fibres of the ES. Adapted and reprinted from Macintosh and Bogduk (1987) with permission from Wolters Kluwer Health.

2.3.3.3 Quadratus lumborum muscles

The quadratus lumborum muscle is composed of four regions of fascicles (defined by their bony attachments as; iliocostal- pelvis to rib, iliolumbar-pelvis to lumbar vertebrae, iliothoracic-pelvis to 12th thoracic vertebrae and lumbocostal-lumbar vertebrae to 12th rib) which are arranged in three layers (anterior, middle and posterior) (Figure 2-4). Anatomical texts describe that the nerve supply is from the 12th costal nerve (Scheunke et al. 2006). EMG evidence suggests that the anterior
and posterior layers are active during lateral flexion of the trunk (Park et al. 2012) and the posterior layer is active during trunk lateral flexion and extension and also has an influence on respiration (Park et al. 2013a, Park et al. 2012).

Figure 2-4 Three layers of quadratus lumborum and their component fascicles. The lines depicting each type of fascicle have been drawn with a thickness proportional to the incidence of the fascicle. The dotted lines indicate fascicles that were seen infrequently. Adapted and reprinted from Phillips et al. (2008) with permission from SAGE Publications.

2.3.3.4 Psoas major muscles

The psoas major muscle originates from the vertebral bodies and transverse processes of T12 to L5 and forms a single round tendon which attaches to the lesser trochanter of the femur. Five fascicles arise from the intervertebral discs (T12-L1 to L4-L5), five fascicles arise from the transverse processes (L1-5) and irregularly another fascicle arises from the L5 vertebral body (Bogduk et al. 1992b) (Figure 2-5). Anatomical texts report that the nerve supply is from the lumbar plexus (L1-3) (Scheunke et al. 2006). Importantly, biomechanical modelling suggests psoas major flexes the hip and in erect posture tends to extend the upper lumbar vertebrae and flexes the lower lumbar vertebrae exerting compression and shear loads on the spine (Bogduk et al. 1992b). Investigation of muscle activity with EMG techniques demonstrates that the fascicles of psoas major which arise from the intervertebral discs are more involved in hip flexion whereas those fascicles that arise from the transverse processes are more involved in trunk extension (Park et al. 2013a) and that both regions are active in trunk lateral flexion (Park et al. 2012).
Figure 2-5 Sites of attachment (shaded areas) and the lines of action of the fascicles of psoas major as seen in the sagittal and anterior projections. Adapted and reprinted from Bogduk et al. (1992b) with permission from Elsevier.

2.3.3.5 Transversus abdominis muscles

The transversus abdominis muscle has broad and diverse origins from the 7-12th costal cartilages, all layers of the thoracolumbar fascia, the iliac crest, the anterior superior iliac spine and the lateral part of the inguinal ligament. The muscle fibres spread across the abdomen to insert on the linea alba and posterior layer of the rectus sheath (Scheunke et al. 2006)(Figure 2-6). Although some authors note that, rather than an insertion, the area between the two sides of the muscle should be considered as an aponeurotic area between muscle strata (Askar 1977). Anatomical texts report that innervation is from the intercostal nerves (T5-12), the iliohypogastric nerve, ilioinguinal nerve and genitofemoral nerve (Scheunke et al. 2006).

The transversus abdominis muscle has multiple functions. Detailed dissection has revealed that the muscle can be divided into three regions with the upper fascicles running horizontally and the middle and lower fascicles running inferomedially. These regions can produce different actions on the trunk (Urquhart et al. 2005). When the transversus abdominis muscle produces torque during trunk rotation (Cresswell et al. 1992) the upper fascicles are active in the opposing direction to that of the ipsilateral lower and middle regions (Urquhart and Hodges 2005). EMG studies demonstrate that the transversus abdominis muscle is tonically active in upright posture (Urquhart and Hodges 2005) and is a major contributor to intra-abdominal pressure (Cresswell et al. 1992). These findings
along with anatomical observations (Askar 1977, Urquhart et al. 2005) provide evidence that the transversus abdominis muscle supports the abdominal contents and has a role in respiration. Contraction of the transversus abdominis muscle also reduces abdominal circumference and increases tension in the thoracolumbar fascia (Bogduk and Macintosh 1984). It is argued that activation of the transversus abdominis muscle has a role in trunk stability by increasing intra-abdominal pressure (Cresswell et al. 1994, Hodges et al. 2001b), tensioning the fascias (Bogduk and Macintosh 1984, Hodges 1999) and compressing the sacroiliac joints (Richardson et al. 2002, Snijders et al. 1995). These functions may be particularly important for dancers.

Figure 2-6 Diagram representing the anatomy of the transversus abdominis muscle. The attachments of transversus abdominis to the lumbar vertebrae via middle and anterior layers of the thoracolumbar fascia (TLF) are not shown. To demonstrate the bilaminar fascial attachment of the posterior layer of the TLF it is shown connecting only to the spinous processes. LR; lateral raphe, LA; linea alba, SP; superficial lamina of the posterior layer of the TLF, DP; deep lamina of the posterior layer of the TLF. Adapted and reprinted from Hodges (1999) with permission from Elsevier.

2.3.3.6 Obliquus internus abdominis muscles

Obliquus internus abdominis muscle has similar origins to the transversus abdominis muscle with the exception of attachment to costal cartilages. It originates from the deep layer of thoracolumbar fascia, the intermediate line of the iliac crest the anterior superior iliac spine and the lateral part of the inguinal ligament. It inserts into the lower borders of the 10-12th ribs, the linea alba and anterior and posterior layers of the rectus sheath (Scheunke et al. 2006) (Figure 2-7). Similar to the transversus abdominis muscle, there is a complex arrangement of aponeurotic fibres decussating from one side of the muscle to the other across the midline (Askar 1977). According to anatomical texts, the muscle receives innervation from the intercostal nerves (T8-12), the
iliohypogastric nerve and the ilioinguinal nerve (Scheunke et al. 2006). Muscle fascicles of obliquus internus can be distinguished into an upper, middle and lower region and extend lower than those of the transversus abdominis muscle. There are two distinct muscle layers in the lower and middle regions (Urquhart et al. 2005). The upper and middle fascicles are oriented superomedially and below the iliac crest, where as the lower fascicles are oriented horizontally with increasing inferomedial angulation below the anterior superior iliac spine (Urquhart et al. 2005). The anatomical distinction of regions is consistent with EMG evidence of differential action e.g. the lower and middle regions of the right obliquus internus abdominis muscle are active with rotation to the left (Urquhart and Hodges 2005) and the orientation of the upper and middle fascicles is consistent with a role in trunk flexion (Cresswell et al. 1992). The anatomical findings also support suggestions that the lower region of the obliquus internus abdominis muscle contributes to support of lower abdominal contents and compression of the sacroiliac joints (Richardson et al. 2002, Snijders et al. 1995, Urquhart et al. 2005).

![Figure 2-7 Anterior abdominal wall showing the internal oblique muscle, under the external oblique muscle. Adapted and reprinted from Skandalakis and Skandalakis (2014) with permission from Springer.]

2.3.4 Mechanisms of motor control

2.3.4.1 Motor control – a systems dynamic approach

In addition to understanding the theory of motor control, the stability of trunk and spine and the key trunk muscle anatomy and functions, it is also important to review the mechanical aspects of
motor control. As mentioned in the section on the development of the theory of motor control (Section 2.3.1), the systems dynamic approach with engineering modelling has improved the understanding of attributes of the trunk such as stability and mechanical properties (e.g. stiffness and damping). In this thesis, Study III estimates the mechanical properties of the trunk in dancers and dancers with LBP (Study III [Chapter 5]). Definitions of the terms and description of the concepts used in the systems dynamic approach provide a framework for discussing the static and dynamic control of the spine system in order to improve understanding of the mechanical aspects of LBP.

In biomechanical terminology, stability, along with robustness and performance are key behavioural attributes which are necessary for any system, including the trunk and spinal system to function (Reeves et al. 2007). Fundamentally a system is either stable or unstable and in the spine, this is applied to the behaviour of individual vertebrae as well as the entire region (Reeves et al. 2007). Stability can be defined in mechanical terms as the ability of a system to return to equilibrium of position or movement after a small perturbation (Gardner-Morse and Stokes 2001). Robustness describes how well a system copes with uncertainties and disturbances and maintains stable behaviour for both small and large perturbations. Performance refers to how closely and rapidly the disturbed position of the system tends to the undisturbed position i.e. accuracy and speed of recovery with minimal error (Reeves et al. 2007).

Confusion arises when discussing stability of the spine in clinical terms. For instance describing dysfunction such as ‘segmental clinical instability’ as a result of structural instability (e.g. spondylolisthesis) or altered motor control (O'Sullivan 2000, Panjabi 2003). From a clinical perspective, spinal stability is often considered a continuum with an optimally functioning spine at one end, total loss of integrity and function at the other end and in between a range of degrees of dysfunction. These clinical entities are difficult to reconcile with an engineering approach to stability which may describe ‘segmental clinical instability’ as ‘reduced robustness of segmental control’.

To assess stability, the behaviour of the system (spine/trunk) in response to a small perturbation is observed (see Study III). The system is deemed stable if the new behaviour is similar to the original behaviour and unstable if it differs significantly. Stability is context dependent and needs to be defined for static conditions which exist when the system is in equilibrium as well as for dynamic systems in which the system is moving or changing over time (Reeves et al. 2007). The description of the mechanism of spine stability in Section 2.3.2 is largely focused on analysis of the static condition of the spine. Studies in this area have provided knowledge about the potential for injury under low level loading (Cholewicki and McGill 1996) and the importance of coordinated recruitment of trunk muscles to enhance stiffness to maintain spine stability and prevent injury.
(Bergmark 1989, Crisco and Panjabi 1990, Crisco and Panjabi 1991). For dynamic systems the new trajectory is compared to the undisturbed trajectory and for the path to be maintained there must be a relationship between the size of the perturbation and the limit of the region in order to state the system is stable. Feedback control of the state of a system, especially a dynamic system like the spine and trunk, is vital to ensure stability (Reeves et al. 2007).

From a mechanical perspective an important component of control in the trunk system is feedback. Feedback refers to the output of the system and is used to modify the input (Reeves et al. 2007). Feedback signals come from sensors that provide information about the ‘state of the system’. These signals are processed by the feedback controller which then generates control signals to be applied to the system. Feedback gain is input proportional to output, and refers to the ability of the system to vary the feedback control (Reeves et al. 2007). In the trunk (plant), the feedback controller is comprised of the intrinsic properties of joints and trunk muscles (stiffness and damping) and the CNS, which can respond with reflexive and voluntary muscle activation (Figure 2-8). Alternatively, the intrinsic properties can be included in the plant (trunk) which allows more logical connection between the ‘feedback controller’ in systems dynamics and the CNS (Reeves et al. 2007). In response to perturbation, feedback from the CNS (by reflex and voluntary muscle activation) incurs delays due to signal transmission, processing time and time required to generate muscle force (Reeves et al. 2007). The size of the perturbation and initial state of the spine system determines the relative contribution of reflex and voluntary muscle activation. In addition to responding to perturbation, the system can prepare for perturbation. It is likely that sensory signals are compared with neural models of the trunk system and used to predict the state of the system. Prediction of the state of the system is used to generate feedback control signals to activate trunk muscles (Reeves et al. 2011).
Although in the trunk/spine control system there is considerable redundancy with several muscles able to perform similar functions and a number of neural pathways available; for a given task there is likely to be an optimum control strategy that minimizes metabolic costs and/or maximizes the system’s performance (Reeves et al. 2007). In order to be optimally effective in maintaining trunk stability the feedback controller needs to satisfy several requirements. The CNS must accurately track the position and velocity of spine movement for each degree of freedom (i.e. 3 rotations and 3 translations for each lumbar vertebrae). Feedback signals come from sensors e.g. muscle spindles which are sensitive to muscle length (position) and rate of change (velocity) (Buxton and Peck 1989), and are processed by the feedback controller (CNS) which generates several signals to be applied at different segmental levels. This feedback needs to be precise as impairment in tracking will impair control, leading to non-optimal recruitment of trunk muscles and utilisation of higher forces to stabilise the system which in turn will increase strain and stress on spinal tissue (Reeves et al. 2007). It has been proposed that the segmental muscle wasting (e.g. in multifidus muscles)(Hides et al. 1996) (see also Study I) or impaired proprioception (Brumagne et al. 2000, Leinonen et al. 2003) found in people with LBP could impair tracking of the spine and lead to aberrant motion (Reeves et al. 2011). It has also been argued that the higher level of trunk muscle co-activation frequently seen in people with LBP may indicate non-optimal recruitment (van Dieen et al. 2003) to compensate for poor perception of spine position or movement. Another requirement for optimal stability is that the architecture and neural recruitment of trunk muscles must allow the feedback controller to have independent control of spine segments (Reeves et al. 2011). It has been proposed that multifidus muscles have the ideal anatomical structure and segmental innervations to perform this role (MacDonald et al. 2006) and that changes in the recruitment pattern (MacDonald et al. 2009) and morphology (Hides et al. 1996) of multifidus muscles...
muscles in people with LBP may reduce the robustness of the spine system (Hodges 2013). A further requirement is that the trunk system needs to be controllable and observable to minimise metabolic costs and keep stabilising forces low to allow people to perform activities for long periods of time without undue fatigue (Reeves et al. 2011). The time taken for information about the ‘state of the system’ and the application of control is important as delays in either of these aspects are problematic especially with fast movement (Reeves et al. 2007, Reeves et al. 2011). An example of this issue is the finding of delayed reflex response of trunk muscles to sudden load release in people with chronic LBP (Radebold et al. 2000).

Stability of the trunk requires a balance between stiffness and movement. To maintain stability under different conditions the CNS must learn the dynamics of the spine system and choose a strategy to fulfil the goals. Stiffening strategies such as co-contraction of large flexor and extensor muscles are proposed to be for situations of high load (Cholewicki et al. 1991) or unpredictable forces (van Dieen and de Looze 1999) whereas dynamic strategies involve underlying tonic contraction of deep muscles and early activity prior to perturbation with precisely timed alternating bursts of superficial muscle activity (Hodges 2013, Hodges and Richardson 1997a, Hodges and Richardson 1997b)(Figure 2-9). In this dynamic strategy, adjusting the ‘feedback gains’ allows ‘fine tuning’ of the performance with the option of increasing response time and weighting performance over energy cost (Reeves et al. 2011). Evidence from EMG studies suggests that healthy non-dancers use a dynamic strategy for control of the trunk in tasks like moving the arm in standing (Hodges and Richardson 1997b) and walking (Saunders et al. 2004). However, non-dancers with LBP often demonstrate different control strategies (Hodges and Richardson 1996). For instance, in slow trunk movements and isometric contractions people with LBP use a muscle recruitment pattern of co-activation which has been modelled and shown to increase spinal stability (van Dieen et al. 2003). Although achieving the short term goal of increasing stability, this stiffening strategy may have longer term negative repercussions for the spine (Hodges 2013) secondary to increased compressive load (Gardner-Morse and Stokes 1998, Stokes and Gardner-Morse 2003). Approaching the stability of the trunk from a mechanical perspective allows investigation of trunk stiffness in healthy participants and participant with LBP (Hodges et al. 2009) (see Section 2.5 and Study III [Chapter 5]).
Figure 2-9 Spectrum of control strategies. Dynamic control of the spine involves a spectrum of control strategies that range from co-contraction stiffening to more dynamic control strategies that involve carefully timed muscle activity and movement. Multiple factors such as load, movement, predictability, proprioceptive function and error tolerance are likely to influence the selection of the appropriate dynamic control strategy. Adapted and reprinted from Hodges (2013) with permission from Elsevier.

2.3.4.2 Motor control - a neural perspective, open-/closed-loop strategies

As described in the previous section on mechanical perspective of motor control (Section 2.3.4.1), optimal function of the trunk system requires feedback control. The CNS, which can be thought of as the ‘feedback controller’ of the trunk system, uses several motor control strategies to coordinate the activity of trunk muscles in response to internal and external challenges. These strategies can be broadly classified as closed-loop (feedback) or open-loop (feedforward) control systems (Figure 2-10). Both systems are used in combination during most functional tasks (including maintaining postural equilibrium see Section 2.6) to activate trunk muscles for control of stiffness and movement.

In a closed-loop system, the intended movement task is compared with the feedback about the status of the body and its relationship to the environment (Schmidt and Lee 2011). Sensory information from receptors in eyes, vestibular apparatus, muscles, joints and skin, is used to detect the position and movement of the body in relation to the environment. If the feedback derived during a movement is different from the intended movement, the movement is corrected with an error command. This feedback system provides a method for counteracting unexpected trunk
perturbations and correction of non-ballistic voluntary movement (Schmidt and Lee 2011). Several closed-loop mechanisms have potential to contribute to motor control of the spine. One mechanism, short latency reflex responses have been observed in abdominal (Cresswell et al. 1994) and lumbar spine muscles (Moseley et al. 2003) in response to unexpected trunk and upper limb loading. These responses are fast but inflexible demonstrating a basic mechanism for the motor system to correct an error (e.g. regulates skeletal muscle length in response to stretch). There is, however evidence that input from higher centres can influence these responses when the perturbation is more predictable (Moseley et al. 2003).

Triggered responses are another closed-loop control mechanism which are faster than voluntary reaction time but involve a more complex and extensive response than reflex mechanisms (Schmidt and Lee 2011). In contrast to reflex responses, triggered responses exhibit increased flexibility, more integration, and are specific to the size and direction of perturbation (Nashner 1976). An example of this type of response occurs when the support surface under a standing subject is tilted backwards causing a stretch of the triceps surae muscles. Triggering a short-latency reflex response resulting in a calf muscle contraction would cause a loss of balance so the stretch reflex is suppressed and a more appropriate muscle response is activated (Nashner 1976).

**Figure 2-10 Motor control systems. A. Closed-loop and B. Open-loop control systems. 1. Executive determines actions to maintain the desired goal. 2. Effector carries out the desired action. 3. Feedback information produced from movement. 4. Comparator compares feedback of desired state to feedback of actual state. Adapted and reprinted from Schmidt and Wrisberg (2008) with permission from Human Kinetics.**
In an open-loop or feedforward system of control, movement is pre-planned by the CNS and can be executed without ongoing sensory feedback. This control system is useful for movements that are ballistic, repetitive and involve predictable perturbation to the body e.g. during voluntary limb movements (Hodges and Richardson 1997b). It is hypothesised that the CNS constructs a sensory motor representation of the body from movement experience which contains information about the interaction of internal and external forces (Clément et al. 1984). The CNS uses the predicted effect of these forces to trigger a sequence of coordinated muscle activation to anticipate these forces (Massion 1992). The muscle contractions which produce the voluntary movement (e.g. arm flexion) also generate internal forces which disturb posture of body segments and equilibrium. Evidence suggests that feedforward parallel commands are created by the CNS so that anticipatory postural adjustments are made to minimise the equilibrium disturbance associated with performance of the movement (Massion 1992). This open-loop control is used to stabilise the spine when perturbations are predictable for example: activation of the trunk (Hodges and Richardson 1997b) and leg muscles (Aruin and Latash 1995) prior to activation of the shoulder muscles during upper limb movements. In addition, these open-loop control mechanisms are organised in a specific manner as they are linked to the direction (Hodges and Richardson 1997b) and speed of movement (Hodges and Richardson 1997c), and knowledge of the load (van Dieen and de Looze 1999). When the perturbation is less predictable (e.g. variable load), trunk muscles are co-activated bilaterally and the rate of movement is slower (van Dieen and de Looze 1999). This recruitment pattern of co-activation is reduced when the predictability of the task is increased (Radebold et al. 2000).

2.3.4.3 Motor control strategies- a muscle perspective

As outlined in the previous section on the neural perspective of motor control (Section 2.3.4.2), perturbation studies in combination with EMG provide information about which motor control strategy (open-/closed-loop) is used in specific tasks to control specific muscles or portions of muscles. Different responses of trunk muscles to predictable and unpredictable perturbations together with knowledge of the muscle anatomical structure demonstrates the potential roles of specific muscles. Several studies examining a variety of tasks have observed different responses in superficial trunk muscles such as rectus abdominis, obliquus internus, obliquus externus abdominis, erector spinae and superficial fibres of multifidus when compared with the responses of deep trunk muscles such as transversus abdominis and the deep fibres of multifidus muscles. For example, in response to a predictable perturbation to the trunk by limb movement, activation of the superficial trunk muscles is dependent on and opposite to the direction of the perturbation (i.e. when the spine is perturbed into flexion the lumbar extensor muscles are activated earlier and when the spine is perturbed into extension the superficial abdominal muscles are activated earlier) (Hodges et al. 2000).
It is suggested the phasic feedforward action (open-loop control) of the superficial muscles results in preparatory trunk motion that opposes the direction of perturbation and assists with control of the centre of mass and spinal stability (Hodges et al. 1999). In contrast, when responding to an unpredictable lifting task, superficial trunk muscles co-contract bilaterally in a way that is not specific to movement of the centre of mass but increases trunk stiffness (van Dieen and de Looze 1999). The activation pattern of the deep abdominal muscle, transversus abdominis is different to superficial abdominal muscle recruitment. The transversus abdominis muscle is often activated prior to the more superficial abdominal muscles and is not activated in a direction specific manner.

In tasks of multidirectional upper limb movement the transversus abdominis muscle contracts in a feedforward manner irrespective of the direction of perturbation and prior to activation of the prime mover and trunk movement (Hodges and Richardson 1997b) (Figure 2-11). Even when the direction of perturbation is unpredictable, activation of the transversus abdominis muscle is in a feedforward, non-direction specific manner (Hodges and Richardson 1999). This is consistent with a role in trunk robustness and inconsistent with control of trunk orientation (Hodges and Richardson 1997b). A similar pattern of activation, in response to perturbation by arm movements, has been demonstrated in the deep portion of the back muscle multifidus, which supports a role in segmental spinal control (Moseley et al. 2002). These findings build on the anatomical differences between deep and superficial trunk muscles (described in Section 2.3.2, Section 2.3.3) and support differential motor control of deep and superficial trunk muscles in people without LBP.

Figure 2-11 Raw electromyography (EMG) recordings from a single subject showing activation of trunk muscles during arm movements in different directions. The onset of deltoid is denoted by the heavy line. The onset of transversus abdominis (TrA) is denoted by the dashed line and notably is prior to that of the prime mover (deltoid) and the other trunk muscles regardless of direction of arm movement. (OI, Obliquus internus abdominis; OE, Obliquus externus abdominis, RA, rectus abdominis, MF, multifidus). Adapted and reprinted from Hodges et al. (1997b) with permission from Springer.
2.3.5 Motor control strategies in healthy dancers

There is limited research about motor control strategies in healthy dancers, particularly with respect to trunk stiffness and movement (Rickman et al. 2012). The most detailed information available is provided by a series of studies which compared experienced dancers with naïve non-dancers. Participants completed a task of moving in response to a light signal, from two legged standing in a ‘toes out’ position to one leg standing with the other leg elevated to the side (Mouchnino et al. 1990, Mouchnino et al. 1991, Mouchnino et al. 1992, Mouchnino et al. 1993). Analysis of data from ground reaction forces, kinematic analysis and EMG recordings revealed several differences in motor control between the two groups. The observations have important implications for this thesis as they show difference in trunk/head control between dancers and non-dancers. Dancers performed the body weight transfer in almost one step, achieving the new centre of gravity position with minimal displacement as they thrust with the moving leg and requiring only a short adjustment period to reach the final steady-state position. In contrast, non-dancers used a two step process with a longer adjustment component. The timing of events during this sequence was fairly fixed in dancers whereas there was considerable variation between trials in non-dancers. These differences imply that dancers’ training forms a better internal representation of the biomechanical limits of stability as they had more accurate, efficient and repeatable movement patterns. The movement strategy used was also different between the two groups. Naïve non-dancers used an inclination strategy. This involved external rotation of the supporting leg around the ankle joint and lateral inclination of the body over the hip joint with compensatory counter-rotation at the neck to restore the interorbital line in the horizontal plane. Dancers used a translation strategy, which involved external rotation of the supporting leg around the ankle joint associated with counter-rotation of the trunk around the hip joint. In turn, this maintained verticality of the head-trunk axis and kept the eyes horizontal. There are several reasons why this translation strategy is important with regard to trunk control in dancers (Mouchnino et al. 1990). First, keeping the trunk axis vertical minimises the change in body geometry as it reduces displacement of the centre of gravity. Second, there is better stabilisation of the interorbital line as the main adjustment is performed at the level of the trunk and only minimal adjustment is required at the head level. Third, the position of the trunk appears to be regulated independently of the leg position (Massion 1992) and may be utilized as a reference position for the organisation of movement in dancers (Mouchnino et al. 1990). These studies provide evidence of the important role of the trunk in movement strategies of healthy dancers. The findings also invite speculation about the potential effects of LBP on the movement strategies of dancers; which inspired the investigations in this thesis.
In the translation strategy (described above), dancers coordinated counter-rotation around the
hip prior to the ankle joint rotation. This movement pattern involves feedforward (open-loop)
control which suggests that new motor programs evolve in response to dance training (Mouchnino
evidence of the development of motor programs in response to dance training is provided by studies
which compare the execution of dance-specific movements in dancers of different skill levels
(Bronner 2012, Chatfield 2003). Motion analysis of a développé arabesque (moving the gesture leg
from the ground to an elevated position behind the body) was used to compare dancers at
intermediate, advanced and expert skill levels. The dancers performed similarly with regard to
movement organisation, timing and spatial orientation. The least skilled dancers demonstrated less
optimal postural control which was mostly accounted for by large variability in the position of the
pelvis in all planes of motion (Bronner 2012). The increased lumbo-pelvic control by the expert
dancers appeared to be the key to minimising movement variability and facilitating inter- and intra-
limb coordination. The data from these studies suggests that dancers develop specific motor control
strategies which are focused on the spine and pelvis.

Support for change in motor control as a result of dance training comes from a number of
studies that have demonstrated specific adaptations of the spinal stretch reflex circuit (involved in
closed-loop control); although the possibility that dancers possess inherently different motor control
prior to engaging in dance training cannot be discounted (Simmons 2005a). One technique used to
study the spinal stretch reflex circuit is electrical stimulation of the peripheral nerve (in this
example the tibial nerve) which directly activates the target muscle (soleus) via stimulation of the
efferent motor neuron (M-wave) as well as indirectly activating the muscle (H-reflex) via
stimulation of the sensory fibres (1a afferents from the muscle spindle). This H-reflex (Hoffmann-
reflex) is considered the electrical equivalent of the stretch reflex but it bypasses the muscle spindle
so this methodology allows assessment of the central mechanisms involved in motor neuron
excitability (Nielsen et al. 1993). Professional ballet dancers have smaller soleus H-reflex responses
than other athletes and show decreased levels of reciprocal inhibition of the antagonistic muscle,
tibialis anterior. This was interpreted as an adaptation to the prolonged training of dancers which
requires co-contraction of antagonistic lower leg muscles to maintain balance (Nielsen et al. 1993).
Other evidence that dancers may suppress spinal stretch reflexes to facilitate balance comes from
the finding that although dancers demonstrate similar reflex gain (the ratio between the amplitude
of the H-reflex and background EMG) to non-dancers in the prone position there is a marked
reduction in reflex gain in the standing position. This suggests that dancers have differential control
of reflex modulation to maintain postural stability (Mynark and Koceja 1997). It was proposed that
these changes in reflex activity may reflect increased pre-synaptic inhibition, however, a pilot study
comparing modern dancers to untrained participants did not show evidence of pre-synaptic inhibition in the tibialis anterior despite persistent depression of the soleus Hmax/Mmax ratio (Ryder et al. 2010). Change in this ratio which represents the proportion of alpha motor neurons that can be activated reflexively versus stimulated directly is thought to be a sign of plasticity of spinal mechanisms in response to dance training (Nielsen et al. 1993, Ryder et al. 2010). There is also evidence that the H reflex can increase (Hale et al. 2003) or decrease (Jeannerod 2001) in response to mental practice or motor imagery which are frequently used in dance training to change movement performance (Coker Girón et al. 2012, Couillandre et al. 2008, Ryder et al. 2010).

Adaptation to dance training has also been suggested as the reason for the findings of faster and more consistent response of tibialis anterior to mechanical perturbation of balance in dancers (Simmons 2005a). The onset time of short (stretch reflex) and medium latency reflex response of medical gastrocnemius muscle and long latency reflex response of tibialis anterior muscle were measured in response to a dorsiflexion (toes up) perturbation. There was no difference between ballet dancers and non-dancers in the short or medium latency responses, however, the faster and more consistent long latency responses in dancers were suggested to be related to changed CNS morphology and improved central processing respectively (Simmons 2005a). In summary, evidence of adaptation of both open- and closed-loop control mechanisms has been demonstrated in response to dance training and although the precise neural mechanisms mediating these changes remain unclear plasticity of the CNS appears to be involved. In this thesis, two studies examine the response of dancers to perturbation of the trunk to provide further insight into the nature of the adaptation of motor control to training. Where possible the unique aspects of classical ballet were considered in the design of these studies in order to ensure the investigations were relevant to dancers. One study investigated the mechanical response of the trunk to perturbation and used motor imagery to promote different qualities of movement (Study III [Chapter 5]). The other study investigated the response of the body when maintaining postural control in standing (i.e. balance) using a dance-specific position (see Study IV [Chapter 6]).

2.3.6 Impact of motor control changes

As the trunk and spine are the central part of a multi-joint kinetic chain organised by a complex control system, changes in one area (e.g. the back) are not isolated and have potential to affect other areas. Prospective studies have examined the relationship between motor control and injury and have identified factors which could have considerable clinical impact. Healthy athletes with delayed abdominal muscle shut-off time in response to quick release of force to perturb the trunk into flexion and lateral bending were at higher risk of sustaining a low back injury. In addition, the delayed latency of muscle shut-off appeared to be a pre-existing risk factor (Cholewicki et al. 2000).
Female athletes with impaired proprioception, as measured by active repositioning of the trunk, were at higher risk of developing a knee injury (Zazulak et al. 2007b). Increased trunk displacement after sudden force release also predicted knee injury in female athletes (Zazulak et al. 2007a). Delayed muscle reflex response, impaired accuracy of trunk repositioning and reduced ability to maintain equilibrium after trunk perturbation are proposed to be evidence of decreased motor control of the trunk (Cholewicki et al. 2005, Zazulak et al. 2007a, Zazulak et al. 2007b). Similar deficits in motor control, in response to quick force release have been found in people with LBP (Radebold et al. 2000) and athletes with a history of low back injury (Cholewicki et al. 2002). Increased trunk repositioning error has also been found in association with LBP (Brumagne et al. 2000). The data from these studies suggest a relationship between effectiveness of motor control and injury.

Within the pain-free population there appears to be a spectrum of aspects of motor control from less optimal to more optimal. It is possible that assessment of motor control could have a place in screening of dancers to identify those at risk of developing injury as well as those with incomplete recovery from previous low back injury. Methodology utilized in the studies in this thesis (Studies I-IV) may have potential to be developed into screening tools to identify dancers at risk of primary or recurrent LBP.

2.3.7 Motor control changes associated with LBP

In the words of Gordon (1987) a motor control “theory is not right or wrong in an absolute sense, but it is judged to be more or less useful in solving the problems presented by patients with movement dysfunction”. Findings from studies about the alterations that occur in motor control in association with LBP provide further insight into the complexity of function and dysfunction of the trunk system. This knowledge provides the background for interpreting differences between dancers and dancers with LBP; in muscle morphology (Studies I [Chapter 3] and II [Chapter 4]), mechanical properties (Study III [Chapter 5]), and postural control tasks (Study IV [Chapter 6]).

2.3.7.1 Motor control in dancers and other elite sporting groups with LBP

There is minimal published literature about motor control in dancers with LBP (Rickman et al. 2012, Smith 2009). In the absence of population specific research it is necessary to consider literature from other groups; particularly sporting groups. This highlights areas of consideration that may be relevant to dancers and may require further investigation.

The muscle response to sudden trunk loading was examined in athletes who had a recent history of low back injury. Compared with healthy athletes those with previous LBP demonstrated an altered muscle response of shutting-off fewer muscles with longer switch-off latencies.
(Cholewicki et al. 2002). This suggests a pattern of increased muscle co-activation which is similar to the pattern seen in people with chronic LBP (Radebold et al. 2000) and is consistent with the alteration of motor control discussed in the following sections (Section 2.3.7.2, Section 2.3.7.3). The similarity in the pattern of muscle response between these two physically contrasting groups suggest that at least in some aspects of motor control it is relevant to extrapolate from a more sedentary group to an elite athletic population. In contrast, (and further detailed in sections 2.4.2) although elite cricket players and football players with LBP have reduced ability to voluntarily contract the abdominal wall (Hides et al. 2010a, Hides et al. 2011a, Hides et al. 2008a) changes in other trunk muscles e.g. psoas and quadratus lumborum muscles appear to be associated with specific sports (Hides et al. 2008a, Hides et al. 2010b). This highlights a need to study motor control specifically in dancers with LBP as it may not be accurate to extrapolate findings from non-dancers to dancers.

2.3.7.2 Association between motor control and pain

Dancers regularly dance through pain (Anderson and Hanrahan 2008) and exhibit different pain coping styles compared to other athletes (Encarnacion et al. 2000). Dancers also experience difficulty distinguishing performance and injury pain (Anderson and Hanrahan 2008) and demonstrate higher pain thresholds and pain tolerance thresholds than non-dancers (Tajet-Foxell and Rose 1995). These findings suggest that dancers may continue to perform despite experiencing back pain. In non-dancers motor control changes have been shown even with anticipation of back pain (Moseley et al. 2004). Therefore is probable that dancers perform with adaptation of their motor control system related to LBP.

The association between pain in the low back region and changes in motor control of the trunk muscles has been reported frequently (Hodges and Moseley 2003, van Dieën et al. 2003). There are several theories proposed to interpret these changes. In the ‘vicious cycle’ model, pain results in increased muscle activity which further increases pain (Roland 1986). To explain the ‘vicious cycle’ (pain-spasm-pain model), two distinct neural pathways have been proposed which both result in hyper excitability of the alpha motor neuron pool (van Dieën et al. 2003). Several neurophysiological studies have been conducted (mostly in animals) which verify the existence of these distinct neural pathways (van Dieën et al. 2003).

In another model, the ‘pain adaptation’ model, it is proposed that pain reduces activation of muscles when acting as agonists and increases activation of muscles when acting as antagonists, which results in a restricted spinal motion (Lund et al. 1991). There is also strong support from neurophysiological studies for the ‘pain adaptation’ model showing induced pain in human gastrocnemius muscles resulted in reduced activity of this muscle (the agonist) and increased
activity of tibialis anterior (the antagonist) during gait (Arendt-Nielsen et al. 1996). Although there is evidence from clinical studies on spinal control which supports the ‘pain adaptation’ model (showing reduced agonist muscle activation with submaximal activity) (van Dieën et al. 2003), some studies have reported increased activity (Graven-Nielsen et al. 1997) and others no change in activity (Collins et al. 1982) of the lumbar erector spinae muscles. Also contradictory to the predictions of the ‘pain adaptation’ model is the finding of paraspinal muscle activation in full flexion of the trunk in some people with LBP (Shirado et al. 1995).

It has been argued that neither model is consistently supported by the research evidence and that the contradictory evidence lends support to the stability theory proposed by Panjabi (1992, 2003). This theory suggests changes in muscle activity may be a compensatory mechanism for a decrease in robustness to prevent noxious tensile stress rather than a simplistic response to pain (van Dieën et al. 2003). Further development of this idea in conjunction with evidence from people with LBP has led to the proposal of a more comprehensive theory about the changes in motor control in LBP (Hodges 2013). In summary this theory hypothesizes that adaptation of motor control to acute pain; leads to ‘protection’ from further pain/injury or threatened pain/injury; involves redistribution of activity within and between muscles; changes mechanical behaviour like movement or stiffness; cannot be explained merely by changes in excitability of the nervous system but involves changes at multiple levels of the motor system which may be complementary, additive or competitive; and has short-term benefit with potential long term consequences (Hodges 2011, Hodges 2013, Hodges and Tucker 2011) (Figure 2-12).

Figure 2-12 New theory of motor adaptation to pain and implications for rehabilitation. Adapted and reprinted from Hodges (2011) with permission from Elsevier.
It has frequently been reported that LBP is associated with augmented recruitment of the more superficial muscles which is generally variable between individuals (Arendt-Nielsen et al. 1996, Cholewicki et al. 2002, Hodges and Moseley 2003, Hodges and Richardson 1996, Radebold et al. 2000) and is proposed to be a strategy to protect or splint the spine (Hodges 2011). There are many examples in the literature. In people with LBP, increased lumbar erector spinae activity was recorded during gait at heel strike and during the normally electrically silent period double support phase of gait (Arendt-Nielsen et al. 1996). Compared with healthy individuals, recordings from surface EMG in people with chronic LBP (Radebold et al. 2000) and athletes with acute pain (Cholewicki et al. 2002), show increased co-contraction of trunk muscles (thoracic and lumbar erector spinae, latissimus dorsi, rectus abdominis, internal and external oblique abdominal muscles) in response to a quick load release task. More detailed EMG examination of lumbar erector spinae muscle activity along with activity of the deeper trunk muscles psoas major and quadratus lumborum show that people with LBP who demonstrated low erector spinae activity during isometric trunk efforts in sitting had enhanced regional activation patterns of psoas major and posterior layers of quadratus lumborum towards lumbar extension. This contrasts with people with high erector spinae activity who have less psoas major activity towards extension (Park et al. 2013b). These findings support the concept of redistribution of motor activity within and between muscles (Hodges and Tucker 2011) in contrast to the previous theories of uniform reduction of activation of agonists and increased activation of antagonists in response to pain (Lund et al. 1991). In addition, these two different activation patterns highlight that people with LBP are not homogenous and specific subgroups and individual variation must be considered (Hodges and Tucker 2011, Park et al. 2013b).

In contrast to the variably augmented activity of the more superficial trunk muscles, studies using EMG to investigate activation patterns of trunk muscles in people with LBP show a consistent pattern of delayed response and compromised activity in the deep muscles in people with LBP (Hodges et al. 2003b). There is evidence of delayed activation of the transversus abdominis muscle in association with rapid limb movements in people with chronic low back pain (Hodges and Richardson 1996, Hodges and Richardson 1998) and in healthy people with induced lumbar pain (Hodges et al. 2001c, Hodges et al. 2003b). There is also evidence of reorganisation of the motor cortex related to the transversus abdominis muscle in people with low back pain (Tsao et al. 2008). Similar changes have been demonstrated for multifidus, the deepest of the paraspinal muscle. During rapid arm movement the onset of activation of the deep/short fibres of multifidus is delayed in people with LBP compared with healthy participants (MacDonald et al. 2009). Activity in the multifidus muscle is decreased in response to an unpredictable load and activity in the deep multifidus muscle is reduced in response to a predictable load in people with LBP (MacDonald et
al. 2010) (Figure 2-13). People with LBP have a single area of motor cortex that evoke responses in back muscles in contrast to the two areas of motor cortex that evoke a response to separate back muscles in response to transcranial magnetic stimulation in people without LBP (Tsao et al. 2011a, Tsao et al. 2011b) (Figure 2-14). This change may represent loss of the differential activation between short/deep and long/superficial fibres of the multifidus muscle which may be accompanied by subtle loss of function (MacDonald et al. 2009). These changes have been observed despite remission from pain and suggest that disturbance of the normal pre-planned response of the nervous system may demonstrate altered motor control which could render the spine vulnerable to further injury (Hodges and Moseley 2003, MacDonald et al. 2009).

Figure 2-13 Mean latency of short (SF) and long fibres (LF) of the lumbar multifidus EMG onsets relative to the onset of EMG activity in the deltoid muscle (vertical dashed line). Data for the healthy (open symbols) and LBP participants (filled symbols) during shoulder flexion (circles) and extension (squares) are shown. Error bars represent 95% confidence intervals. (P*<0.05). From MacDonald et al. (2009) “This figure has been reproduced with permission of the International Association for the Study of Pain®(IASP). The figure may NOT be reproduced for any other purpose without permission.”
2.3.7.3 Association between motor control and other sensory impairments

As well as pain, change in other sensory input has been associated with alteration to motor control strategies in people with LBP. For optimal spinal control (as described in a systems dynamic approach [see Section 2.3.4.1]) the CNS needs to be able to precisely track the position and velocity of spinal segments (Reeves et al. 2011). Back pain has been associated with proprioceptive deficits in the lumbar spine (Parkhurst and Burnett 1994) although not universally (Silfies et al. 2007). These changes include: decreased ability to reproduce a target trunk position in standing and four-point kneeling (Gill and Callaghan 1998); increased repositioning error during lumbar flexion in standing, but decreased error in extension (Newcomer et al. 2000); decreased perception of passive lumbar rotation in sitting (Taimela et al. 1999); and decreased repositioning accuracy of lumbar position via sacral tilt in sitting (Brumagne et al. 2000). It has been suggested that these proprioceptive deficits place the lumbar spine at increased risk of re-injury (Parkhurst and Burnett 1994, Taimela et al. 1999). Altered proprioceptive acuity in people with LBP has also been associated with a change of motor control strategy during balance control tasks (see Section 2.6.4.2).

Inaccurate sensory information or misinterpretation of sensory information may alter motor control dictating that a stiffening strategy is used rather than a finely tuned dynamic approach (Brumagne et al. 2008b, Hodges 2013). Considering the evidence of altered recruitment of deep
intrinsic and superficial muscles in association with LBP, along with the predictions from modelling studies (Panjabi 2003, Wilke et al. 1995) there are indications that trunk and spine function may be compromised. Compromised activity of the deep muscles may reduce their contribution to ‘fine-tune’ intervertebral motion (Hodges et al. 2003a). Along with increasing spinal stiffness, increased co-activation of the superficial muscles increases the compressive load on the spine (Gardner-Morse and Stokes 1998, Stokes and Gardner-Morse 2003), increases energy expenditure (Lamoth et al. 2002) and may compromise movement (Hodges et al. 1999, Mok et al. 2007).

2.3.8 Motor control training for the treatment of LBP

In the rehabilitation of ballet dancers with LBP some case series have described the effectiveness of interventions based on principles of motor control training (Beckmann Kline et al. 2013, Hagins 2011). These observations provide support for the association between motor control changes and LBP in ballet dancers. In addition they imply that the implementation of a motor control training approach would be useful in the management of dancers with LBP to address the multiple components necessary to achieve optimal trunk control (Figure 2-15) Studies on non-dancers show that treatment or training approaches which target motor control issues can reduce or restore many of the changes in motor control that have been associated with LBP. For instance, motor control approaches to train independent voluntary activation of the deep abdominal muscle (transversus abdominis) in people with LBP changes the activation of this muscle in an untrained functional task to a response which resembles that of pain-free individuals (Tsao and Hodges 2007). Furthermore, this improved automatic postural response persists over time (Tsao and Hodges 2008). In contrast, training the muscle in a more general manner, e.g. sit-ups, results in concurrent activation of the abdominal muscles, and contrasts the pattern observed in healthy individuals (Tsao and Hodges 2007). Motor control training also reduces activity of the superficial paraspinal trunk muscles in people with LBP (Tsao et al. 2010a). A motor control approach is also effective in restoring the changes in the organisation of the motor cortex that are reported in people with recurrent LBP (Tsao et al. 2008, Tsao et al. 2010b).
Another aspect of motor control which has shown change in association with LBP is the morphology (e.g. muscle size) and contraction behaviour of trunk muscles (e.g. symmetry) which is discussed in detail in the following sections (see Section 2.4). A number of clinical studies have shown that using a motor control approach can restore trunk muscle size, symmetry and coordination (Hides et al. 2008b, Hides et al. 2009). Furthermore, the changes in muscle morphology and behaviour associated with this intervention are linked to clinically meaningful outcomes such as reduced pain and disability in people with LBP. For example, improved contraction of transversus abdominis muscles in people who have chronic LBP and low baseline measures of contraction is associated with long-term pain reduction (Unsgaard-Tøndel et al. 2012) and reduced disability (Ferreira et al. 2010). The efficacy of motor control training to reduce pain and disability and recurrence (Hides et al. 2001) associated with LBP has also been shown in specific groups such as: people with acute LBP (Hides et al. 2001), people with spondylolisthesis (O'Sullivan et al. 1997), and athletes with LBP (Hides et al. 2008b). These findings imply that the investigation of trunk muscle morphology and behaviour has potential to be very important when considering motor control in dancers with LBP.
2.4 Morphology and behaviour of trunk muscles

As the trunk muscles are a major component of the motor control system further insight into motor control is gained from knowledge of the morphology and behaviour of trunk muscles. The following sections outline the findings from studies which have investigated trunk muscle morphology and behaviour in healthy individuals (see Section 2.4.1) and in people with LBP (see Section 2.4.2). More specifically these sections will describe what is known about the size, symmetry, and contraction behaviour of the trunk muscles which were investigated as part of this thesis (see Studies I [Chapter 3] and II [Chapter 4]) and why this information is relevant. A comprehensive literature search did not locate any previous studies that had used MRI to measure the CSA, thickness or contraction behaviour of the trunk muscles in ballet dancers. Evidence from studies on elite sporting populations and other non-dancers is summarized in the following sections to use as a basis for comparison with ballet dancers (see Studies I [Chapter 3] and II [Chapter 4]).

2.4.1 Morphology and behaviour of trunk muscles in healthy non-dancers

Examining the morphology and behaviour of a muscle provides knowledge of its function as the role of a muscle is related to its architectural structure (Lieber and Fridén 2000, Narici 1999). Muscles with a large physiological CSA (the calculated cross-section that cuts all muscle fibres at right angles) (Narici 1999), short fibres and high pennation angles can generate large forces (e.g. soleus, multifidus) (Ward et al. 2009). In contrast, muscles with relatively small physiological CSAs and long muscle fibres are adapted for large excursion with low forces (e.g. sartorius) (Lieber and Fridén 2000). It is well accepted that muscle physiological CSA can be used to accurately calculate muscle and joint forces (Brand et al. 1986, Narici 1999) and is frequently used in biomechanical modelling of the spine (Brand et al. 1986, McGill et al. 1988, McGill et al. 1993, Narici 1999). Similarly, the anatomical CSA (the CSA normal to the muscle belly) (Narici 1999) of trunk muscles is also closely related to muscle performance (Raty et al. 1999). In former elite males athletes CSA of the psoas muscle correlates significantly with isometric trunk flexion, isoinertial maximal torque velocity and power. In addition, higher ratio of psoas CSA to quadriceps CSA relates to better performance in 100 m sprints in runners (Hoshikawa et al. 2006). CSA of the quadratus lumborum muscle is also positively correlated with trunk flexion and side flexion strength (Raty et al. 1999). The combined area of multifidus and lumbar erector spinae muscles also correlates with isometric and isoinertial muscle strength in trunk extension (Raty et al. 1999). As trunk extensor strength torques are reported to be increased in professional dancers compared with semi-professional dancers and non-dancers (Cale-Benzoor et al. 1992) it is anticipated that dancers may have larger extensor muscle CSAs than non-dancers (see Study I [Chapter 3]).
Of the techniques available to measure the morphology and behaviour of trunk muscles, MRI provides several advantages. It painlessly captures the total cross-section of the trunk muscles in situ at the same time which provides a detailed image for measuring aspects of muscle structure such as CSA, thickness of the contractile tissue at rest and during contraction and presence of non-contractile tissue e.g. fat, in the muscles that are imaged. Furthermore, measures of muscle behaviour such as change in muscle thickness with contraction (measured by real-time ultrasound) are related to EMG activity at low levels of muscle activity (Hodges et al. 2003c). Because of these advantages, MRI was used in this thesis to investigate muscle morphology and behaviour of trunk muscles in dancers and dancers with LBP (see Studies I [Chapter 3] and II [Chapter 4]).

Figure 2-16 Relationship between muscle contraction and electromyographic (EMG) recordings  A. Ultrasound image of lateral abdominal wall and measurement of thickness of transversus abdominis (TrA). B. Group data of regression between changes in TrA thickness and EMG activity. Note linear relationship between changes in TrA thickness and EMG activity at low level of contractions. OE, obliquus externus abdominis, OI obliquus internus abdominis, MVS, maximum voluntary contraction. Adapted and reprinted from Hodges et al. (2003c) with permission from John Wiley and Sons.

The potential for gender difference in morphology of trunk muscles is highlighted by findings from several studies that show muscle CSA is often larger in males than females (Hoshikawa et al. 2006, Marras et al. 2001). The anatomical CSA of lumbar erector spinae combined with multifidus and quadratus lumbarum muscles is larger in males than in females (Marras et al. 2001). The CSA of psoas muscles is also larger in male athletes and non-athletes (Hoshikawa et al. 2006, Marras et al. 2001). Some of the variability among participants can be explained by the wide range of height and weight in the sample populations. As the height and weight of dancers is relatively consistent it was anticipated that male dancers would have larger trunk muscle CSA’s than female dancers (see Studies I [Chapter 3] and II [Chapter 4]).

Another key aspect of muscle morphology is symmetry or asymmetry of muscle size and contraction. Several studies of trunk muscle geometry have reported symmetry of the abdominal
muscles between sides in participants without LBP, (Marras et al. 2001, Springer et al. 2006) irrespective of hand dominance or gender (Springer et al. 2006). Symmetry of abdominal muscles is thought to be important as bilateral contraction is argued to have a greater affect on spine control than unilateral contraction (Hodges et al. 2003a). Similarly, healthy non-athletic individuals have no significant right to left side difference in the CSA of erector spinae, multifidus, psoas or quadratus lumborum muscles (Chaffin et al. 1990, Marras et al. 2001). A mean difference in multifidus muscle CSA of less than 5% between sides across all lumbar levels has been reported (Hides et al. 1994). Even in a group of elite oarsmen (a relatively asymmetrical sport) there was no asymmetry in CSA of multifidus, erector spinae or psoas muscle between sides (McGregor et al. 2002). In contrast, muscle CSA differs between sides in sports that are predominantly asymmetrical. For instance, the lumbar erector spinae and multifidus muscles (Hides et al. 2008a, Ranson et al. 2008) were shown to be larger in the dominant side in cricket fast bowlers and the obliquus internus abdominis muscle was thicker on the side of the non-dominant hand (Hides et al. 2008a). In addition, the quadratus lumborum muscle has been shown to hypertrophy on the side of the bowling arm in fast bowlers (Engstrom et al. 2007, Hides et al. 2008a, Ranson et al. 2008). Quadratus lumborum is also larger on the side of the preferred stance leg in elite Australian League Football players, whereas the CSA of the psoas muscle has been shown to be larger on the preferred kicking leg (Hides et al. 2010a). In relation to this thesis, a key objective in classical ballet is the maintenance of symmetrical body structure with the ability to perform tasks equally on either leg (Kimmerle 2010). The symmetrical emphasis of classical ballet would be predicted to encourage symmetrical abdominal and back muscle development in dancers, although an asymmetrical bias in teaching (Farrar-Baker and Wilmerding 2006) and some specific dance tasks (Kimmerle and Wilson 2007) has been observed. As dancers aspire for symmetry of body structure and there is potential for asymmetry; trunk muscle symmetry was assessed from MR images of dancers in this thesis (see Studies I [Chapter 3] and II [Chapter 4]).

2.4.1.1 The relevance of trunk muscle morphology and behaviour to dancers

The strong relationship between muscle CSA and muscle performance provides support for measurement of muscle CSA to assess aspects of motor control in dancers. Further support comes from evidence of the link between muscle CSA and injury in football players. Small multifidus size is predictive of hip/groin/thigh injury in elite football players in the pre-season period (Hides et al. 2011b) and small multifidus or quadratus lumborum muscle CSA is predictive of lower limb injury during the season (Hides and Stanton 2014). A specific intervention programme aimed at improving motor control patterns by targeting voluntary contractions of the multifidus, transversus abdominis and pelvic floor muscles with feedback from ultrasound imaging and progressing to a functional
rehabilitation programme increased multifidus size and the ability to ‘draw-in’ the abdominal wall compared to footballers who did not receive this intervention. In addition, footballers who completed the intervention programme had lower risk of sustaining a severe lower limb injury (Hides and Stanton 2014) and missed fewer games due to injury during the season (Hides et al. 2012). These data imply that muscle CSA could be used as a screening tool to identify dancers at risk of injury or to monitor the effectiveness of intervention programmes to improve motor control.

2.4.2 Morphology and behaviour of trunk muscles in non-dancers with LBP

It has been proposed by several authors that inadequate abdominal muscle strength is a common reason for LBP in dancers (Kelly 1987, Micheli 1983). Results of isokinetic strength tests have not shown any correlation with peak torque of trunk flexor or extensor muscles and reported back pain in professional or semi-professional dancers (Cale-Benzoor et al. 1992). In general, muscle strength has weak prognostic value for LBP in athletes (Kujala et al. 1994) and industry (Battie et al. 1989, Battie et al. 1990). In contrast, change in morphology and behaviour of the trunk muscles has been consistently associated with LBP (Hides et al. 2008a, Hides et al. 1996, Hides et al. 1994). Despite the prevalence of LBP in professional dancers (see Chapter 1) there are no studies investigating the potential changes in the morphology of behaviour of the trunk muscles in dancers with LBP (see Studies I [Chapter 3] and II [Chapter 4]).

In non-dancers and athletes, LBP is associated with changes in multifidus muscle morphology and behaviour which include; reduction in muscle size, reduced symmetry (Barker et al. 2004, Danneels et al. 2000, Hides et al. 2008a, Hides et al. 1994) and increased fat content (Mengardi et al. 2006). These changes are consistent with the compromised activity reported in muscle activation studies in humans (Hodges and Moseley 2003) and the morphological changes that occur with disc or nerve root lesions in animal studies (Hodges et al. 2006). Changes in the multifidus muscles include reduced CSA in acute (Hides et al. 1994), subacute (Hides et al. 1996) and chronic LBP. (Barker et al. 2004, Beneck and Kulig 2012, Danneels et al. 2000) Decreased multifidus CSA is also found in elite cricketers with LBP (Hides et al. 2008b). In unilateral back pain, multifidus muscle wasting is correlated to the duration of symptoms (Barker et al. 2004), the side (Barker et al. 2004, Hides et al. 1994) and level of pain (Hides et al. 1994). Some people with unilateral LBP have deceased CSA of the multifidus bilaterally and symmetrically (Beneck and Kulig 2012) (Figure 2-17). The reduction in muscle size of the lumbar extensor muscles seems to be specific to the multifidus muscles, as when the CSA of erector spinae muscles was differentiated from the multifidus, no reduction in size of the erector spinae muscle was demonstrated in active people with chronic LBP (Beneck and Kulig 2012, Danneels et al. 2000) (Figure 2-17).
Changes have also been identified in other trunk muscles. The CSA of the psoas muscle is reduced bilaterally in people with chronic LBP (Cooper et al. 1992, Parkkola et al. 1993). Furthermore, in people with unilateral LBP, the decrease in CSA of the psoas muscle is associated with increased symptom duration on the painful side (Barker et al. 2004, Dangaria and Naesh 1998). Greater asymmetry of the CSA of the quadratus lumborum muscle is associated with LBP in elite cricket fast bowlers and (Hides et al. 2008a) and is proposed to be related to defects of the pars interarticularis (Engstrom et al. 2007).

Figure 2-17 Mean and standard deviation values for multifidus (A) and erector spinae (B) muscle volume at the L5-S1 region. The group with LBP is in dark shades and the control group in while. Adapted and reprinted from Beneck and Kulig (2012) with permission from Elsevier.

In association with LBP, changes in the morphology and behaviour of the abdominal muscles have also been reported. In non-dancers with LBP smaller increase in transversus abdominis muscle thickness with contraction has been observed with ultrasound imaging (Ferreira et al. 2004). This is consistent with EMG recordings demonstrating delayed activation (Hodges and Richardson 1996) and reduced amplitude of activity in transversus abdominis muscles in people with LBP (Ferreira et al. 2004) (Figure 2-18) and supports altered motor control of abdominal muscles (Hodges et al. 1996, Hodges and Richardson 1996). As the transversus abdominis muscle contributes to spine control via its attachment to the thoracolumbar fascia, (Barker et al. 2006) and by modulation of intra-abdominal pressure, (Hodges et al. 2003a) delayed and reduced activation of the transversus abdominis muscle may compromise spinal robustness (Hodges 2011, Hodges and Richardson 1996).
Change in CSA of the trunk, observed with ultrasound imaging and MRI during the voluntary task of ‘drawing-in’ the abdominal wall has been used as a clinical muscle test of the transversus abdominis muscle (Richardson and Hides 2004). During this manoeuvre, as the muscle bellies of transversus abdominis thicken and shorten, there is an associated lateral slide of the anterior extent of the transversus abdominis muscle (transversus abdominis muscle slide) and reduced trunk CSA (Hides et al. 2006b). These actions are consistent with descriptions of transversus abdominis muscle function from anatomical studies (Barker et al. 2006). Less transversus abdominis muscle slide and smaller reduction in trunk CSA have been observed in people with LBP than those without LBP (Hides et al. 2008a, Richardson et al. 2004). Reduced ability to decrease the CSA of the trunk by ‘drawing-in’ the abdominal wall has also been observed in elite cricketers and elite footballers with LBP (Hides et al. 2008a, Hides et al. 2010b) (Figure 2-19). These parameters have been argued to primarily reflect transversus abdominis activation. Data from EMG studies suggest that deep muscles like transversus abdominis are recruited relatively symmetrically in healthy individuals (Hodges et al. 2003a). Clinical studies support this finding, for example, the thickness of transversus abdominis muscles was symmetrical in elite cricket players (a sport with substantial asymmetrical trunk load) whereas there was greater thickness of obliquus internus abdominis muscles on the side of the non-dominant hand (Hides et al. 2008a). Measures of thickness of transversus abdominis, obliquus internus abdominis or obliquus externus abdominis muscles at rest and in the contracted state, transversus abdominis muscle slide and the CSA of the trunk before and
after ‘drawing-in’ the abdominal wall, and the CSA of lumbar multifidus, lumbar erector spinae, psoas and quadratus lumborum muscles were included in measures taken from the MR images of dancers to assess the function of these muscles in dancers and dancers with LBP (see Studies I [Chapter 3] and II [Chapter 4]).

Figure 2-19 Magnetic resonance imaging of the trunk showing the trunk muscles (A) at rest and (B) on contraction during the draw-in manoeuvre. Panel (C) shows the cross-sectional area of the trunk outlined in while in a subject with current low back pain. The cross-sectional area of the trunk increases in response to the draw-in manoeuvre in association with increased thickness of the oblique abdominal muscles and bulging of the abdominal wall. Adapted and reprinted from Hides et al. (2010b) with permission from Journal of Orthopaedic and Sports Physical Therapy.

2.4.2.1 Mechanisms for changed morphology and behaviour of muscles

The evidence presented above of rapid change in muscle morphology associated with LBP demonstrates that human skeletal muscle is very plastic. The potential mechanisms for the changed morphology and behaviour of trunk muscles observed in association with LBP are very complex (Figure 2-20). Contractile tissue can increase in response to load and decrease with disuse (Narici 1999). Muscle hypertrophy is due to an increase in muscle fibre CSA by accumulation of contractile proteins within muscle fibres whereas atrophy is accompanied by reduction of muscle CSA as a result of the loss of contractile proteins via molecular mechanisms that regulate the rate of protein synthesis and degradation (Nader 2005). Disuse atrophy in the human medial gastrocnemius
results in reduced muscle CSA, fibre pennation angle and fibre length which suggests loss of both parallel and in-series sarcomeres with potential to reduce the force-generating capacity of the muscle (Narici 1999). It is difficult to investigate the physiological response to low back injury in humans, however, in a porcine model, injury to the L3-4 intervertebral disc resulted in rapid reduction in multifidus muscle CSA at the ipsilateral L4 level and nerve lesion to the L3 dorsal ramus caused reduced multifidus CSA from L4-6 (Hodges et al. 2006). As well as reduced muscle CSA, water and lactate concentrations were reduced and histology revealed enlargement of adipocytes and clustering of myofibres as a consequence of the disc and nerve lesions. These data confirm that spinal disc or nerve injury can cause rapid atrophy of multifidus muscles and is related to the reduction in muscle CSA, however, the mechanism/mechanisms for these changes are not well understood. Rapid muscle atrophy is argued to be due to reduced neural drive to the muscle (Fitts et al. 2001) and has been observed in response to many conditions including; disuse/immobilisation (Appell 1990), muscle (Weber et al. 1997), and tendon lesions (Meyer et al. 2005).

One mechanism of decreased motor drive to muscles is reflex inhibition i.e. the reduction in alpha motor neuron excitability as a consequence of afferent input from joint structures (Stokes and Young 1984). Reflex inhibition is proposed to be responsible for the reduced activity of quadriceps muscles in response to mechanical stimuli such as pinching the knee joint capsule (Ekholm et al. 1960), joint effusion (Spencer et al. 1984) and joint injury/surgery (Stokes and Young 1984). Reflex inhibition may affect specific regions within a muscle group e.g. selective inhibition of vastus medialis muscles has been observed with experimental effusion of the knee joint (Spencer et al. 1984) and this is consistent with greater atrophy found in the region of the deeper fibres of multifidus muscles which cross the intervertebral joints in the porcine model (Hodges et al. 2006). However, although reflex inhibition is a likely mechanism for the reduction in CSA in multifidus muscles other mechanisms may also contribute e.g. reduced intra-muscular water, vaso-constriction or inflammatory effects (Hodges et al. 2006, Hodges 2013). These mechanisms, however, did not explain the acute changes in CSA found in the porcine model (Hodges et al. 2006).

In addition to reduced muscle CSA, signs of muscle degeneration include increased proportion of fat and connective tissue relative to contractile tissue (Kader et al. 2000, Parkkola et al. 1993). In association with chronic LBP, several studies have found fatty infiltration of the multifidus muscles (Kader et al. 2000, Kjaer et al. 2007, Mengardi et al. 2006, Parkkola et al. 1993) but not the erector spinae muscles (Mengardi et al. 2006) or the psoas muscles (Parkkola et al. 1993). This observation, however, is not universal and other authors have not found increased amounts of fat in the multifidus muscles of participants with chronic LBP when compared with age- and activity level-matched pain-free participants (Beneck and Kulig 2012, Danneels et al. 2000). In addition, the
presence of fat infiltration does not predict future back pain (Hebert et al. 2014). Age appears to be an important factor as there is a higher incidence of fat deposits with increasing age (Danneels et al. 2000) and a strong association between the presence of fat deposits in multifidus and LBP in adults but not adolescents (Kjaer et al. 2007). Although Parkola et al. (1993) report a higher incidence in females and comment that this may be due to increased percentage of body fat, Kjaer et al. (2007) did not show an association between fat and gender, body composition or physical activity. At the initiation of this thesis it was unclear whether fat would be present in multifidus muscles in a population of young, slim, highly active dancers with LBP. Consequently, MR images of dancers’ multifidus muscles were observed for fat deposits (Study I [Chapter 3]).

Symmetry and size of spinal musculature can also be affected by spinal scoliosis (Kennelly and Stokes 1993, Zetterberg et al. 1983). Dancers with scoliosis also report a higher incidence of back pain (Liederbach et al. 1997). The incidence of scoliosis in the normal adult population ranges between 2 to 4 % with females 5 times more likely to be affected than males (Bunnell 1988). The reported incidence in dancers is considerably higher ranging from 8% of dancers aged 18-35 (Liederbach et al. 1997) to 24% in young dancers (Warren et al. 1986) and 50% of female and 27%
of male professional dancers (Hamilton et al. 1992). As scoliosis occurs frequently in dancers, the
degree, shape and site of curvature was assessed as well as the presence of leg length difference in
this population of dancers. This information was used in Studies I (Chapter 3) and II (Chapter 4) to
identify if scoliosis influenced the CSAs of trunk muscles.

2.5 Mechanical properties of the trunk and spine

The mechanical or dynamic properties of the trunk and spine are substantially influenced by the
motor control system. One method used to examine the mechanical properties of the trunk and
spine stability in vivo is to measure the dynamic behaviour of the trunk in response to perturbations
(see Study III [Chapter 5]). No studies have been conducted on the dynamic properties of the trunk
in dancers. Investigation of the dynamic properties of the trunk utilizes concepts from dynamical
systems theory (described in Section 2.3.4.1) to reveal behavioural elements measured from the
response to perturbations. The dynamic behaviour of a system depends on the inertial (mass),
stiffness and damping properties of the system (Gardner-Morse and Stokes 2001).

Stiffness is the degree to which an object resists deformation when subjected to a known force
(Hogan 1985) and, with respect to the trunk, can be defined as the dynamic relation between a small
perturbation force and the subsequent trunk displacement. It represents position control of the trunk
(Moorhouse and Granata 2005). Forces which return the trunk after a small perturbation include
passive and active components. The passive component includes forces generated by the visco-
estastic forces of the spine and activated muscle stiffness (i.e. the visco-elastic properties of the
muscle). The active component includes reflex and voluntary muscle contraction (Cholewicki et al.
primarily by three mechanisms, muscle contraction, posture selection (Trumbower et al. 2009) and
stretch reflexes (Hogan 1985). The time scale of the response is the major determining factor in
whether stiffness is controlled by reflex or voluntary muscle contraction. Feedforward mechanisms
(open-loop control) are used to select optimal stiffness in anticipation of a task or to adapt to the
environment (Hogan 1985). For example the CNS increases stiffness in preparation for very
accurate movements to limit variability (Trumbower et al. 2009). Muscle stiffness increases with
muscle activation as a result of the increased number of cross-bridges between actin and myosin
filaments in muscle cells (Crisco and Panjabi 1991). For example, even low levels of voluntary
trunk extension increase lumbar stiffness (Shirley et al. 1999). In healthy individuals trunk stiffness
increases in association with increased trunk load and muscle activity (Cholewicki et al. 2000). As
trunk stiffness during active flexion or extension is dominated by muscle contraction, the stiffness
of these muscles is regarded as a primary control mechanism for spinal stability (Bergmark 1989,
Cholewicki and McGill 1996). Increased trunk stiffness in people with recurrent LBP compared
with people without back pain, has been estimated from perturbation studies (Hodges et al. 2009) (Figure 2-21). This increased stiffness is thought to be related to augmented trunk muscle activity and altered reflex control of trunk muscles in people with LBP (Hodges et al. 2009).

Damping is an influence on an oscillatory system which absorbs energy and has the effect of reducing or preventing its oscillations. Damping represents velocity control of the trunk (Reeves and Cholewicki 2010). In estimates of damping of the spine system a single degree of freedom mass-spring-damper model is used to represent the trunk (Bazrgari et al. 2011). In this linear model damping is directly related to the speed of the movement; with higher speed there is more resistance to movement from the damping component. Damping effectively smoothes movement at higher frequencies and has potential to influence the qualitative behaviour of the trunk system. As the ability to modulate quality of movement is an important feature in classical ballet; the estimation of damping could be very relevant to dancers. Lower damping has been reported in people with recurrent LBP compared to pain-free individuals for both forward and backward trunk perturbations (Hodges et al. 2009) (Figure 2-21). It was argued that the reduced damping may be due to changes
in motor control (e.g. reflex delays), sensory impairment or physiological changes in passive structures (Hodges et al. 2009).

It is not known whether trunk mechanical behaviour is altered in ballet dancers with a history of LBP. The evidence of change in mechanical properties of the trunk in non-dancers with LBP justifies the investigation of these properties in dancers (see Study III [Chapter 5]).

2.6 Motor control of balance

Postural control is a complex aspect of motor control which refers to control of the body’s position in space relative to gravity and the position of body segments relative to each other. Control of the body’s position is necessary for orientation (posture) and stability (balance) (Shumway-Cook and Woollacott 2012). Many of the principals of control of the trunk for movement and stiffness (stability) described in the previous sections are applicable to control of the trunk for balance (postural stability). As the trunk is the major component of the body’s mass (70%) and the centre of mass/gravity (CoM) is at the level of the hip (Massion 1992) alteration in trunk muscle function could have a substantial impact on balance. The previous sections of this chapter have described a wide range of changes in trunk muscles and motor control of trunk muscles that have been observed in people with LBP (Ferreira et al. 2004, Hides et al. 2006a, Hodges and Richardson 1998, Radebold et al. 2000). There is also evidence that dancers move differently to non-dancers and that trunk function is a key element in this population. It has been shown that dancers consistently ‘stabilise’ the vertical head-trunk axis and may utilise the trunk as the reference position for the organisation of many movements in contrast to non-dancers who normally use the head as the reference (Mouchnino et al. 1990, Mouchnino et al. 1991, Mouchnino et al. 1992). It follows that investigation of balance in dancers with and without LBP compared with non-dancers has potential to provide important information about motor control of the trunk in dancers (Study IV [Chapter 6]).

2.6.1 Balance control in elite dance

Balance is a fundamental element of dance. Audiences acclaim the ability of a dancer to ‘suspend time’ by maintaining an extreme position on the toes of one foot with the other leg extended up in the air and to appear in control during rapid, repetitive spinning. When observing the manner in which professional dancers balance they appear to be ‘risk takers’ Dancers appear to allow themselves to deviate frequently, use movement to recover equilibrium and keep their centre of mass inside the base of support. In contrast non-dancers seems to be focus on holding a rigid position and then take a step to increase their base of support when they are about to fall. There is some evidence which supports these ‘clinical observations’ of the balance strategy used by elite
dancers. Commenting on data comparing the balance control of dancers with track athletes, Schmit and co-workers (2005) noted that dancers’ postural motions were somewhat noisier but occurred around a relatively constant mean position. The authors suggested that this finding reflected greater behavioural flexibility than more regular, stable systems as described by Kelso (1995). Some studies have shown superior balance skills in dancers (e.g. maintenance of unipedal stance under sensory challenged conditions) (Crotts et al. 1996) and superior performance on functional balance tests (Ambegaonkar et al. 2013). Other studies suggest that dancers only demonstrate better postural control in dance-specific conditions (i.e. not in daily life positions) (Hugel et al. 1999). This discrepancy can be debated in the context of theories proposed for the transfer of motor ability. The general motor ability hypothesis predicts that any skill should remain observable under various conditions (Adams 1987). An alternative hypothesis is that transfer of skills is minimal as motor abilities are specific to a particular task (Schmidt and Lee 2011). In this thesis a ‘daily life’ and a dance-specific foot position were compared to explore the concept of transfer of balance ability (Figure 2-22) (Study IV [Chapter 6]).

Figure 2-22 Foot positions. Dancer in quiet standing. A. standard foot position. B. ‘First position’, a dance-specific toes out position.

Balance control involves interaction between input from the sensory system and motor output. The three major sensory systems involved in balance and posture are the visual, vestibular and somatosensory systems (Massion 1992). The visual system is involved in planning movement and avoiding obstacles, the vestibular system senses linear and angular accelerations and the somatosensory system senses the position and velocity of body segments via a multitude of muscle, joint and cutaneous receptors (Winter 1995). The CNS identifies and locates the most reliable sensory information, and varies the response to adapt to conflicting and demanding conditions in order to maintain postural stability (Brumagne et al. 2004). Balance adjustments to sensory input are characterised by the timing and amplitude of specific coordinated motor patterns or strategies.
which are controlled by the CNS (Horak and Nashner 1986). Balance research often involves; manipulating sensory inputs to explore the relative contribution of each input; changing or perturbing the support surface to investigate the strategy utilised to maintain equilibrium; and more recently diverting attention to another task to assess the cognitive contribution to balance control.

To maintain equilibrium in quiet standing and in response to small perturbations, the body has been modelled as an inverted pendulum rotating around the ankle joints (Winter 1995). Although this model is useful and accurately describes the movement of the body around the ankle joint, contemporary evidence has shown it to be too simplistic as it underestimates the complex multi-joint body. For example, even in quiet standing small amplitude movements of the trunk and lower limbs are necessary to dampen the periodic perturbation from respiration (Hodges et al. 2002). Data suggests that these movements are controlled by active neuromuscular strategies that coordinate recruitment of muscles over multiple segments (Hodges et al. 2002).

Movement strategies to maintain postural control in standing are primarily organised into two distinct strategies or a combination of these separate strategies which appear to be coordinated from the automatic postural-control system (Horak and Nashner 1986). The ankle strategy restores equilibrium, particularly during quiet stance and small perturbations, by moving the body primarily around the ankle joints (Winter 1995). The muscle activation pattern utilised to achieve this strategy commences with the ankle plantarflexors and dorsiflexors radiating in sequence to the thigh and trunk muscles (Horak and Nashner 1986). When the ankle muscles cannot act or during larger perturbations, the trunk and thigh muscles are activated in a proximal to distal sequence, and there is minimal ankle muscle activation. This hip strategy, the second distinct strategy, produces minimal ankle torque and a compensatory horizontal shear force against the support surface (Horak and Nashner 1986, Winter 1995). Dancers have been reported to demonstrate greater use of the hip strategy than non-dancers particularly when maintaining balance in challenging conditions (Golomer et al. 1999a, Simmons 2005b). This is discussed further in section (Section 2.6.2.4).

When reviewing the research on balance control in dancers, it is difficult to consistently quantify the difference between dancers and non-dancers as there is considerable variation in the methodology used to test and analyse control of balance. This makes interpretation of results complex. It is also difficult to interpret the literature due to multiple definitions of postural sway (Winter 1995). In this research (like the majority of balance research) centre of pressure (CoP) recordings (from a single force platform) have been used as the outcome measure and interpreted as a weighted average of all the pressures over the surface of the feet in contact with the force platform, independent from movement of the CoM or ‘sway’ (Winter 1995). In order to keep the CoM within the base of support and thus maintain balance, the CoP moves continuously. The distance between the CoP and the CoM is the ‘error signal’ that is detected by the CNS and used to
drive the postural control system. The interaction between the CoP and the CoM (i.e. the CoP motion recorded by the force platform) is then an estimate of the efficacy of the postural control (Shumway-Cook and Woollacott 2012) (Figure 2-23).

Figure 2-23 CoP trajectory of a healthy young non-dancer during quiet standing (30 seconds). Adapted and reprinted from Collins and De Luca (1993) with permission from Springer.

The efficacy of postural control has frequently been termed “good” or “poor” based on the interpretation that lower values for measures of CoP motion such as path length, area and velocity equate with more stable balance and represent “good” balance. This assumption is often found in balance literature on dancers (see Section 2.6.2.2) and people with LBP (see Section 2.6.4.1). Clinical observation of dancers when balancing challenges this assumption as does some balance literature on dancers (Lin et al. 2014) and non-dancers including people with LBP (Mazaheri et al. 2013). This thesis investigated this assumption by comparing characteristics of postural control in professional dancers (who are generally considered to have superior balance ability, Section 2.6.2) with non-dancers and dancers with a history of LBP (who potentially have compromised balance, Section 2.6.3).

Linear measures calculated from CoP trajectories include path length, area, standard deviation of anteroposterior (AP)/ mediolateral (ML) oscillations and root mean square (RMS) velocity. Complexity of CoP motion can also be measured from dynamic characteristics of CoP trajectories. One of these measures is normalised CoP displacement, which discriminates between large frequent deviations and small infrequent deviations, providing a scale-independent measure of the ‘spikiness/curviness’ of the CoP trajectory. In non-dancers, normalised CoP displacement increases with eye closure and when cognitive attention is drawn away from the balance task. It is considered to reflect functional modification of balance control (Donker et al. 2007). It is not known if normalised CoP displacement is modified in dancers (see Study IV [Chapter 6]).

More recently non-linear methods of analysis of CoP trajectories have also been used to investigate balance control. These methods may reveal more information about the control of
balance as analysis of the dynamic characteristics of CoP motion takes into consideration evolution of CoP trajectories over time (Roerdink et al. 2006, Zatsiorsky and Duarte 2000). For example, a non-linear measure (recurrence quantification analysis) used to analyse the dynamic patterns of CoP in dancers compared with track athletes found differences in postural control that were not apparent using standard linear measures (Schmit et al. 2005). CoP motion of dancers was less non-linearly autocorrelated (% recurrence lower), less mathematically stable (max line lower), more stationary (trend magnitude lower for dancers) and less complex (entropy was lower for dancers) irrespective of visual condition. This was interpreted as demonstrating noisier CoP motion with greater flexibility to adapt (Schmit et al. 2005).

Non-linear methods of analysis are based on principles from statistical mechanics which have been applied to the study of physiological systems. The general principal underlying statistical mechanics is that although the outcome of an individual random event is unpredictable, it is possible to calculate the probability of aspects of a stochastic (probability) mechanism (Collins and De Luca 1993). A classic example of statistical mechanics is the equation proposed by Einstein to describe Brownian motion, (the random movement of a single particle along a straight line), known as a one-dimensional random walk. The dynamic structure of postural sway is considered to reflect a combination of deterministic and stochastic mechanisms (Collins and De Luca 1993, Riley and Turvey 2002). Stochastic time series (for example, postural sway) are governed by chance alone (e.g. Brownian motion) or by a combination of deterministic and random processes (e.g. biased random walk) (Collins and De Luca 1993, Roerdink et al. 2006). A number of measures derived from statistical mechanics have been used to analyse the temporal structure underlying CoP trajectories. Two methods were chosen for this thesis, diffusion analysis and sample entropy.

Diffusion analysis (stabilogram-diffusion analysis) is derived from calculations of fractional Brownian motion and quantifies the rate at which the CoP diffuses (spreads) over time (Collins and De Luca 1993). An analogy of this is the estimation of the rate (diffusion) at which a drop of food colouring disperses (diffuses) across a saucer of water. In relation to balance control, movement of CoP is limited to the area of support defined by the participant’s feet. Diffusion of CoP continues at the same rate in one direction until the moment when CoP is corrected to prevent a fall. At this point the diffusion rate will be lower with a more ‘corrective’ nature. Several measures can be extracted from diffusion analysis; these measures take into account the temporal nature of balance control and provide insight into mechanisms of balance control. Diffusion analysis separates balance control into short and long-term components and estimates a critical point and time between these two components. Some authors argue that the short-term component represents open-loop control mechanisms and the long-term component represents closed-loop control with the critical point in displacement representing the switch from open-loop to closed-loop control.
mechanisms and thus the sensory threshold (Collins and De Luca 1993, Collins et al. 1995, Priplata et al. 2002, Priplata et al. 2003). Diffusion analysis also allows calculation of a ‘saturation point’ which has been viewed as the boundary allowed by an individual’s postural control system (Collins and De Luca 1993, Collins et al. 1995). To assess the ‘corrective’ nature of CoP motion, diffusion plots can be log-transformed (Collins et al. 1995). Furthermore, diffusion analysis has been used to examine the control mechanisms underlying balance in a number of populations including: young participants (Collins and De Luca 1993); elderly participants (Collins et al. 1995, Laughton et al. 2003, Priplata et al. 2003); elderly fallers (Laughton et al. 2003); people with diabetic neuropathy, and people with stroke (Priplata et al. 2006). It should provide valuable information about balance control in dancers and dancers with LBP compared with non-dancers (see Study IV [Chapter 6]).

The second method used to examine the dynamic structure of CoP trajectories in this thesis is analysis of irregularity or complexity (entropy). Based on evidence that reduced regularity or complexity of biological signals (e.g. neonatal heart rates) is related to less healthy systems (Lake et al. 2002, Pincus and Goldberger 1994, Richman et al. 2004), sample entropy values are calculated from fluctuations in postural sway. In dynamic systems, entropy is the rate of information production (Richman and Moorman 2000) and higher entropy values relate to increased generation of new information (Peng et al. 2009). In the context of balance, lower sample entropy values calculated from CoP motion (i.e. more regular sway fluctuations) have been related to a decrease in the effectiveness of postural control in people recovering from stroke (Roerdink et al. 2006), children with cerebral palsy (Donker et al. 2008) and dancers with eyes closed (Pérez et al. 2014, Stins et al. 2009). It is also argued that entropy values are indicative of the amount of attention given to balance control and that lower sample entropy values (synonymous with more regular sway fluctuations), are related to increased cognitive involvement in postural control i.e. less automatic control (Donker et al. 2007, Roerdink et al. 2011). Conversely, higher sample entropy values extracted from CoP trajectories of dancers compared with non-dancers, have been attributed to the balance expertise of dancers and said to reflect relatively more automatic control of balance (Stins et al. 2009). Multiscale sample entropy was included in this thesis as a measure to examine regularity of balance control in dancers with and without LBP.

It can be confusing to use multiple separate measures to analyse balance control and it is, therefore, acknowledged that there is interdependence between some measures (e.g. velocity and path length). It is important to recognise that balance is very complex. Several authors have concluded that no single measure or calculation can effectively describe the difference in balance between participant groups hence investigation of multiple measures is essential (Donker et al. 2007, van Dieën et al. 2010b).
2.6.2 Balance control in dancers

The majority of studies investigating balance control in dancers have found differences between dancers and non-dancers in some conditions (Crotts et al. 1996, Golomer et al. 1999a) but no difference in other conditions (Crotts et al. 1996, Perrin et al. 2002). Thus to develop an understanding of how dancers control balance and how this may potentially differ from non-dancers and dancers with LBP, it is necessary to consider the findings from research of several conditions. An explanation for conflicting data in balance studies on dancers could be that studies often fail to consider the participant’s history of LBP. This is likely to influence balance outcome measures (see Section 2.6.4.) For example, inclusion criteria outline that dancers were “healthy” (Golomer and Dupui 2000, Golomer et al. 1999b), had “no acute articular accidents during the last six months” (Hugel et al. 1999, Perrin et al. 2002) or do not mention musculoskeletal pain or injury (Pérez et al. 2014, Stins et al. 2009). As there is a high prevalence of LBP in dancers (see Chapter 1) it is very likely that dancers with at least a history of LBP will have been included in many studies.

2.6.2.1 Standing with eyes open

Several studies have found no differences in CoP motion between dancers and non-dancers when standing on a flat surface with eyes open. For example, there is no difference between dancers and untrained participants (Hugel et al. 1999, Perrin et al. 2002) or dancers and track athletes, for the linear measures of path length, or standard deviation of either AP or ML oscillations (Schmit et al. 2005). Similarly, Simmons (2005b) did not find a difference in AP motion between dancers and
untrained participants when standing on a platform with eyes open or when movement of the visual surround matched platform movement. In contrast, a series of studies measuring self-induced body sways on a free seesaw platform found differences in ability to maintain equilibrium when comparing male dancers (Golomer et al. 1999a, Golomer and Dupui 2000) and female dancers (Golomer and Dupui 2000) with untrained participants (Golomer et al. 1999a, Golomer and Dupui 2000, Pérez et al. 2014) and acrobats (Golomer et al. 1997). For example, dancers had lower values for total energy of the power spectrum (a measure derived from spectral frequency analysis calculated by fast Fourier transformation of the platform oscillations) than untrained participants but higher values than acrobats (Golomer et al. 1997): although there was no difference between groups for total length of displacement of the platform on the ground (Golomer et al. 1999a, Golomer and Dupui 2000, Golomer et al. 1997). These authors suggested that the lower values recorded by dancers reflected reduced amplitude body oscillations resulting from dance training, which had established a more developed motor program (Golomer et al. 1999a, Golomer et al. 1997). Other authors have made similar interpretations from different measures. Using a force platform to assess CoP trajectory characteristics of dancers compared with non-dancers, two authors (Hugel et al. 1999, Stins et al. 2009) found smaller mean area for dancers and interpreted this as indicating more precise and stable balance. Overall when vision is available, the quantifiable differences between dancers and non-dancers appear minimal. One reason for this lack of difference could be that control of balance over time may be different in dancers and simple linear measures of balance may not reveal these differences. Findings from studies using non-linear measures are promising although not consistent. A measure of irregularity of dynamical CoP trajectories (i.e. sample entropy), showed that adolescent dancers (11-14 years) have higher sample entropy of the sway path (lower statistical regularity of CoP motion) with eyes open, compared with non-dancers (Stins et al. 2009). Other authors have also found dancers to have less regular CoP motions than track athletes irrespective of vision (Schmit et al. 2005). This is considered to demonstrate more optimal balance as it is interpreted that postural sway demands less attention (Stins et al. 2009) and implies increased efficiency of balance control (Donker et al. 2007, Roerdink et al. 2006). A contrasting result showed no difference in regularity (sample and permutation entropy) between a group of undergraduate dancers (20-26 years) and non-dancers when vision was available and more regular (lower sample and permutation entropy) CoP motion in dancers when vision was removed (Pérez et al. 2014). As postural control of dancers’ changes with maturation (Golomer et al. 1997, Golomer et al. 1999b) and expertise (Golomer et al. 1999b, Lin et al. 2014), differences in study participants may explain some of the contrast in results. These conflicting findings highlight the difficulty of interpreting data from studies which have used different populations, methodology and data analysis and justify further research using non-linear and linear measures to clarify
understanding of balance control in professional ballet dancers and dancers with a history of LBP compared with non-dancers (see Study IV [Chapter 6]).

2.6.2.2 Standing with eyes closed

Most studies on dancers have tested eyes open versus eyes closed tasks. Although vision was not occluded in this thesis; this section has been included to further inform about the use of vision in balance control of dancers. In dancers, brain imaging shows increased volume of regions associated with vision and reduced volume of those related to vestibular function compared with non-dancers. This was interpreted to imply greater use of visual cues for balance (Hüfner et al. 2011). In contrast to this finding, several authors have concluded that dancers are less reliant on visual input to maintain postural equilibrium than non-dancers (Golomer et al. 1999a, Golomer and Dupui 2000). It has even been proposed that rather than vision being used to maintain balance in classical ballet, it is used for; artistic expression (Hugel et al. 1999); gaze fixation/’spotting’ during spinning to prevent post-rotatory nystagmus (Teramoto et al. 1994); and taking landmarks to avoid collisions with other dancers and scenery (Perrin et al. 2002). Comparing the effect of visual suppression between dancers and non-dancers using linear measures of CoP motion reveals conflicting data. Several studies report no difference between dancers and non-dancers (Kiefer et al. 2013, Schmit et al. 2005, Simmons 2005b) across a range of standing tasks without vision. Other work has shown less increase in CoP motion with eye closure (Golomer et al. 1999a, Golomer and Dupui 2000, Stins et al. 2009) and greater CoP motion with eye closure in dancers compared with untrained participants (Hugel et al. 1999, Perrin et al. 2002). Non-linear measures are also inconclusive. Although one study found that sample entropy reduced similarly with eye closure in dancers and non-dancers (Stins et al. 2009) another study found that dancers were more affected by eye closure (Pérez et al. 2014). These contrasting results make it difficult to assess the importance of visual input to balance control of dancers.

2.6.2.3 Other sensory input

Although the proprioceptive and vestibular systems are not investigated directly in this thesis they require consideration. There is some consensus regarding the importance of the somatosensory system (which includes proprioceptive input) in balance control in dancers (Crotts et al. 1996, Golomer and Dupui 2000, Simmons 2005b). It has been demonstrated that when somatosensory information is made unreliable and even when visual information is available, dancers increase CoP motion more than non-dancers (Simmons 2005b). There is also evidence that professional dancers compared with untrained individuals, are less dependent on vision for maintaining equilibrium on a moving platform (Golomer et al. 1999a, Golomer and Dupui 2000, Golomer et al. 1997). These
data support the idea proposed by Golomer and co-workers (2000) that professional dance training shifts sensorimotor dominance from vision to proprioception.

Vestibular input is important in balance for sensing linear and angular accelerations (Winter 1995) and may have a particular role in dance tasks like pirouettes (spinning). It has been suggested that vestibular input may be less important in dancers than in other sports like acrobatics (Golomer et al. 1997) and judo (Perrin et al. 2002). This hypothesis is based on data that demonstrate that acrobats are less dependant than dancers on vision for the regulation of equilibrium (Golomer et al. 1997). Judoists also perform better than dancers with eyes closed, with lower values for the parameters of CoP path length, area and lateral oscillation (Perrin et al. 2002). In addition, CoP motion of professional dancers is unaffected by vestibular stimulation (pirouettes) compared with less experienced dancers (Hopper et al. 2014) which suggests that dancers habituate to specific vestibular input (Teramoto et al. 1994). Moreover brain imaging suggests that vestibular input may be suppressed in favour of visual input in professional dancers (Hüfner et al. 2011).

2.6.2.4 Standing in different positions

In classical ballet, specific foot and leg postures are used for unipedal and bipedal support. Although ‘parallel’ positions where the feet and legs are aligned along a sagittal plane are used in contemporary dance, most training and performance of classical ballet is based on a ‘turned out’ ('toes out') position (i.e. the lower limbs are externally rotated from the hips and the toes of the feet angle outwards while the heels are approximated together) (Figure 2-22). The position of the lower limbs potentially has a multifactorial influence on the balance of dancers. In an early balance study, a ‘toes out position’ of 45 degrees compared to the ‘Romberg position’ (feet and heels together) was deemed more stable as it was associated with lower values for CoP path length (Fearing 1924). Despite the importance of ‘turned out’ positions in classical ballet, few studies have examined balance in ‘turned out’ positions in dancers (Hiller et al. 2004, Hugel et al. 1999) and none were found which examined “first” position. To increase information about balance control in dance-specific conditions the ‘turned out first’ position of externally rotated legs was investigated in this thesis (Study IV [Chapter 6]).

Examination of the ‘turned out’ first position also has potential to increase knowledge about the contribution of trunk control in balance. There is evidence from studies on non-dancers that different foot positions affect: the base of support; the relationship between the body’s CoM relative to the limits of stability; the biomechanical stiffness of the musculoskeletal system; and the postural strategy utilised (Henry et al. 2001). Increasing stance width, (measured by increasing inter-malleolar distance), increases stiffness of the lower trunk and legs and hip-ankle coupling (Day et al. 1990, Day et al. 1993). Although equilibrium control in wider stance relies more on an
increase in passive stiffness, control in narrow stance requires more active postural strategy that includes loading/unloading of limbs and horizontal force vectors (Henry et al. 2001). Standing in the ‘turned out’ position compared with a more traditional parallel foot position changes the dimensions of the support (e.g. shortens the AP radius and increases the ML radius) and also potentially changes the balance strategy used. The ‘turned out’ position restricts ankle plantarflexion and dorsiflexion which may instigate increased use of the hip strategy to maintain postural equilibrium (Horak and Nashner 1986, Winter 1995). Evidence supports increased use of the hip strategy in dancers compared to non-dancers for maintaining equilibrium in specific and challenging conditions (Golomer et al. 1999a, Simmons 2005b). When forced to rely solely on vestibular input to maintain balance, dancers demonstrated greater body sway and a significant shift towards a hip strategy (Simmons 2005b). Furthermore, less dependence on vision only for the AP direction and low frequency body sway seen in dancers compared with untrained participants (Golomer et al. 1997) was attributed to increased use of hip movement to maintain equilibrium (Golomer et al. 1999a). These authors argued that dance training which is predominantly in the ‘turned out’ position promotes increased use of the hip strategy (Golomer et al. 1999a).

It is surprising, given the established relationship between foot position and postural sway (Day et al. 1990), that there is such variety of positions used to measure postural control in dancers. Some studies use a foot position referencing shoulder distance apart (Schmit et al. 2005, Simmons 2005b); others use a stance with the heels separated by 4cm (Golomer et al. 1997, Golomer et al. 1999b); 8cm (Stins et al. 2009); and 10cm (Perrin et al. 2002); or do not specify the position (Golomer and Dupui 2000, Hugel et al. 1999). The variation in stance position during testing may account for some of the conflicting results that have been described previously (see effect of vision Section 2.6.2). Consequently, in this thesis, the foot positions (in Study IV [Chapter 6]) were standardized between trials and participants. In the parallel position, the distance between the midline of the feet was equal to half the length of the respective participant’s foot and a comfortable degree of external rotation up to 10 degrees (Horak and Nashner 1986). For the classical dance positions, the position of ‘functional turn out’ was used i.e. the maximum sustainable and comfortable ‘turned out’ position on a flat support surface (Negus et al. 2005).

2.6.2.5 Influence of other factors on balance

It is acknowledged that there are other influences on balance in dancers which are not specifically tested in this thesis but where possible have been considered in the design of the study. For example, maturation has an effect on the sway frequency of female dancers when maintaining equilibrium on a moving platform. Pre-pubertal girls including dancers predominantly user lower sway frequencies and are more reliant on visual input than post-pubertal girls (Golomer
Male 14-year old dance students are less visually dependant than 11-year old students but more dependent than 18-year old students perhaps due to the later onset of puberty in males (Golomer et al. 1999b). It is considered that the age range in this thesis is narrow and the dancers should be a relatively homogeneous group regarding physical maturation i.e. all post pubertal. Another potential factor which can influence balance is the gender of participants. Although a gender difference in postural sway parameters has been demonstrated in elderly non-dancers (Wolfson et al. 1994) there is less evidence for gender differences in a young population (Kollegger et al. 1992). The young population of dancers and age- matched control participants in this thesis should limit the impact of gender on balance (Perrin et al. 2002). In addition, findings from studies that have investigated gender differences in the postural control of dancers suggest that adult male and female professional dancers perform similarly in balance tests (Golomer and Dupui 2000).

2.6.3 Balance control and LBP

2.6.3.1 Balance control in dancers with LBP

As there is very limited information about the effect of LBP on balance characteristics of dancers it is necessary to consider the evidence from studies on non-dancers including other athletic groups. Centre of pressure measurements have been found to be reliable in a population of elite gymnasts (a population with similarities to dancers) and elite gymnasts with LBP (Harringe et al. 2008). Furthermore, these measures demonstrated changes in balance control compared with gymnasts with lower leg injury (Harringe et al. 2008). This finding, together with data outlined in the following sections from other populations of non-dancers with LBP (see Section 2.6.4), provide a basis for conjecture that balance control may be compromised in dancers with LBP.

2.6.4 Balance control in non-dancers with LBP

2.6.4.1 Standing with eyes open/ closed

There is evidence that LBP in non-dancers is associated with alteration in balance (Byl and Sinnott 1991, Ruhe et al. 2011a), although several studies have not found difference between people with LBP and healthy individuals in some conditions (Mazaheri et al. 2013). During quiet standing on a flat, firm surface with eyes open, the presence of LBP has been associated with increased CoP motion (Alexander and LaPier 1998, Byl and Sinnott 1991, Leinonen et al. 2003). When vision is removed in static balance tests, people with LBP demonstrate greater fluctuations in AP, ML and total excursion of CoM (Alexander and LaPier 1998) and increases in CoP motion during tasks of increasing complexity (e.g. leaning forwards) especially in the ML direction (Mientjes and Frank 1999). In quiet standing with eyes closed, higher mean CoP velocity and larger CoP area are found
in people with LBP compared with healthy controls (Ruhe et al. 2011a). Furthermore, these increases in measures of CoP motion are linearly related to self-reported higher pain ratings (Ruhe et al. 2011b) and decrease with reduction of LBP (Ruhe et al. 2012). Reduction in AP displacement of CoP motion has also been associated with an intervention for LBP based on spinal stabilization exercises (Rhee et al. 2012). Together these studies suggest that LBP is frequently associated with increases in measures of CoP motion which increase further when vision is removed (Ruhe et al. 2011a).

In contrast, some studies have shown no difference between postural control of healthy participants and people with LBP in quiet standing on a firm surface (Brumagne et al. 2008b, della Volpe et al. 2006, Harringe et al. 2008). For instance, on a rigid surface with eyes open or closed, values of CoP displacement were not different in young people with or without recurrent LBP (Brumagne et al. 2008b). Similarly, CoP velocity and RMS of AP and ML CoP displacement were comparable between people with chronic LBP and age-matched controls irrespective of visual condition (della Volpe et al. 2006). CoP excursion was not different in top-level gymnasts with LBP compared to healthy gymnasts when standing on a firm surface with or without vision (Harringe et al. 2008). Furthermore, in populations of people with LBP, there was poor correlation between CoP measures (velocity, AP displacement and Romberg Ratio) and pain, fear of pain and physical function (Maribo et al. 2012). Other studies have demonstrated reduction of CoP measures in people with LBP (Lafond et al. 2009, Mientjes and Frank 1999, Mok et al. 2004, Salavati et al. 2009). For example, CoP velocity was less in people with LBP than in healthy people and remained consistently lower in dim light and eyes closed conditions (Mok et al. 2004). Measures of mean total velocity, phase plane portrait and standard deviation of velocity in the AP and ML direction, taken with eyes open or closed on a rigid surface and with eyes closed on a foam surface, were lower in people with LBP than in pain-free people (Salavati et al. 2009). People with LBP also swayed less and exhibited less postural change during a prolonged standing task (30min) than healthy people (Lafond et al. 2009).

It is possible that variations in methodology or differences in the LBP participants (e.g. pain intensity, chronicity or level of disability), account for the some of conflicting reports about the association between CoP motion and LBP. The quality of the majority of papers which demonstrated no difference or decreased CoP motion is high, so it is unlikely that this is the primary reason for the widely contrasting data (Mazaheri et al. 2013). Most interpretations of postural parameters are based on the assumption that low values for CoP measures like path and area are representative of good balance control (Perrin et al. 2002), i.e. less movement is better and conversely higher values mean increasingly unstable balance. This interpretation has largely evolved from studies on people with neurological disease. For example, people who have sustained
a stroke demonstrate increased CoP amplitude and velocity compared to age- and gender-matched participants. Values for these parameters decrease during rehabilitation suggesting that balance has improved (de Haart et al. 2004). Considering, the studies presented in this section, which have found similar or lower values of CoP parameters in people with LBP compared with pain-free people, the applicability of this interpretation to people with LBP could be questioned. It is also important to recognise that efficient balance control involves trunk movement both in anticipation of and as a response to perturbation of the CoM (Hodges et al. 1999, Winter 1995). People with LBP demonstrate delayed (Mok et al. 2007) and reduced (Grimstone and Hodges 2003, Mok et al. 2011a) use of spinal movement in the maintenance of balance and in response to perturbation from arm movement (Mok et al. 2011b). Furthermore reduced lumbo-pelvic movement is associated with compromised balance control (Mok et al. 2011a, Mok and Hodges 2013). This supports the contribution of trunk movement to balance and the proposal that movement aids optimal postural control.

It has been suggested that non-linear measures may enable more consistent discrimination between people with and without LBP as they are more informative about control of balance over time (Roerdink et al. 2006) and cognitive control of balance (Donker et al. 2007, Mazaheri et al. 2010). For example, a non-linear method of postural analysis (recurrence quantification analysis) found that CoP measures in people without LBP became less regular (reduced CoP% recurrence and % determinism) and more stationary (lower trend) with increasing difficulty of cognitive task whereas the people with LBP did not change to the same extent (Mazaheri et al. 2010). In contrast, when people with and without LBP were asked to perform a cognitive task during quiet standing with manipulation of vision and support surface, there was a reduction in linear measures of CoP related to increasing difficulty of cognitive task but no group difference (Salavati et al. 2009). As dynamic measures reveal different aspects of CoP motion to linear measures some authors argue that both methods offer value in the analysis of postural control in people with LBP (Roerdink et al. 2006).

Another factor to consider is that people with LBP are not a homogenous group. In a study of balance responses in people with chronic LBP, it was noted that although overall there was a significant increase in postural sway in challenging conditions, some individuals with LBP demonstrated decreased postural sway (Mientjes and Frank 1999). This result suggests that there may be more than one strategy utilized by people with LBP or that subgroups of people with LBP use different balance strategies. Another aspect to be considered is the effect of different levels of pain and disability on balance. For instance, in a group of people with self-reported high and low levels of LBP changing from a rigid surface to a foam surface was associated with reduced sample entropy (more regular CoP motion) in the low pain group while no change was noted in the high
pain group. This was interpreted to imply that people with high levels of LBP were less able to adapt to a change in postural condition and showed a lower level of postural automaticity (Sipko and Kuczyński 2013).

2.6.4.2 Balance strategies and LBP

Several studies show that people with LBP demonstrate reduced ability to adapt postural control strategy during complex conditions (Claeys et al. 2011). For example, when people without LBP stand on foam they adapt their postural control strategy to increase input from the back muscles whereas people with LBP continue to preferentially and inappropriately rely on input from the ankles (Brumagne et al. 2008b, Johanson et al. 2011). In addition, when standing on a short base of support (which forces participants to use a hip strategy) (Horak and Nashner 1986, Winter 1995); there is evidence that people with LBP have reduced ability to utilize a hip strategy and increased reliance on vision (Mok et al. 2004). This reduced postural flexibility could be due to a number of factors including: altered proprioceptive input (della Volpe et al. 2006, Mok et al. 2004); an inability to reweight sensory input (Brumagne et al. 2008b, Vuillerme et al. 2001); or alteration in motor control (Mok et al. 2004). Several studies have demonstrated proprioceptive deficits in people with LBP (Brumagne et al. 2000, Gill and Callaghan 1998, Newcomer et al. 2000, Taimela et al. 1999) (see Section 2.3.7.3). There is also evidence that people with LBP demonstrate poor sensory reweighting; relying less on back muscle proprioceptive input and favouring ankle muscle proprioceptive control (Brumagne et al. 2008b, Vuillerme et al. 2001). Alterations in the motor control of people with LBP are also indicated by reduced and delayed sagittal plane CoP responses to support surface translations (Henry et al. 2006). In addition, EMG studies have reported that people with LBP have higher baseline activity in the erector spinae muscles (Jacobs et al. 2011) and altered activation pattern of trunk and lower leg muscles following perturbation of balance. Increased co-activation of superficial trunk muscles (i.e. a trunk stiffening strategy) in response to unexpected support surface perturbations has also been reported in people with LBP (Jones et al. 2012, Radebold et al. 2000) and is consistent with altered motor control. Furthermore, delayed trunk muscle (surface EMG of 12 muscles) response times, (consistent with increased trunk muscle co-contraction), are correlated with increased CoP path length and velocity during sitting balance (eyes closed) in people with LBP (Radebold et al. 2001). Overall, these reports demonstrate that a number of factors contribute to the reduced flexibility of balance control observed in people with LBP and have potential to impact on balance control in dancers with LBP.
2.6.4.3  Relevance of balance control for dancers with LBP

Either an increase or a decrease in CoP motion in association with LBP is relevant for dancers. The data presented in Section 2.6.3 indicate that LBP could compromise performance of the dancer directly by altering the characteristics of CoP motion (Mazaheri et al. 2010, Ruhe et al. 2011a) or by imposing a change in balance strategy (Brumagne et al. 2008b). LBP could also indirectly affect performance in dancers by restricting flexibility in the postural control system. For example, in conditions of imposed fatigue of the inspiratory (Janssens et al. 2010) or back muscles (Johanson et al. 2011) people with healthy backs used an ankle-steered postural control strategy rather than the ‘multisegmental’ control used in the unfatigued state (Janssens et al. 2010). People with LBP used the same ankle strategy in both the fatigued and unfatigued states. As ballet places high demand on both the respiratory system and lumbar extensor muscles reduced flexibility in the choice of balance strategy could have a negative impact on the performance of dancers with LBP.

The increased reliance of dancers on somatosensory information for postural control and evidence that dancers cannot adequately compensate with vision for the loss of somatosensory input (Simmons 2005b) may have particular implications for dancers who are injured. There is evidence that dancers who experience a sprained ankle (which can result in altered proprioceptive input), have increased mean CoP amplitude and area (Leanderson et al. 1996). Proprioceptive deficits have been associated with LBP in non-dancers (see Section 2.3.7.3) and suggested to be responsible for some of the changes in postural control seen in people with LBP (Brumagne et al. 2000, Brumagne et al. 2008a). It follows that dancers with LBP may also have proprioceptive deficits which impact on balance. Alteration in balance control has been linked with falls in non-dancers (Masud and Morris 2001), and with recurrent ankle injury in dancers (Hiller et al. 2004). An inability for dancers with LBP to maintain postural equilibrium also has potential to lead to falls or concurrent injury. The investigation of balance control in dancers with LBP in this thesis should provide insight into the potential impact of LBP on dancers (Study IV [Chapter 6]).

In summary, this section (2.6) has identified several areas of balance control in dancers which warrant investigation. Many previous studies on dancers have not controlled for history of LBP in dancers and there is limited information about balance in dancers with a history of LBP. In this thesis dancers are grouped for history of LBP and no history of LBP to facilitate investigation of the impact of LBP on the balance strategy of dancers. There is limited consensus about the difference in balance strategies between dancers and non-dancers. Balance control will be investigated in this thesis with non-linear and linear measures to increase knowledge of the characteristics of balance in these participant groups. Few studies have considered balance control in the ‘turned out first’ position, which is trained in dancers and unfamiliar to non-dancers. As foot position influences
balance and in particular the contribution of the trunk this position should reveal differences between dancers with and without LBP and non-dancers. It may also provide insight into the effect of dance training on balance.

2.7 Other factors for consideration in motor control of dancers

In the dance literature, several factors have been identified to have potential impact on the development of LBP in ballet dancers. In the following sections, explanation of how these factors may impact on LBP is provided. Where possible these factors were used in this thesis as covariates in the analyses of the studies to assess their effect on motor control.

2.7.1 The influence of a hypermobile system

Dance often requires movement at the limit of available range where the resistive forces of ligaments and other connective tissues contribute substantially to control of movement. It is argued that decreased resistance in components of the passive subsystem, like ligaments and intervertebral disc, results in an increased neutral zone and may necessitate a compensatory increase in the contribution of the active subsystem (muscles) to maintain spinal stability and minimise injury (Panjabi 2003). Hypermobility, which is characterised by increased flexibility of connective tissues, is common in dancers (OR11, 95% CI 3.3-31.8) (McCormack et al. 2004). It has been associated with increased risk of injury (Klemp et al. 1984) and increased incidence of scoliosis and stress fractures (Hakim and Grahame 2003). However, researchers conducting three dimensional electrogoniometer measurements of ballet positions found no link between lumbar spine or hip flexibility and back or hip pain (Feipel et al. 2004). In addition, although McMeeken et al. (2002) found that thoracic and lumbar sagittal excursion was increased in pre-professional dancers, there was no interaction between thoracolumbar flexibility and back pain. Furthermore, poor performance of two clinical tests of lumbo-pelvic motor control (Knee Lift Abdominal Test and Standing Bow) was associated with an increased risk of lower limb or lumbar spine injury in a group of dance students whereas generalised joint hypermobility was not (Roussel et al. 2009). There is preliminary evidence that hypermobility is associated with changes in motor control, as more erector spinae activity and less thigh muscle co-contraction was found in pain-free hypermobile non-dancers than non-dancers with normal flexibility in standing tasks (Greenwood et al. 2011). As it is unknown whether there is a relationship between professional dancers who are hypermobile and LBP, hypermobility scores were calculated and used as a covariate in the analysis of muscle parameters (see Studies I [Chapter 3] and II [Chapter 4]).
2.7.2 The influence of lower limb external rotation

Classical dance requires extreme external rotation of the lower limbs. This external rotation known as ‘turnout’ is maintained in static postures and during movement. Increased lumbar lordosis is used as a compensatory mechanism for inadequate external hip rotation to meet the expectations of dance has been proposed as a factor which is linked to back pain (Bachrach 1986, Kelly 1987, Micheli 1983, Solomon et al. 2000). In college level dancers, increased risk of injury to the low back and lower limbs has been shown if dancers use turnout which is greater than the range of bilateral passive hip external rotation (Coplan 2002). An increased number and severity of injuries has also been associated with decreased functional turnout in pre-professional dancers (Negus et al. 2005). However, McMeeken et al. (2002) found that dancers aged 10-25 years had less lumbar lordosis than non- dancers. Furthermore, although back pain in non-dancers was significantly associated with reduced pelvic tilt and decreased lumbar lordosis, there was no interaction between spinal posture and back pain in dancers. As the relationship between range of hip external rotation and LBP in professional dancers is not clear, range of functional turnout was included as a covariate in Studies I (Chapter 3) and II (Chapter 4). It was also used to establish the ‘turned out’ position in the balancing tasks in Study IV (Chapter 6).

2.7.3 The influence of spinal load

The mechanical loads applied to the spine during classical ballet are high (Alderson et al. 2009). The compressive loads on male dancers during lifting their partners have been shown to exceed the National Institute of Occupational Safety and Health, Back Compression design Limit (3400N) (Alderson et al. 2009). There is also some evidence that the volume of physical activity incurred by dancers has an impact on the development of back pain (McMeeken et al. 2001). Although young dancers (aged 12-27) had a lower incidence of back pain per activity hour compared with age matched controls; when their activity exceeded above a threshold of 30 hours/week the incidence of back pain increased (McMeeken et al. 2001). Dance training over 8.5 hours/week at 14 years and over 10 hours/week at 15 years is a significant risk factor for the development of chronic injury including lumbar spine injury (Purnell et al. 2003). Furthermore, dancing more than 5 hours a day is significantly correlated with the development of stress fractures, including spinal stress fractures which implies exposure to repetitive, high loads (Kadel et al. 1992). The average hours of activity per week of a professional dancer is 38 hours, but there is wide variation (17- 45 hours) depending on the role in the company and the time of year surveyed (Ramel et al. 1999). This overall total is made up of 9 class hours (range 7-10), 20 rehearsal hours (range 5-25) and 9 performance hours (range 5-10). Within a ballet company there is individual
variation in physical load and fatigue, some of which is determined by the dancer’s role/rank in the company (e.g. principal or soloist) (Wyon and Koutedakis 2013). As it is unknown whether the activity levels of the professional dancers in this population would influence measures such as muscle size or balance parameters, demographic data about position, years of dancing and activity levels were collected and applied as covariates in the analyses (see Studies I [Chapter 3] and II [Chapter 4]).

2.7.4 The relationship between anthropometric characteristics and low back pain

Low back pain has been related to a higher Body Mass Index (BMI) (an anthropometric measure) in pre-professional female dancers, non-dancers (McMeeken et al. 2002) and athletes (Cholewicki and Van Vliet 2002, Kujala et al. 1994). This is despite the low mean BMI in pre-professional female dancers (18.6 ± 2.1) relative to non-dancers (20.8 ± 2.6) (McMeeken et al. 2002). The majority (84%) of professional female dancers in Australia have a BMI less than 20.0 with a mean of 18.76. The remaining 16% have a BMI less than 25.0, whereas the normal range of BMI is 20.0-25.0. The mean BMI of male professional dancers is 20.97 with 90% in the range of 20.0-25.0 (Crookshanks 1999). Paradoxically, LBP has also been related to low BMI in dancers. For example, dancers with a BMI under 19 missed more days from training with injury, than those with a BMI above 19 (Benson et al. 1989). The relationship between BMI and LBP in Australian professional dancers is not known. Anthropometric details are important for comparison between populations and, as outlined above, may have particular importance in dancers hence these data were collected for this thesis (see Studies I-IV [Chapter 3 to Chapter 6]).

2.8 Summary of background chapter

Motor control of the trunk and spine is complex and multifaceted. This background has described motor control from several perspectives such as systems dynamics, neural and muscle to facilitate understanding of the components of the motor control system and how the system functions in healthy individuals and people with LBP. Specific emphasis has been placed on aspects of motor control that are potentially important to classical ballet dancers and that are central to understanding the studies in this thesis i.e. trunk muscle morphology and behaviour, mechanical properties of the trunk and balance control. Review of the existing knowledge about motor control in dancers has revealed key areas which warrant investigation. These have been used to develop the following aims for the studies of this thesis in order to contribute to the body of knowledge about motor control in dancers with and without LBP and non-dancers.
2.9 Aims of thesis

The overall objective of this thesis was to advance the understanding of the motor control of professional classical ballet dancers with and without low back pain to provide a foundation to understand the potential role of motor control of the trunk in dancers.

The specific aims of the studies in this thesis were:

Study I. To investigate the cross-sectional area of the lumbar multifidus, lumbar erector spinae, quadratus lumborum and psoas muscles in professional classical ballet dancers with and without low back pain.

Study II. To determine the size, symmetry and behaviour of the abdominal muscles; transversus abdominis and obliquus internus abdominis, in professional classical ballet dancers and investigate whether low back pain in dancers is associated with changes in these parameters.

Study III. To investigate the dynamic properties of the trunk (stiffness and damping) in professional classical ballet dancers with and without a history of low back pain.

Study IV. To investigate the characteristics of balance control when standing with feet parallel and in the dance-specific turned out ‘first' position in professional classical ballet dancers with and without a history of low back pain and non-dancers.
Chapter 3  Size and symmetry of trunk muscles in ballet dancers with and without low back pain (Study I)1

3.1  Preamble

This chapter of the thesis investigates the CSA of trunk muscles from MR images of professional classical ballet dancers with and without LBP. The muscles investigated in Study I were multifidus, lumbar erector spinae, psoas and quadratus lumborum on right and left sides of the body. These muscles were chosen as changes in these muscles have been associated with LBP, in other sporting and non-sporting populations. This study presented a unique opportunity to investigate these trunk muscles as MRI for the purposes of studying muscle size and symmetry has not been previously performed on classical ballet dancers. It would have been ideal to also investigate a group of non-dancers who were similarly active, however, finding an appropriate matched group and the expense and assessment time of additional images precluded this inclusion. Findings from this chapter have implications for the prevention and rehabilitation of lumbar spine injury in classical ballet dancers.

3.2  Abstract

Purpose: LBP is the most prevalent chronic injury in classical ballet dancers. Research on non-dancers has found changes in trunk muscle size and symmetry to be associated with LBP. There are no studies which examine these changes in ballet dancers. The aim of this study was to investigate the CSA of trunk muscles in professional ballet dancers with and without LBP.

Methods: MRI was performed in 14 male and 17 female dancers. The CSAs of 4 muscles (multifidus, lumbar erector spinae, psoas and quadratus lumborum) were measured and compared among 3 groups of dancers: those without LBP or hip pain (n=8), those with LBP only (n=13), and those with both hip-region pain and LBP (n=10).

**Results:** Dancers with no pain had larger multifidus muscles compared to those with LBP at L3-L5 ($p<0.024$) and larger than those with both hip-region pain and LBP at L3 and L4 on the right side ($p<0.027$). Multifidus CSA was larger on the left side at L4 and L5 in dancers with hip-region pain and LBP compared to those with LBP only ($p<0.033$). Changes in CSA were not related to the side of pain (all, $p>0.05$). The CSAs of the other muscles did not differ between groups. The psoas ($p<0.0001$) and quadratus lumborum ($p<0.01$) muscles were larger in male dancers compared to female dancers. There was a positive correlation between the size of the psoas muscles and the number of years of professional dancing ($p=0.03$).

**Conclusions:** In classical ballet dancers, LBP and hip-region pain and LBP are associated with a smaller CSA of the multifidus muscles but not the erector spinae, psoas or quadratus lumborum muscles.

### 3.3 Introduction

Classical ballet dancers are a unique combination of athlete and artist who perform complex movement patterns requiring both muscle strength and control. Ballet places particularly high demands on the trunk due to the requirement for extreme range of motion and tolerance of high compressive forces (Alderson et al. 2009). Possible sequela of these spinal loads may be LBP, which is consistently reported to be one of the most prevalent chronic injuries in professional ballet dancers (Allen et al. 2012, Crookshanks 1999, Geeves 1990, Jacobs et al. 2012). In non-dancers, LBP is associated with musculoskeletal changes including alteration in muscle size, symmetry, (Barker et al. 2004, Beneck and Kulig 2012, Danneels et al. 2000, Hides et al. 1994) and fat content (Mengardi et al. 2006). These changes include reduced CSA of multifidus in acute, subacute (Hides et al. 1994) and chronic LBP (Barker et al. 2004, Danneels et al. 2000). Two investigations have found people with unilateral LBP had a smaller size of multifidus on the side (Barker et al. 2004, Hides et al. 1994) and at the spinal level of pain (Hides et al. 1994). These changes were associated with longer symptom duration (Barker et al. 2004). Another study found people with unilateral LBP had decreased CSA of the multifidus muscles bilaterally and symmetrically (Beneck and Kulig 2012). By contrast, when the CSA of the erector spinae muscles has been differentiated from the multifidus muscles, changes in CSA have not been demonstrated in active people with chronic LBP (Beneck and Kulig 2012, Danneels et al. 2000). Changes in other muscles have been identified. The CSA of the psoas muscle has been shown to be reduced bilaterally in people with chronic LBP (Parkkola et al. 1993) and the decrease in CSA has been associated with increased symptom duration on the painful side in individuals with unilateral LBP (Barker et al. 2004, Dangaria and Naesh 1998). In cricketers with LBP, when compared with pain-free cricketers, the CSA of the quadratus lumborum muscle is smaller unilaterally (Hides et al. 2008a) and is proposed to be
related to defects of the pars interarticularis (Engstrom et al. 2007). Despite the prevalence of LBP in professional dancers, changes in the CSA of the trunk muscles (e.g. multifidus, lumbar erector spinae, psoas and quadratus lumborum) have not been investigated in this group.

A key objective in ballet is the maintenance of symmetrical body structure with the ability to perform tasks equally on either lower extremity (Kimmerle 2010). There is evidence that healthy non-athletic individuals have no significant right-to-left side difference in the CSA of erector spinae, multifidus, psoas or quadratus lumborum muscles (Chaffin et al. 1990, Marras et al. 2001). Hides et al. (1994) reported a mean difference in multifidus CSA of less than 5% between sides across all lumbar levels. Similarly, in a group of elite oarsmen there was no asymmetry in the CSA of the multifidus, erector spinae or psoas between sides (McGregor et al. 2002). In contrast, muscle CSA differs between sides in sports that are predominantly asymmetrical. For instance, the lumbar erector spinae and multifidus muscles were shown to be larger on the dominant side in cricket fast bowlers (Hides et al. 2008a, Ranson et al. 2008). The quadratus lumborum muscle has been shown to hypertrophy on the side of the bowling arm in fast bowlers (Engstrom et al. 2007, Hides et al. 2008a, Ranson et al. 2008). The quadratus lumborum is also larger on the side of the preferred stance limb in elite Australian Football League players, whereas the CSA of the psoas muscle has been shown to be larger on the preferred kicking leg (Hides et al. 2010a). Due to the symmetrical intention of ballet it would be predicted that trunk muscles should be symmetrical in this group.

In addition to reduced muscle CSA, signs of muscle degeneration include increased proportions of fat and connective tissue (Kader et al. 2000, Parkkola et al. 1993). Several studies have found an increased CSA of fat in the multifidus (Kader et al. 2000, Kjaer et al. 2007, Mengardi et al. 2006, Parkkola et al. 1993) (but not in the psoas (Parkkola et al. 1993) or the erector spinae muscles(Mengardi et al. 2006) to be associated with chronic LBP. However, this observation is not universal and other authors have not found increased fat in the multifidus muscles of participants with chronic LBP compared to pain-free participants matched for age and activity level (Beneck and Kulig 2012, Danneels et al. 2000). Age appears to be an important factor, as there is a higher incidence of fat deposits with increasing age (Danneels et al. 2000) and a strong association between the presence of fat deposits in the multifidus and LBP in adults but not adolescents (Kjaer et al. 2007). Although Parkkola et al. (1993) reported a higher incidence in females and commented that this may be due to increased percentage of body fat, Kjaer et al. (2007) did not show an association between fat and gender, body composition, or physical activity. At the initiation of this study, it was unclear whether fat would be present in the multifidus muscles in a population of young, slim, highly active dancers with LBP.

There is evidence that muscle CSA differs between genders (Hoshikawa et al. 2006, Marras et al. 2001). The anatomical CSA of the lumbar erector spinae combined with the multifidus and
quadratus lumborum muscles has been shown to be larger in males than in females (Marras et al. 2001). The CSA of psoas muscles is also larger in males in both athletes and non-athletes (Hoshikawa et al. 2006, Marras et al. 2001). In these studies, some of the variability among participants can be explained by the wide range of height and weight in the sample population. As the height and weight of dancers were relatively consistent, it was anticipated that male dancers would have larger CSAs than female dancers.

On the basis of existing data of muscle CSA in elite sporting populations and people with LBP we developed a number of hypotheses. The primary hypothesis was that dancers with LBP would have decreased CSA of the multifidus, psoas and quadratus lumborum muscles, but unchanged CSA of erector spinae muscles. We predicted that there would be no fatty infiltrate in dancers with LBP compared to pain-free dancers. Further, we hypothesised that the multifidus, erector spinae, psoas and quadratus lumborum muscles would be symmetrical in healthy ballet dancers and larger in male dancers than in female dancers.

### 3.4 Methods

#### 3.4.1 Participants

Thirty-one dancers (14 male, 17 female) from The Australian Ballet volunteered from a possible 49 dancers present on tour for the Brisbane season of the production of *Giselle*. From this sample, dancers with and without LBP were identified. The mean (SD) age, height and weight were 23.7 (3.6) years, 172.9 (10.1) cm and 61.5 (12.9) kg, respectively (Table 3-1). The length of time dancing ranged from 7 to 28 (mean 17.7; SD 5) years, including dancing professionally for 1 to 13 (mean 5.2, SD 3.4) years. Their positions ranged from corps de ballet to principals. All dancers who completed the physical activity questionnaire (n=27) scored in the high physical activity category (Craig et al. 2003). The majority of the dancers indicated that they were right-hand dominant (94%) and preferred to kick a ball with their right leg (97%). One dancer nominated left-hand and left-leg dominance. Demographic data including age, gender, years of dance, limb dominance and anthropometric measures, were recorded from each participant. Hypermobility scores, (McCormack et al. 2004) site and degree of spinal curvature, (Liederbach et al. 1997) leg-length difference, (Liederbach et al. 1997) and functional leg turnout (Negus et al. 2005) were measured by an experienced physiotherapist.

LBP was investigated in a number of ways. Participants completed the International Physical Activity Questionnaire long form (Craig et al. 2003) and questionnaires related to general health and injury, the latter of which included a body chart on which the dancers were to indicate the area of pain. Dancers who indicated that they had pain (current or previous) in the region of the lower
back, buttock or hip (groin or lateral hip) were asked to complete a more detailed questionnaire related to their condition. Presentation was discussed with the physiotherapy team, who provided care for the dancers to determine, on the basis of their detailed physical assessment, whether the pain was reproduced by provocation of the low back only or also by provocation of structures other than the low back (i.e. the hip or pelvis). As 10 dancers were reported to have hip-region pain in addition to LBP, and there were no cases of hip-region pain without LBP, dancers were divided into 3 groups for comparison: dancers without hip-region or LBP [no-pain group] (n=8), dancers with LBP only [LBP group] (n=13), dancers with both hip-region and LBP [hip pain and LBP group] (n=10). This grouping was considered necessary because preliminary analysis of muscle measures indicated that the presence of hip-region pain influenced the relationship between LBP and muscle CSA. Severity of pain in the low back and hip was measured using a 10-cm visual analogue scale. Participants with LBP also completed the Roland-Morris disability questionnaire (Stratford et al. 1996) and Oswestry Disability questionnaire (Fairbank and Pynsent 2000). Except for pain, there was no difference in demographic data among groups (Analysis of Covariance [ANCOVA]) (Table 3-1).

Dancers were excluded if they had LBP of a non-musculoskeletal aetiology, or if they had neurological or respiratory disorders, a history of surgery to the spine, or contraindications to MRI. Only 1 dancer was excluded, due to pregnancy. All of the dancers were on full workloads. The number of participants in the study was determined by availability rather than by power analysis.

The Medical Research Ethics Committee of the University of Queensland approved the study. Participants gave informed consent, and the study was undertaken in accordance with the Declaration of Helsinki.
Table 3-1 Demographic and pain characteristics of the no pain, low back pain (LBP) and hip and LBP groups.

<table>
<thead>
<tr>
<th></th>
<th>No pain (n=8)</th>
<th>LBP (n=13)</th>
<th>Hip and LBP (n=10)</th>
<th>p value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>22 ± 3</td>
<td>24 ± 3</td>
<td>25 ± 5</td>
<td>0.45</td>
</tr>
<tr>
<td>Gender</td>
<td>3F,5M</td>
<td>9F,4M</td>
<td>5F,5M</td>
<td></td>
</tr>
<tr>
<td>Height (cm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>176 ± 12</td>
<td>171 ± 10</td>
<td>173 ± 9</td>
<td>0.59</td>
</tr>
<tr>
<td>Female</td>
<td>164 ± 9</td>
<td>165 ± 3</td>
<td>165 ± 4</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>183 ± 7</td>
<td>185 ± 3</td>
<td>181 ± 5</td>
<td></td>
</tr>
<tr>
<td>Weight (kg)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>63 ± 13</td>
<td>58 ± 13</td>
<td>64 ± 14</td>
<td>0.53</td>
</tr>
<tr>
<td>Female</td>
<td>50 ± 7</td>
<td>51 ± 4</td>
<td>52 ± 4</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>71 ± 7</td>
<td>76 ± 3</td>
<td>77 ± 6</td>
<td></td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>20 ± 2</td>
<td>20 ± 2</td>
<td>21 ± 2</td>
<td>0.41</td>
</tr>
<tr>
<td>Female</td>
<td>18 ± 1</td>
<td>19 ± 1</td>
<td>19 ± 1</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>21 ± 1</td>
<td>22 ± 1</td>
<td>23 ± 1</td>
<td></td>
</tr>
<tr>
<td>Years Prof dance</td>
<td>4 ± 3</td>
<td>5 ± 3</td>
<td>6 ± 4</td>
<td>0.33</td>
</tr>
<tr>
<td>Years Dance</td>
<td>16 ± 4</td>
<td>18 ± 6</td>
<td>19 ± 4</td>
<td>0.41</td>
</tr>
<tr>
<td>Spinal curve (degrees)</td>
<td>4 ± 4</td>
<td>2 ± 2</td>
<td>3 ± 5</td>
<td>0.57</td>
</tr>
<tr>
<td>Hypermobility score (0 – 9)</td>
<td>5 ± 3</td>
<td>5 ± 2</td>
<td>5 ± 2</td>
<td>0.61</td>
</tr>
<tr>
<td>Degrees of turnout</td>
<td>141 ± 8</td>
<td>137 ± 10</td>
<td>140 ± 11</td>
<td>0.73</td>
</tr>
<tr>
<td>VAS LBP (0 -10)</td>
<td>0</td>
<td>3 ± 3</td>
<td>4 ± 2</td>
<td>0.9</td>
</tr>
<tr>
<td>Roland-Morris score (0 – 24)</td>
<td>0</td>
<td>1 ± 2</td>
<td>1 ± 1</td>
<td>0.41</td>
</tr>
<tr>
<td>Oswestry Disability Index (0 – 100%)</td>
<td>0</td>
<td>8 ± 10</td>
<td>4 ± 2</td>
<td>0.77</td>
</tr>
<tr>
<td>VAS Hip (0 -10)</td>
<td>0</td>
<td>0</td>
<td>5 ± 2</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: BMI, body mass index, F, female; LBP, low back pain; M, male; VAS, visual analogue scale.

*Between-group comparison. Values represent mean ± Standard Deviation
3.4.2 Magnetic Resonance Imaging

After a medical screening for MRI contraindications, the participants were positioned in supine, with their hips and knees resting in slight flexion on a wedge. MRIs from L2 to the lesser trochanter were made using a 1.5-T MAGNETOM Sonata magnetic resonance system (Siemens AG, Erlangen, Germany). A true fast imaging with steady-state precession sequence using 28 x 8-mm and 12 x 4-mm contiguous slices centred on the L3-4 disc was employed for the static images.

MR images were digitally archived for later analysis and deidentified prior to measurement. The CSAs of the multifidus, lumbar erector spinae, psoas and quadratus lumborum muscles were measured by manually tracing around the muscle borders using Image J Version 1.42q,(National Institutes of Health, Bethesda, MD) (Figure 3-1). All measurements were made by the same person, who was blinded to the participant grouping. The CSAs of the multifidus and lumbar erector spinae muscles were measured bilaterally at the lumbar levels L2 through L5 from images taken at the level of the intervertebral disc, where the lumbar zygapophyseal joints and muscle borders were clearly identified (Hides et al. 1995). The CSAs of quadratus lumborum muscles were measured bilaterally at the level of the L3-4 disc, and the psoas muscles were measured at L4-5 disc. These vertebral levels represent the greatest CSA of these muscles (Marras et al. 2001), which is thought to be related to the greatest force generated by the muscles (Narici 1999). Non-contractile tissue that could be distinguished from muscle tissue was excluded from the calculation of CSA (Kader et al. 2000). Repeatability and reliability of CSA measurements of trunk muscles from MR images have been reported previously (Hides et al. 2007, Hides et al. 1995). Presence of fat in the multifidus muscles was graded by visual inspection and, when present, its CSA was measured using the following criteria: ‘normal’ for estimates of 0% to 10% fat in the muscle, ‘slight’ for 10% to 50% fat, and ‘severe’ for greater than 50% fat (Kjaer et al. 2007).
3.4.3 Statistical Analysis

STATISTICA Version 9 (StatSoft Pacific Pty Ltd, Melbourne, Australia) was used for data analysis. The alpha level was set at $p<0.05$. Preliminary analysis was conducted to reduce the large range of potential variables that could be included. As the cohort involved a mix of participants with unilateral and bilateral pain, it was not intended to include the side of pain in the analysis (LBP group: unilateral pain, n=3 and bilateral pain n= 10; hip-region and LBP group: unilateral LBP, n=5 and bilateral LBP n=5; unilateral hip-region pain, n=7, bilateral hip-region pain, n=3). However, to confirm that this decision was valid, an ANCOVA was used to determine whether side of back or hip-region pain was related to multifidus or lumbar erector spinae muscle CSA. The analysis revealed that there was no difference between CSAs of the multifidus and erector spinae if the back or hip-region pain was right, left, or bilateral (all, $p>0.05$). Hypermobility score, range of functional leg turnout, years of dance training, leg-length difference and site and degree of spinal curvature were eliminated from the analysis, as they did not influence muscle CSA in a preliminary ANCOVA (all, $p>0.05$). As all the dancers were of slim build, height provided the main variance across subjects, and weight and body mass index (BMI) were not included in the analysis.

For the main analysis separate ANCOVAs using a general linear model were undertaken to compare the CSAs of the multifidus and lumbar erector spinae muscles (at levels L2-L5), psoas major (at levels L4-L5), and quadratus lumborum (at levels L3-L4), between right and left sides.
(repeated measure) and between the 3 groups. Age, height, gender and years of professional dance were the factors included as covariates in the analysis. Post hoc analysis was undertaken using the Bonferroni test for multiple comparisons.

3.5 Results

Analysis of multifidus CSA revealed a significant difference between groups (main effect for group, \( p=0.049 \)). Multifidus CSA at lumbar levels L3, L4 and L5 on both sides was larger in dancers with no pain compared to those with LBP (post hoc for all, \( p<0.024 \)) (Figure 3-2). The CSA of the multifidus muscle at L3 on both sides and L4 on the right was also larger in the no-pain group compared to hip pain and LBP group (post hoc for all, \( p<0.027 \)). Furthermore, multifidus CSA on the left side at L4 and L5 was larger for the hip pain and LBP group compared to the LBP group, (post hoc for all, \( p<0.033 \)). There was a similar pattern on the right side, which did not reach significance at L5 (\( p=0.06 \)) or L4 (\( p=0.27 \)). Multifidus CSA did not differ between groups at L2 (post hoc for all, \( p>0.44 \)). There was no difference between dancers in the no-pain group and those with pain (LBP and hip pain and LBP), or between the 2 pain groups (LBP and hip pain and LBP), for erector spinae CSA (main effect for group, \( p=0.10 \)) (Figure 3-3), psoas CSA (main effect for group, \( p=0.55 \)) or quadratus lumborum CSA (\( p=0.70 \)). Fat was only evident in the multifidus muscles of 5 participants (4 females and 1 male, all in pain groups) and all were graded ‘normal’, as the total CSA of fat was less than 10% in the muscles.

CSAs of psoas (main effect for gender, \( p<0.0001 \)) and quadratus lumborum muscles (main effect for gender: \( p=0.01 \)) were larger in male compared to female dancers (Figure 3-4), but not the erector spinae and multifidus. There was a significant effect of years of professional dancing on psoas CSA (main effect for years of professional dance, \( p=0.03 \)). A linear regression fitted to the relationship between psoas CSA and years of professional dance indicated increasing CSA with greater number of years of professional dance.
Figure 3-2 Cross-sectional area of the multifidus muscles at each lumbar level on the left and right side of the body for the three participant groups: no pain, low back pain (LBP) pain, and hip pain and LBP. Data are shown as mean and standard deviation. * - $p<0$.

Figure 3-3 Cross-sectional area of the erector spinae muscles at each lumbar level on the left and right side of the body for the three participant groups; no pain, low back pain (LBP) pain, and hip region pain and LBP. Data are shown as mean and standard deviation. No significant difference between groups ($p<0.05$).
3.6 Discussion

This study found asymmetry in multifidus CSA between sides in classical ballet dancers. The results also demonstrate that LBP is associated with a smaller multifidus CSA in dancers. Dancers with current LBP or a history of LBP had a smaller CSA of the multifidus muscles at the lower lumbar levels and this was not affected by dominance or gender or side of back or hip-region pain. The apparent atrophy of the multifidus was present in this young and highly athletic population, despite the dancers operating at full function and reporting low disability. Thus, high levels of physical activity are not sufficient to maintain properties of this muscle.

Consistent with our primary hypothesis and data from other populations, the CSA of the multifidus muscles was decreased in dancers with LBP (Barker et al. 2004, Danneels et al. 2000, Hides et al. 1994, Parkkola et al. 1993). Dancers with combined hip-region pain and LBP pain also had significantly smaller multifidus muscles at L4 and L5 compared to dancers without LBP, but the difference in size compared to pain-free individuals was less than those with only LBP. The presence of hip-region pain may be associated with different lumbo-pelvic muscle function compared to that associated with isolated LBP. Alternatively, the difference between groups may be due to the potential for some of the individuals with combined hip-region pain and LBP to have primary pathology in the hip, with compensatory spinal loading and subsequent LBP. Future
investigation of CSAs of hip-region muscles in dancers with both hip and LBP may prove informative. In addition, as changes in control of the abdominal muscles are commonly reported in association with LBP in athletes,(Hides et al. 2008a, Hides et al. 2010b) further examination of CSAs of these muscles in dancers could be valuable.

Although several authors have reported higher fat content in the multifidus in people with LBP, (Kader et al. 2000, Mengardi et al. 2006, Parkkola et al. 1993) qualitatively our dancer population had very little fat in any of the muscles studied. This is consistent with our null hypothesis and with observations from other groups (Beneck and Kulig 2012, Danneels et al. 2000) that have compared people with LBP to age- and activity-matched participants and have not found an association between fat and chronic LBP. The explanation for the contrasting observations is unclear. The age range of the present population of dancers (17-32 years) is between the ages investigated by Kjaer et al. (2007) who showed no association between fat infiltration and LBP in 13 year olds and a strong association with 40 year old participants. Thus, age may explain the absence of fat deposits. Body composition has also been suggested as a factor by some authors (Parkkola et al. 1993) but disputed by others (Kjaer et al. 2007). The BMI of the dancers with LBP was lower (mean-20kg/m²) than that of populations studied by authors who did not observe fat in the multifidus muscle: mean-23kg/m² (Danneels et al. 2000); mean-24 kg/m² (Beneck and Kulig 2012), and those who did; mean-24 kg/m² (Mengardi et al. 2006); mean-27 kg/m² (Parkkola et al. 1993). BMI does not appear to fully explain the differences in fat content reported in association with atrophy of the multifidus muscle in some studies.

Whether the smaller size of the multifidus in dancers with LBP indicates atrophy of the muscles or is due to hypertrophy of the multifidus muscles in the dancers without pain is unclear. The size of the multifidus muscles has been shown to be decreased in non-dancers with acute/subacute (Hides et al. 1994) and chronic (Danneels et al. 2000) LBP bilaterally,(Beneck and Kulig 2012) on the side of pain, and at the level of pain provocation, and is related to the duration of symptoms (Barker et al. 2004). In human cross-sectional studies, it is not possible to determine whether the reduction in size precedes or follows the onset of pain. However, in a porcine model, Hodges et al. (2006) demonstrated that injury to the L3-4 intervertebral disc induced atrophy of the multifidus ipsilaterally, with the greatest loss of CSA adjacent to the L4 spinous process immediately caudal to the injured disc. Complicating the issue in dancers, the multifidus muscles appeared to be larger in dancers with no pain than in the general population, although a specific comparative study of matched subjects has not been conducted and some of the differences between studies may relate to differences in methodology (e.g. identification of muscle boundaries) (Table 3-2). It is possible that larger multifidus muscles in dancers are protective of LBP and may be related to the specific functional demands of dance (e.g., spinal posture or sustained and repetitive
lumbar and hip extension). It follows that failure of hypertrophy could contribute to the onset of LBP and account for the smaller CSA of the multifidus muscles seen in dancers with LBP. The alternative explanation is that the smaller multifidus in dancers with LBP (relative to dancers without pain) could be due to an inhibitory mechanism similar to that proposed to explain the smaller muscle size in LBP/injury for non-dancers and animals. Further research is needed to resolve this question.

We predicted that LBP in dancers would be associated with decreased CSA of the multifidus, psoas and quadratus lumborum muscles, but that the CSA of erector spinae muscles would be unchanged. In contrast to our hypothesis, the CSAs of the psoas and quadratus lumborum muscles did not differ between dancers without pain, those with LBP only or those with both hip region pain and LBP. This is consistent with data of Danneels et al. (2000) who compared the CSA of the psoas in people with LBP to that in matched healthy controls and found no difference between groups. However, it contrasts the findings of other authors who reported decreased psoas CSA in individuals with LBP (Barker et al. 2004, Dangaria and Naesh 1998, Parkkola et al. 1993) especially in conjunction with leg pain (Barker et al. 2004, Dangaria and Naesh 1998). Asymmetry of the quadratus lumborum has been associated with LBP in elite cricketers and may be related to asymmetrical activities (Engstrom et al. 2007, Hides et al. 2008a) but was not evident in this population of dancers. Although no differences were apparent in the group analysis, specific differences might have been present in individuals or subgroups. This would be consistent with evidence of changes in psoas muscle CSA in the specific subgroup of people with LBP associated with sciatica (Barker et al. 2004, Dangaria and Naesh 1998). The finding that the CSA of the erector spinae did not differ between dancers without pain, with LBP only or with both hip region pain and LBP was consistent with our hypothesis and is supported by data from other studies.

In contrast to our prediction of symmetrical multifidus CSAs in healthy dancers, the CSA of the multifidus muscle was larger on the right side compared with the left for both the pain-free and LBP groups. This is similar to observations in other populations, such as elite cricketers (Hides et al. 2008a) and other athletes (Ranson et al. 2008) who have larger multifidus CSA, erector spinae CSA and/or combined multifidus and erector spinae CSA on the side of the dominant arm and contrasts observations in non-dancers (Chaffin et al. 1990, Hides et al. 1994, Marras et al. 2001)
and rowers (McGregor et al. 2002) who have symmetrical CSAs of these muscles. It is notable that, despite the aspiration in ballet for equal proficiency on either leg there is evidence for limb preference in dance tasks and lateral bias in teaching, which is typically towards the right side (Kimmerle 2001, Kimmerle 2010). The majority of dancers in the current study indicated that they were right-limb dominant. The findings of a larger right multifidus coincide with the dancers’ dominant side and may be related to this laterality preference.

The larger CSA of the psoas and quadratus lumborum muscles in male compared to female dancers concurs with data from non-dancers (Marras et al. 2001). However, unlike our data, Marras et al. (2001) also reported larger multifidus/erector spinae CSA in males. Although male dancers do more lifting than females, both genders perform a range of other actions that place large demands on the spine (e.g., repetitive holding of leg extension and prolonged trunk extension). This latter point may account for the similarity in paraspinal muscle size relative to height between male and female dancers.

It is difficult to directly compare the muscle CSAs recorded in our pain-free group with other populations, due to the small number of dancers who have never experienced LBP and to variation in methods and data analysis between studies (e.g., many studies have combined the multifidus and erector spinae). It could be reasoned that dancers would have larger CSAs of spinal extensor muscles than non-dancers due to higher values of peak extension torque recorded in this group compared to non-dancers (Cale-Benzoor et al. 1992) and to the correlation between the combined multifidus and erector spinae CSA with extension torque (Raty et al. 1999). From the limited data available, male dancers appear to have larger multifidus CSA at L3 (McGill et al. 1993), L4 (Hides et al. 1992, Lee et al. 2006, Stokes et al. 2005), and L5 (Lee et al. 2006) than healthy non-dancers (Table 3-2). They also had larger multifidus muscles at L2-L5 than elite cricketers with a similar mean age and height but greater mean weight (Hides et al. 2008b). Female dancers also had larger multifidus CSA at L2, L3 (Hides et al. 1992) and L4 (Hides et al. 1995, Stokes et al. 2005) compared with non-dancers, but not at L5. (Hides et al. 1995, Stokes et al. 2005) Healthy dancers also had larger multifidus muscles at L4 compared to L5. This finding is consistent with some authors (Lee et al. 2006); however, other authors report that the multifidus muscle is usually larger at L5 than L4. (Hides et al. 2008a, Hides et al. 1995, Stokes et al. 2005) No comparable data could be found for the CSA of the lumbar erector spinae.
Table 3-2 Lumbar multifidus morphometry and demographics for healthy populations of males and females.

<table>
<thead>
<tr>
<th>Group</th>
<th>Age (years)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>Method</th>
<th>CSA at L3 (cm²)</th>
<th>CSA at L4 (cm²)</th>
<th>CSA at L5 (cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Males</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current Study</td>
<td>Dancers</td>
<td>23(3)</td>
<td>183(7)</td>
<td>MRI supine disc/z jt</td>
<td>5.96(1.3)</td>
<td>9.5(0.91)</td>
<td>8.78(1.15)</td>
</tr>
<tr>
<td>McGill et al 1993</td>
<td>Non-d</td>
<td>25.3(4)</td>
<td>176.1(7)</td>
<td>MRI supine disc centre</td>
<td>4.6(2.7)</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>Lee et al 2006</td>
<td>Non-d</td>
<td>41.7(5)</td>
<td>NR</td>
<td>US prone lamina</td>
<td>NR</td>
<td>7.65(1.34)</td>
<td>7.2(1.83)</td>
</tr>
<tr>
<td>Hides et al 1992</td>
<td>Non-d</td>
<td>[18-35]</td>
<td>178.9(8)</td>
<td>US prone lamina</td>
<td>NR</td>
<td>6.15(0.93)</td>
<td>NR</td>
</tr>
<tr>
<td>Stokes et al 2005</td>
<td>Non-d</td>
<td>40.1(13)</td>
<td>178</td>
<td>US prone lamina</td>
<td>NR</td>
<td>7.87(1.85)</td>
<td></td>
</tr>
<tr>
<td>Hides et al 2008</td>
<td>Cricketers</td>
<td>21.4(2)</td>
<td>182.7(6)</td>
<td>US prone lamina</td>
<td>4.32(1.48)</td>
<td>6.49(2.18)</td>
<td>8.01(1.75)</td>
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<tr>
<td>Females</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current Study</td>
<td>Dancers</td>
<td>21(2)</td>
<td>164(9)</td>
<td>MRI supine disc/z jt</td>
<td>4.14(0.08)</td>
<td>7.24(0.52)</td>
<td>6.57(0.44)</td>
</tr>
<tr>
<td>Hides et al 1992</td>
<td>Non-d</td>
<td>25.5</td>
<td>NR</td>
<td>US prone lamina</td>
<td>3.29(0.77)</td>
<td>4.99(1.09)</td>
<td>7.15(0.58)</td>
</tr>
<tr>
<td>Hides et al 1995</td>
<td>Non-d</td>
<td>[18-35]</td>
<td>197.3(6)</td>
<td>US prone lamina</td>
<td>3.33(0.85)</td>
<td>4.87(1.22)</td>
<td>7.12(0.68)</td>
</tr>
<tr>
<td>Stokes et al 2005</td>
<td>Non-d</td>
<td>34.2(13)</td>
<td>165</td>
<td>US prone lamina</td>
<td>5.55(1.28)</td>
<td>5.55(1.28)</td>
<td>6.65(1.0)</td>
</tr>
</tbody>
</table>

Abbreviations: Non-d–Non-dancer; CSA- cross-sectional area; L-lumbar level; n-number; MRI-magnetic resonance imaging; US-real time ultrasound imaging; z jt-zygapophyseal joint; NR-not reported
Multifidus anatomic CSA at L3-5 averaged between right and left sides
* Values represent mean and (standard deviation) or [range]

The increase in the CSA of the psoas muscles with advancing years of professional dancing is an interesting finding. Peltonen et al. (1997) also found a correlation between physical training time, psoas CSA and trunk flexion force in a group of adolescent female ballet dancers, gymnasts and figure skaters. The correlation between the size of the psoas muscles and years of professional
dancing may reflect the high use of the psoas muscles in ballet, supporting the proposed role of the psoas muscles as hip and trunk flexors (Bogduk et al. 1992b).

A limitation of this study was the small sample size, which was due to the elite nature of the professional classical ballet population. This might have affected some of the analyses. For example, there is evidence that presence of scoliosis is associated with asymmetry of the size of the multifidus muscles (Kennelly and Stokes 1993). The small number of dancers in this study, with spinal curves greater than 10 degrees (n=4) may explain the failure of this relationship to reach significance. The small number of dancers without LBP and the necessity to divide the pain group into LBP only and both hip region pain and LBP may also impact the conclusions that may be drawn from the results.

3.7 Conclusion

The results of this study demonstrate asymmetry of multifidus CSA in dancers. The study also provides evidence that LBP and combined hip region pain and LBP in classical ballet dancers are associated with smaller size of the multifidus muscles. Clinical trials are necessary to determine whether this change in muscle size can be reversed with specific treatment strategies and whether this is associated with changes in LBP symptoms.
Chapter 4  Morphology of the abdominal muscles in ballet dancers with and without low back pain: a magnetic resonance imaging study (Study II)  

4.1 Preamble

The previous chapter of this thesis examined the morphology of trunk muscles that directly attach to the vertebral column. This chapter investigates the morphology and function of transversus abdominis (TrA) and oblique internus abdominis (OI) muscles in classical ballet dancers with and without low back pain. Alteration of these muscles has been shown in association with LBP in other sporting and non-sporting populations. The measures chosen for this chapter; change in thickness of TrA and OI muscles, lateral slide of the anterior extent of the TrA muscles (TrA slide) and reduction in total CSA of the trunk with contraction taken from MR images reflect the measures used clinically (often with real time ultrasound guidance) to assess the function of these muscles and guide restoration of optimal function during rehabilitation from low back injury. Abdominal muscle training, using verbal cues similar to those used in this study, is also an integral part of classical ballet training and dancers are very familiar with this manoeuvre. The findings of this chapter have implications for rehabilitation of dancers with low back pain and training for muscle symmetry (a goal of classical ballet technique).

4.2 Abstract

Purpose: To evaluate the morphology of TrA and OI muscles and the ability to ‘draw in’ the abdominal wall, in professional ballet dancers without LBP, with LBP or both hip region and LBP.

Methods: MRIs of 31 dancers were taken at rest and during voluntary abdominal muscle contraction. Measurements included the thickness of TrA and OI muscles, lateral slide of the anterior extent of the TrA muscles (TrA slide) and reduction in total CSA of the trunk.

Results: The TrA and OI muscles were thicker in male dancers ($p<0.001$) and the right side was thicker than the left in both genders ($p=0.01$). There was no difference in muscle thickness as a

2 Adapted from: Gildea JE, Hides, JA, Hodges, PW. Morphology of the abdominal muscles in ballet dancers with and without low back pain: A magnetic resonance imaging study. JSAM 2014;17:452-456 (see Appendix IV).
proportion of the total thickness, between dancers with and without pain, although there was a trend for female dancers with LBP only \((p=0.069)\) to have a smaller change in TrA muscle thickness with contraction than those without pain. TrA slide was less in female dancers than in male dancers \((p<0.05)\). When gender was ignored, the extent of TrA slide was less in dancers with LBP only \((p<0.03)\). Reduction in trunk CSA with contraction was not different between genders or groups.

**Conclusions:** This study provides evidence that the abdominal muscles (TrA and OI) are asymmetrical in dancers and although the abdominal muscles are not different in structure (resting thickness) in dancers with LBP, there is preliminary evidence for the behavioural change of reduced slide of TrA during the ‘draw in’ of the abdominal wall.

### 4.3 Introduction

Despite the effortless grace of classical ballet there is a high prevalence and incidence of LBP (Jacobs et al. 2012). The spine is the most common site of chronic pain in professional dancers with the majority of injuries occurring in the lumbar region (Crookshanks 1999). Abdominal muscle weakness has been cited as a contributing factor to LBP in professional dancers (Micheli 1983). However in dancers, peak trunk flexion torque is not correlated with LBP (Cale-Benzoor et al. 1992) and the association between abdominal endurance and LBP in athletes (including dancers) is weak (Kujala et al. 1992). Abdominal muscle strength is also a poor predictor of risk for development of LBP in athletes (Kujala et al. 1994). In contrast, morphology and behaviour of the abdominal muscles has been suggested to have a more consistent relationship to LBP.

In non-dancers with LBP, altered motor control of abdominal muscles has been observed (Hodges et al. 1996, Hodges and Richardson 1996). EMG recordings have demonstrated delayed activation (Hodges and Richardson 1996) and reduced amplitude of activity in TrA muscles in people with LBP (Ferreira et al. 2004). Consistent with EMG changes, a smaller increase in TrA muscle thickness with contraction has also been observed with ultrasound imaging (Ferreira et al. 2004).

Delayed and reduced activation of the TrA muscle may compromise spinal control (Hodges 2011, Hodges and Richardson 1996). The TrA muscle contributes to spinal control via its attachment to the thoracolumbar fascia, (Barker et al. 2006) and by modulation of intra-abdominal pressure (Hodges et al. 2003a). Changes in CSA of the trunk, observed with ultrasound and MRI during the voluntary task of ‘drawing-in’ the abdominal wall has been used as a clinical muscle test of the TrA muscle (Richardson and Hides 2004). During this manoeuvre, as the muscle bellies of TrA thicken and shorten, there is an associated lateral slide of the anterior extent of the TrA muscle (TrA slide) and reduced trunk CSA (Hides et al. 2006b). These actions are consistent with descriptions of TrA muscle function from anatomical studies (Barker et al. 2006). Less TrA muscle
slide and smaller reduction in trunk CSA have been observed in people with LBP than those without LBP (Richardson et al. 2004). Reduced ability to decrease the CSA of the trunk by ‘drawing-in’ the abdominal wall has also been observed in elite cricketers and footballers with LBP (Hides et al. 2008a, Hides et al. 2010b). These parameters have been argued to primarily reflect TrA activation.

Studies of trunk muscle geometry have reported symmetry of the abdominal muscles between sides in participants without LBP (Marras et al. 2001, Springer et al. 2006), irrespective of hand dominance or gender (Springer et al. 2006). Bilateral contraction is argued to have a greater affect on spine control than unilateral contraction (Hodges et al. 2003a). Asymmetry of the TrA muscle slide has been observed in cricketers with LBP (Hides et al. 2008a). Cricketers also had larger resting thickness of the OI muscle on the side of the non-dominant hand and there was a non-significant tendency for greater OI muscle thickness in those with LBP than those without LBP (Hides et al. 2008a).

Maintenance of an aesthetically symmetrical body structure and equal ability to perform tasks on either leg and to either side is a key objective in ballet (Kimmerle 2010). The symmetrical emphasis of classical ballet would be predicted to encourage symmetrical abdominal muscle development in dancers, although an asymmetrical bias in teaching (Farrar-Baker and Wilmerding 2006) and some specific dance tasks (Kimmerle and Wilson 2007) has been observed. As changes in muscle morphology, symmetry and behaviour are related to LBP in non-dancers it is possible that dancers with LBP could also have changes in these trunk muscle parameters.

This study aimed to investigate, in professional ballet dancers, the size and symmetry of the TrA and OI muscles and the lateral slide of the anterior extent of the TrA muscles, changes in thickness of TrA and OI muscles, and trunk CSA with voluntary contraction of the abdominal muscles. A second aim was to compare these parameters between dancers with and without LBP.

4.4 Methods

Seventeen female dancers aged 23(3) years, weighing 51(4) kg with heights of 165(4) cm; and 14 male dancers aged 24(4) years, weighing 74(6) kg, with heights of 183(5) cm volunteered from 49 dancers on tour for The Australian Ballet production of Giselle in Brisbane, Australia. All dancers (corps de ballet to principals) were on full workloads. The majority of the dancers indicated that they were right-hand (94%) and right-leg (97%) dominant. Demographic data, hypermobility scores (McCormack et al. 2004), site and degree of spinal curvature (Liederbach et al. 1997) and range of functional leg turnout (Negus et al. 2005) were collected by an experienced physiotherapist. Dancers completed a general health and injury questionnaire (which included a body chart), the International Physical Activity Questionnaire long form (Craig et al. 2003) and a
laterality profile (Kimmerle and Wilson 2007). All dancers who completed the physical activity questionnaire (n=27) scored in the high physical activity category (Craig et al. 2003). Dancers were excluded if they had LBP of non-musculoskeletal aetiology, neurological or respiratory disorders, a history of spinal surgery, or contraindications to MRI. One dancer was excluded due to pregnancy. The number of participants in the study was determined by availability rather than by a power analysis.

LBP was investigated several ways. Dancers who indicated on the body chart that they had pain in the region of the lower back, pelvis or hip completed a detailed questionnaire. Presentation was discussed with the physiotherapy team who provided ongoing care for the dancers, to determine whether, based on comprehensive physical assessment, pain was reproduced by provocation of the low back only or structures other than the low back i.e. the hip or pelvis. As 10 dancers were reported to have hip-region pain in addition to LBP, and there were no cases of hip-region pain without LBP, dancers were divided into three groups for comparison: no history of hip-region or LBP (n=8), history of or current LBP (n=13), history of or current hip-region and LBP (n=10). Severity of pain in both the low back and hip regions was measured using a 10-cm Visual Analogue Scale (VAS). Participants with LBP also completed the Roland-Morris Disability questionnaire and Oswestry Disability questionnaire. Except for pain, there was no difference in demographic data among groups (Analysis of variance [ANOVA], Table 4-1).

Table 4-1 Demographic and pain characteristics of the no pain, low back pain only (LBP) and hip-region and LBP groups.

<table>
<thead>
<tr>
<th></th>
<th>No pain (n=8)</th>
<th>LBP (n=13)</th>
<th>Hip region and LBP (n=10)</th>
<th>p value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>22 ± 3</td>
<td>24 ± 3</td>
<td>25 ± 5</td>
<td>0.45</td>
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<tr>
<td>Gender per group</td>
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<td>9F,4M</td>
<td>5F,5M</td>
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<tr>
<td>Height (cm)</td>
<td>176 ± 12</td>
<td>171 ± 10</td>
<td>173 ± 9</td>
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<td>164 ± 9</td>
<td>165 ± 3</td>
<td>165 ± 4</td>
<td></td>
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<tr>
<td>Males</td>
<td>183 ± 7</td>
<td>185 ± 3</td>
<td>181 ± 5</td>
<td></td>
</tr>
<tr>
<td>Weight (kg)</td>
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<td>58 ± 13</td>
<td>64 ± 14</td>
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<td>52 ± 4</td>
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<tr>
<td>Males</td>
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<td>76 ± 3</td>
<td>77 ± 6</td>
<td></td>
</tr>
<tr>
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<td>LBP</td>
<td>and LBP</td>
<td>p value*</td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>-----</td>
<td>---------</td>
<td>----------</td>
<td></td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
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<td>20 ± 2</td>
<td>21 ± 2</td>
<td>0.41</td>
</tr>
<tr>
<td>Females</td>
<td>18 ± 1</td>
<td>19 ± 1</td>
<td>19 ± 1</td>
<td></td>
</tr>
<tr>
<td>Males</td>
<td>21 ± 1</td>
<td>22 ± 1</td>
<td>23 ± 1</td>
<td></td>
</tr>
<tr>
<td>Years Prof dance</td>
<td>4 ± 3</td>
<td>5 ± 3</td>
<td>6 ± 4</td>
<td>0.33</td>
</tr>
<tr>
<td>Years Dance</td>
<td>16 ± 4</td>
<td>18 ± 6</td>
<td>19 ± 4</td>
<td>0.41</td>
</tr>
<tr>
<td>Spinal curve (degrees)</td>
<td>4 ± 4</td>
<td>2 ± 2</td>
<td>3 ± 5</td>
<td>0.57</td>
</tr>
<tr>
<td>Hypermobility score (0-9)</td>
<td>5 ± 3</td>
<td>5 ± 2</td>
<td>5 ± 2</td>
<td>0.61</td>
</tr>
<tr>
<td>Degrees of turnout</td>
<td>141 ± 8</td>
<td>137 ± 10</td>
<td>140 ± 11</td>
<td>0.73</td>
</tr>
<tr>
<td>VAS LBP (0-10)</td>
<td>0</td>
<td>3 ± 3</td>
<td>4 ± 2</td>
<td>0.9</td>
</tr>
<tr>
<td>Years LBP</td>
<td>0</td>
<td>3 ± 3</td>
<td>6 ± 5</td>
<td>0.14</td>
</tr>
<tr>
<td>Days LBP (prior 6months)</td>
<td>0</td>
<td>49 ± 55</td>
<td>42 ± 60</td>
<td>0.79</td>
</tr>
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<td>R-M score (0-24)</td>
<td>0</td>
<td>1 ± 2</td>
<td>1 ± 1</td>
<td>0.41</td>
</tr>
<tr>
<td>ODI (0-100%)</td>
<td>0</td>
<td>8 ± 10</td>
<td>4 ± 2</td>
<td>0.77</td>
</tr>
<tr>
<td>VAS Hip (0-10)</td>
<td>0</td>
<td>0</td>
<td>5 ± 2</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: BMI, body mass index; F, female; LBP, low back pain; M, male; ODI, Oswestry Disability Index; R-M, Roland-Morris; VAS, visual analogue scale.

*Between-group comparison. Values represent mean ± standard deviation.

The Institutional Medical Research Ethics Committee approved the study. Participants gave informed consent and the study was undertaken in accordance with the Declaration of Helsinki.

After a medical practitioner had screened the participants for MRI contraindications they were positioned in supine with the hips and knees resting in slight flexion on a foam wedge. Measures were made at rest and during abdominal muscle contraction. Dancers were instructed to gently ‘draw-in’ the abdominal wall without moving the spine and without breathing. Dancers were familiar with this manoeuvre from their dance training. Images were taken at rest and after completion of the contraction (which was cued by the operator) with the subject holding their breath at mid expiration. Images were made using a Siemens Sonata MR system (1.5 Tesla) with true fast
imaging and a steady-state precession (TrueFISP) sequence of 14-mm x 7-mm contiguous slices centred on the L3-4 disc. MRIs were saved for later analysis and deidentified prior to measurement. Measurements were made from the MR images using Image J (version 1.42q, http://rsb.info.nih.gov/ij) (Figure 4-1). In all measurements the cursor was placed at the inside edge of the fascia. Measures were: thickness of the TrA and OI muscles on the right and left sides at the muscle’s widest point at rest and at the same location during contraction, the CSA of the entire trunk excluding skin and subcutaneous fat at rest and during contraction, and the lateral slide of the anterior extent (defined as the point at which the muscle attaches to the anterior fascia) of the TrA muscle with contraction, on both sides. These methods have been described previously (Ferreira et al. 2004, Hides et al. 2008a, Hides et al. 2006b). Repeatability and reliability of measurements of trunk CSA from MRI scans have been reported (Hides et al. 2010b).

Figure 4-1 Transverse magnetic resonance image of a male dancer. Transverse magnetic resonance image (MRI) of a male dancer at L3/4 intervertebral level. A, at rest and B during “draw-in” contraction. The cross-sectional area of the trunk is outlined in both images. Enlarged MRI image C and diagram E, show the thickness measurement of the transversus abdominis muscle (2) and obliquus internus abdominis muscle (3). Enlarged MRI image D and diagram F show the measurement point of lateral slide at the medial edge of the anterior extent of the transversus abdominis muscle (1).

STATISTICA, Version 9 (StatSoft Pacific Pty Ltd, Melbourne, Australia) was used for data analysis. Preliminary analysis was conducted to reduce the large range of potential variables. The mix of participants with unilateral and bilateral pain precluded investigation of the side of pain in
the analysis. This decision was validated by the absence of main effect for side of back or hip-region pain on the muscle parameters. Age, height, hypermobility score, range of functional leg turnout, years of dance training, years of professional dancing, leg-length difference and site and degrees of spinal curvature were eliminated from the analysis as they did not influence muscle thickness, trunk CSA or TrA muscle slide in a preliminary ANCOVA (all, $p>0.05$). As all the dancers were of slim build, height provided the main variance across participants so weight and body mass index were not included in the analysis.

For the analysis of change in muscle thickness with contraction, ANCOVAs using a general linear model were undertaken separately to compare the proportional change from rest to after contraction in the linear measurements of TrA and OI muscle thickness between right and left sides (repeated measure) and between the three groups. One-way ANOVAs were used to compare the TrA muscle slide, and the CSA of the entire trunk between rest and contraction. Post hoc analysis was undertaken using Duncan’s test. Significance was set at $p<0.05$.

4.5 Results

At rest the thickness of OI was larger than that of TrA (main effect for muscle, $p<0.01$). Male dancers had thicker TrA (interaction for muscle x gender, $p=0.002$, post hoc $p<0.001$) and OI muscles ($p<0.001$) than female dancers. OI and TrA muscles were thicker on the right than the left in both genders (main effect for side, $p=0.01$) (Figure 4-2).

The increase in TrA muscle thickness with contraction was greater than that for the OI muscle (main effect for muscle, $p<0.001$). There was a tendency, although non-significant, for an interaction between muscle, group and gender ($p=0.069$). Exploration of this finding revealed a tendency for a smaller change between the contracted and resting TrA muscle thickness in females with LBP only. The failure to reach significance is likely explained by the small number of females without LBP ($n=3$).
Figure 4-2 Measurements of the thickness (mm) of the transversus abdominis and obliquus internus abdominis muscles at rest (R) and when contracted (C), in female and male dancers on the left (L) and right (R) sides for the no pain, low back pain, and hip region and low back pain participant groups. Mean and SD are shown.

Lateral slide of the anterior extent of the TrA muscle was less for females than males on both sides (interaction for gender x side, $p<0.03$, both sides $p<0.05$) (Figure 3). Although the primary analysis, which included consideration of gender, failed to show a difference between groups (main effect for group, $p=0.085$), because of the small sample size we undertook an additional analysis in which data were analysed without consideration of gender, and compared between pain groups with an ANOVA. This analysis showed a significantly smaller TrA muscle slide in dancers with LBP only than those without pain (main effect for group, $p<0.001$, post hoc $p=0.015$) and those with hip-region and LBP (post hoc, $p=0.025$). There was no difference in this parameter between the pain-free, and hip-region and LBP groups (post hoc, $p=0.74$). There was no significant difference in reduction of trunk CSA with contraction between groups (main effect for group, $p=0.62$) or between genders (main effect for gender, $p=0.26$).
4.6 Discussion

These data show that thickness of TrA and OI at rest and with contraction is asymmetrical in dancers but did not differ between dancers with and without LBP or combined hip-region and LBP. Other factors with the potential to affect asymmetry, for example, spinal asymmetry due to scoliosis and variance in physical activity levels were eliminated as these factors did not affect results. Although our primary analysis showed no group difference in measures of TrA contraction in dancers with LBP, the additional exploratory analysis that ignored gender revealed a smaller lateral slide of the anterior extent of the TrA muscles in dancers with LBP only (but not combined hip-region and LBP pain), which is consistent with the trend for female dancers with LBP only to show less increases in TRA muscle thickness with contraction. This finding justifies the necessity to conduct a larger study of professional ballet dancers. This would be likely to require a multi-site study, as there is only a small population of dancers who have not experienced LBP.

Asymmetry of the morphology of the abdominal muscles in dancers contrasts with findings in non-dancers, who are generally symmetrical between the sides (Marras et al. 2001, Springer et al. 2006). Asymmetry in OI muscle thickness has been reported in elite cricketers. Cricket involves considerable trunk rotation away from the dominant hand with throwing, bowling and batting actions. In that group the larger OI muscle is on the side of the non-dominant arm (Hides et al. 2008a). This contrasts the larger muscle on the side of the dominant hand in dancers, but is probably explained by the specific kinematic demands of bowling/throwing in cricket and rotating (pirouettes) in dance. A further difference between dancers and cricketers is that dancers had larger TrA on the right side unlike the symmetry of the muscle in cricketers (Hides et al. 2008a). In this
study, as in previous studies on dancers (Kimmerle and Wilson 2007) the majority of dancers indicated right-hand and right-leg dominance. There was also a right bias in preferred turning side. All dancers (except one) preferred to pirouette en dehors or châiné to the right. Rotation of the thorax to the right relative to the pelvis is a primary action of the right OI and TrA (Urquhart et al. 2005). Other authors have observed a right turning bias in university dance students (Kimmerle and Wilson 2007) and bias towards the right hand side in dance teaching which results in 26% higher prevalence of repetitions to the right (Farrar-Baker and Wilmerding 2006). Despite the emphasis in training on achieving and maintaining the appearance of body symmetry and equal proficiency of tasks to both sides, (Kimmerle 2010) the impact of side dominance in teaching and practice may underlie the right-left side differences reported here. It is possible that a focus on restoration of symmetry of morphology of the abdominal muscles could be advantageous to optimise the desired symmetry of structure and movement that is demanded in classical ballet.

Male dancers had larger abdominal muscles and greater TrA muscle slide than female dancers, even when height was accounted for as a covariate in the analysis, and this agrees with gender differences in the non-dance populations (Marras et al. 2001, Rankin et al. 2006, Springer et al. 2006). Absolute resting thickness of TrA muscles in male dancers is similar to the absolute thickness found in non-dancers using ultrasound measurements (Rankin et al. 2006, Springer et al. 2006) but thinner than values reported in elite cricketers (Hides et al. 2008a). However, the resting thickness of TrA in female dancers appears to be less than in non-dancers (Rankin et al. 2006, Springer et al. 2006). This may be related to the lower body weight of the female dancers compared to the non-dancers. The absolute resting thickness of OI muscles in dancers is intermediate between thinner muscles in non-dancers (Rankin et al. 2006) and thicker muscles in elite cricketers (Hides et al. 2008a).

Unlike elite cricketers, Australian Football League players (Hides et al. 2008a, Hides et al. 2010b) and other non-dancers with LBP, (Richardson et al. 2004) the ballet dancers with LBP did not have a compromised ability to reduce the abdominal CSA during the ‘draw-in’ manoeuvre, when compared to the pain-free dancers. The only difference in behaviour of abdominal muscle activation observed in the present study was a reduced TrA muscle slide in dancers with LBP, but not combined hip-region and LBP, when gender was excluded from the analysis. The main impact of removal of the gender factor was the increase in sample size particularly in the pain-free group (only three females had not experienced LBP). Although not related linearly, TrA muscle slide provides an indication of muscle activity. Thus limitation to muscle shortening is consistent with reports of reduced TrA activation (Hodges et al. 1996). There was also a non-significant tendency for female, but not male, dancers with LBP only to have reduced increase in TrA thickness from rest to contraction. Reduced change in TrA muscle thickness with contraction has been reported in
non-dancers with LBP (Ferreira et al. 2004), but not cricketers. The non-significant tendency implies that either difference in muscle activation changes between groups is small, or that it presents variably in dancers. Ballet places very different demands on the trunk from cricket. These physical demands may account for the differences in muscle morphology associated with LBP in these two populations.

The absence of changes in the dancers with hip-region and LBP highlights that these presentations are unique and the muscle changes are specific to primary LBP. The lack of the overall change in abdominal CSA in dancers, unlike other elite athletic populations (Hides et al. 2008a, Hides et al. 2010b), could be explained by the training of the dancers. The action of narrowing the waist, similar to the ‘draw-in’ manoeuvre used here, is a routine component of ballet training and a fundamental aspect of ballet posture. It is possible that familiarity with this task as a result of training might counteract any differences in performance mediated by pain. Evaluation of abdominal muscle activation during other tasks such as automatic response to limb movements (Ferreira et al. 2004) and perturbations to the spine (Hodges and Richardson 1996) may provide additional insight.

There are several methodological issues that require consideration. With respect to the aforementioned familiarity of the participant group with voluntary contraction of the muscles under investigation, future work should include evaluation of automatic activation of the muscles. However, this may preclude use of MRI to measure activation as a result of limitation to tasks that can be performed in a confined space. A further limitation of this study is that the elite nature of classical ballet limits the available sample size. The small number of females without LBP may explain why the relationship between TrA muscle thickness and LBP did not reach significance.

Reduced lateral slide of the anterior extent of TrA muscles during the voluntary ‘drawing-in’ task may have implications for spine health and treatment selection. Earlier studies have shown a relationship between activation of TrA in the voluntary task of ‘drawing-in’ the abdominal wall and compromised automatic function of TrA, such as that tested in association with arm movement (Hodges et al. 1996). As this muscle provides a contribution to control of the spine and pelvis, (Barker et al. 2006, Hodges et al. 2003a, Hodges et al. 2005) this will be likely to have an impact on the robustness of spine control. Further, poor TrA muscle slide is a predictor of responsiveness to a motor control training intervention in non-dancers with pain (Unsgaard-Tøndel et al. 2012). Thus, identification of such deficit may contribute to decision making in planning intervention for LBP. This requires testing in clinical trials.
4.7 Conclusion

The results of this study suggest that resting thickness of the TrA and OI muscles are asymmetrical in ballet dancers regardless of presence of LBP. Asymmetry may relate to limb dominance and subsequent bias in the training of dancers. Addressing the asymmetry of the abdominal muscles found in dancers may facilitate the aim of classical ballet for symmetry of body shape and movement. The preliminary evidence of compromised behaviour of TrA muscles in dancers with LBP provides a foundation upon which treatments may be developed and tested for dancers with pain.
Chapter 5  Trunk dynamics are impaired in ballet dancers with back pain but improve with imagery (Study III)³

5.1 Preamble

The previous two chapters of this thesis examined the morphology of and behaviour of trunk muscles. Changes were shown in the trunk muscles; in association with LBP in dancers, and related to dance training. This chapter investigates the mechanical properties of the trunk in classical ballet dancers with and without low back pain. Alteration of the trunk mechanical properties of stiffness and damping has been observed in association with LBP in non-dancers. As changes in trunk muscle control associated with LBP are thought to underlie estimates of stiffness and damping of the trunk there is potential for these properties to be altered in dancers with LBP. This chapter also investigates the mechanical properties of the trunk when dancers are instructed to use motor imagery to respond in a different manner, i.e. a ‘fluid’ manner. The findings increase understanding of the changes that occur in mechanical properties of the trunk in dancers with LBP and have implication for techniques that may be used to alter trunk mechanical properties in the rehabilitation of dancers with LBP.

5.2 Abstract

Purpose: Trunk control is essential in ballet and may be compromised in dancers with a history low back pain (LBP) by associated changes in motor control. The aim of this study was to compare trunk mechanical properties between professional ballet dancers with and without a history of LBP. As a secondary aim we assessed whether asking dancers to use motor imagery to respond in a ‘fluid’ manner could change the mechanical properties of the trunk, and whether this was possible for both groups.

³ Adapted from Gildea JE, van den Hoorn, W, Hides, JA, Hodges, PW. Trunk dynamics are impaired in ballet dancers with back pain but improve with imagery. MSSE e-published 1-12-2014; DOI:10.1249/MSS.0000000000000594 (see Appendix V).
Methods: Trunk mechanical properties of stiffness and damping were estimated with a linear second order system, from trunk movement in response to perturbations, in professional ballet dancers with (n=22) and without (n=8) a history of LBP. The second order model adequately described trunk movement in response to the perturbations. Trials were performed with and without motor imagery to respond in a ‘fluid’ manner to the perturbation.

Results: Dancers with a history of LBP had lower damping than dancers without LBP during the standard condition (p=0.002) but had greater damping during the ‘fluid’ condition (p<0.001) with values similar to dancers without LBP (p=0.226). Damping in dancers without LBP was similar between the conditions (p>0.99). Stiffness was not different between dancers with and without a history of LBP (p=0.252) but was less during the ‘fluid’ condition than the standard condition (p<0.001).

Conclusions: Although dancers with a history of LBP have less trunk damping than those without LBP, they have the capacity to modulate the trunk’s mechanical properties to match that of pain-free dancers by increasing damping with motor imagery. These observations have potential relevance for LBP recurrence and rehabilitation.

5.3 Introduction

Classical ballet dancers have the ability to change the quality of their movement to portray a particular character, convey an emotion or meet the requirements of the choreographer, dance style or musical accompaniment. A key component is motor control of the trunk (Bronner 2012), which evolves in response to dance training and results in more accurate, efficient and repeatable movement patterns (Mouchnino et al. 1992). For instance, in the execution of a développé arabesque (moving the gesture leg from the ground to an elevated position behind the body) differences in lumbo-pelvic control (kinematics) account for most of the variance between expert and less skilled dancers (Bronner 2012). On the basis of data from non-dancers (Hodges and Richardson 1998, van Dieën et al. 2003) it is reasonable to speculate that trunk control, including the ability to regulate movement quality, might be modified in ballet dancers with a history of low back pain (LBP).

Changes in the recruitment of trunk muscles have been reported in association with LBP and this has implications for control of the spine (Hodges 2013). Electromyography (EMG) recordings of the trunk muscles commonly reveal a pattern of compromised activity of the deeper trunk muscles including multifidus (MacDonald et al. 2009) and transversus abdominis (Hodges and Richardson 1998) and augmented activity of the larger, more superficial trunk muscles such as obliquus externus abdominis (Radebold et al. 2000). Consistent with EMG findings, measurement of deep trunk muscle morphology using MRI has demonstrated that LBP in dancers is associated
with smaller CSA of the multifidus muscles (Study I) and reduced shortening with contraction of the transversus abdominis muscles (Study II). It has been hypothesized that altered recruitment and morphology of trunk muscles underlies changes in the mechanical behaviour of the trunk in people with recurring episodes of LBP (Hodges et al. 2009). However, whether trunk mechanical behaviour is altered in ballet dancers with a history of LBP is unknown.

Although movement quality incorporates many components, viewed simply, the dynamic behaviour of the trunk depends on its inertia, damping and stiffness properties (Gardner-Morse and Stokes 2001, Moorhouse and Granata 2007). Estimation of trunk mechanical properties from the response to small perturbations may yield information about trunk control in ballet dancers with and without a history of LBP. Stiffness (Nm⁻¹) is the resistance to trunk displacement (Moorhouse and Granata 2005) and is dependent on muscle activity (e.g. co-contraction) and passive constraints (Brown and McGill 2009, Moorhouse and Granata 2005). Damping is the resistance to trunk velocity (Nsm⁻¹) (Bazrgari et al. 2011) and prevents unwanted oscillations in a system. As damping smooths movement at higher frequencies, change in damping has the potential to affect the quality of trunk movement, which could be an important feature in dance. Estimation of the dynamic properties of the trunk has identified greater stiffness and less damping in people with recurrent LBP than pain-free individuals (Hodges et al. 2009). Trunk dynamics have not been studied in dancers.

Evaluating the change in mechanical behaviour of the trunk in different conditions may provide insight into how dancers modulate movement quality. Dance training frequently employs mental practice including motor imagery, as a technique to change both qualitative and quantitative aspects of movement performance (Coker Girón et al. 2012, Couillandre et al. 2008, Ryder et al. 2010). For example, when using motor imagery, professional dancers can improve the quality of a dance-specific movement sequence by changing muscle activity level (Couillandre et al. 2008) and kinematics (Coker Girón et al. 2012). Kinesthetic motor imagery simulates the ‘felt’ experience of performing movement (Coker Girón et al. 2012) and produces similar cortical activation to actual movement (Jeannerod 2001). Whether dancers can change basic mechanical properties of the trunk with motor imagery, and whether this can also be achieved by dancers with a history of LBP remains unclear. For the current study, a standard and a ‘fluid’ motor image were developed in conjunction with dance experts to evoke movement responses with different qualities that would be likely to influence the properties of stiffness and damping.

This study had two aims. The first aim was to determine whether dynamic properties of the trunk (i.e. stiffness and damping), as estimated from responses to small perturbations applied to the trunk; differ between dancers with and without a history of LBP. The second aim was to investigate whether these properties could be modified by motor imagery. This was achieved by comparison of
the mechanical responses to perturbations with a standard instruction with the responses when
dancers employed the motor image of using their body in a ‘fluid’ manner. We hypothesized that
dancers with a history of LBP would have less damping and greater stiffness of the trunk than those
without pain, and a reduced ability to modulate these properties in the ‘fluid’ condition.

5.4 Materials and methods

5.4.1 Participants

Thirty professional classical ballet dancers with and without a history of LBP (11 male, 19
female, mean (SD): 24 (4) years, 172 (10) cm, 60 (13) kg) volunteered for this study. Participants
were recruited from a group of dancers on full workloads (n=49) who were on tour with The
Australian Ballet. Dancers of all ranks were included and the participants’ dancing experience
ranged from 7 to 28 years, of which 1 to 13 years was professional. Participants were excluded if
they presented with LBP at the time of testing or LBP of a non-musculoskeletal etiology, spinal
trauma or surgery, major postural abnormality (e.g. severe scoliosis), neurological or respiratory
disorders or pregnancy in the preceding 2 years.

Dancers were categorised into either no LBP or LBP groups on the basis of interview with the
dancer and the dance company’s physiotherapists. Dancers were included in the LBP group if they
reported a history of pain in the low back/pelvic area that required treatment or modification of
class, rehearsal or performance. Dancers were not excluded if they also reported pelvic/hip region
pain. Of the 30 dancers, 22 dancers reported pain in the lower back or pelvic/hip region. Fourteen
dancers reported back pain (pain between the lower ribs and gluteal fold) within the preceding 6
months and 8 dancers reported pain prior to that (range 0.5-13y). Nine of these dancers also
reported pelvic/hip region pain (pain from the top of the pelvis to upper thigh) within the preceding 6
months. To gauge self–reported disability, the LBP group completed the Roland-Morris
questionnaire, (Scoring range 0-24, mean [SD], 1[2]) and the Oswestry Disability Index (version
2.0)(Scoring range 0-100% , 8[9]%). They also recorded their LBP level over the previous 6
months, on a 10-cm Visual Analogue Scale anchored with 0 ‘no pain’ and at 10 ‘worse possible
pain imaginable’ (3[3] out of 10). There was no difference between groups for age, height, weight
and years of dancing (t-test for independent samples: all $p>0.07$). Procedures were approved by the
institutional Medical Research Ethics Committee and were undertaken according to the Declaration
of Helsinki. Participants provided written informed consent prior to participation.
5.4.2 Experimental Procedure

Participants sat in a semi-seated upright position with their arms held relaxed by their sides and their head maintained in a neutral position (Figure 5-1). The pelvis was fixated with a belt to minimize movement. A harness was tightly fitted around the thorax for attachment of cables at the front and back at the level of the 9th thoracic vertebrae, the approximate location of the trunk’s centre of mass (Hodges et al. 2009, Radebold et al. 2000). The cables passed over low friction pulleys to weights (7.5 % body weight) attached by an electromagnet. As the front and back weights were equal, minimal muscle activity was required to hold the trunk upright. Force transducers (Futec, LSB300, USA, Irvine, CA) were placed in series with the cable between the weights and the trunk to measure the force applied to the trunk. Either the front or back weight was released at random by switching off the electromagnet at unpredictable times to induce a trunk perturbation. After each perturbation the weight was reattached after ~5s. Force data were collected at 2000 samples/s using a Micro1401 data acquisition system (Cambridge Electronic Design Limited, UK) and Spike 2.6 software (Cambridge Electronic Design, Limited UK).

![Figure 5-1 Methods](image)

Figure 5-1 Methods. Participants sat in a semi-seated position with the pelvis fixated. Equal weights were attached to front and back so that no force acted on the trunk and minimal trunk muscle activity was required to maintain an upright posture. The weight was released from one side of the trunk by release of an electromagnet. Force transducers placed in series with the cable measured the force applied to the trunk.

Participants were tested under 2 conditions. The aim was to use verbal cues to create a motor image to elicit a different movement response in each condition. The instructions for these
conditions were devised in conjunction with dance experts. Instruction given for the standard condition was; “think of yourself sitting upright in a relaxed manner then respond as if you are sitting on a bus and the driver hits the brakes when you are not expecting it and you right yourself as quickly as possible.” This condition was repeated for 21 front and 21 back weight drops, in random order. Instruction for the second condition aimed to elicit a ‘fluid’ response. It was; “think of yourself as fluid in your movements and respond in a fluid manner; think of holding yourself in a gentle lifted way by sustaining yourself through a gentle humming inside your body.” This condition was repeated for 5 front and 10 back weight drops in random order. The number of repetitions was less for the front weight drops as these were initially only included so the participant could not predict the direction of the perturbation, however, we subsequently elected to include these trials in the analysis. The standard condition was always performed first and not randomized as it was considered that the training of the ‘fluid’ imagery condition could modify the movement response and carry over to the standard condition if it was performed second.

5.4.3 Data analysis (Modelling procedures and analyses)

Force data were analysed offline in Matlab (Mathworks, U.S.A., Natick, MA). Trunk parameters were assumed to be constant over time and were estimated with a second order linear model for each perturbation.

\[ F = m\ddot{x} + B\dot{x} + Kx \]  

(1)

\( F \) (N) is the resultant force acting on the trunk \((F_{\text{front}} - F_{\text{back}})\), \( m \) (kg) the trunk mass, \( B \) (Nsm\(^{-1}\)) trunk damping, and \( K \) (Nm\(^{-1}\)) the trunk stiffness. Trunk linear displacement, velocity and acceleration are represented by \( x, \dot{x}, \ddot{x} \) respectively, and were calculated from the force transducer attached to the weight that remained attached during a perturbation (i.e. opposite side to the released weight). The cable attached to the weight and the force transducer remained tensioned during the perturbations, as participants did not accelerate more than gravitational acceleration. As the perturbation weight and force were known (7.5% of body weight) trunk acceleration was determined by dividing the force by the mass. Trunk velocity and displacement were derived by numerically integrating acceleration once and twice over time, respectively. To increase robustness of the estimation of the trunk parameters, both sides of equation 1 were integrated twice over time (Tsuji et al. 1995). As the participants did not move at the time of the weight drop, initial values of displacement and velocity for the integration procedure were set to zero.

\[ \int_{t_0}^{t_1} \int_{t_0}^{t_1} F \, dt = mx + B\int_{t_0}^{t_1} \dot{x} \, dt + K\int_{t_0}^{t_1} \ddot{x} \, dt \]  

(2)
The moment the weight dropped was $t_0$ and $t_1$ was 0.329 s later. The time duration of the model was held constant between conditions and between participants to avoid bias of the estimated trunk parameters related to differences in model duration between conditions (Bazrgari et al. 2011) and was set to 0.329 s. This duration reflected the common mode of all trials across all participants. The unknown variables of the trunk $m$, $B$ and $K$ were estimated by minimizing the least squares differences between the trunk displacements derived from the second order linear model and the actual trunk displacements. The $R^2$ between the measured trunk displacement and the modelled trunk displacement was calculated. Trunk parameter estimates that explained more than 97% variance of the measured trunk displacement were accepted. In total, 2.4% of all trials were discarded. The amount of trunk displacement was assessed at $t=0.329$s.

5.4.4 Statistical analysis

Statistics were performed with Stata (v12, StataCorp LP, USA, TX). Outcome variables (trunk $m$, $B$, $K$) were averaged across the forward and backward perturbations within each condition (standard and ‘fluid’). A repeated measures ANOVA was performed for each of the outcome variables ($m$, $B$, $K$, trunk displacement) to detect whether there were any differences between the groups, conditions and perturbation direction. Group was entered as a between subjects factor (2 levels: no LBP and LBP dancers) and Condition (2 levels: standard and ‘fluid’ responses) and Direction (2 levels: forward and backward perturbations) were entered as repeated within subjects factors. Stiffness values did not pass the Shapiro-Wilk test for normality and were log transformed. When significant interaction was identified related to group, post hoc comparisons were undertaken with Bonferroni correction for multiple comparisons to evaluate group differences. Because of the smaller number of front weight drop (backward perturbation) trials we undertook an additional analysis with data from the first five repetitions in each direction. This did not change the outcome with respect to differences between direction and the original analysis was included. The corrected $p$-values are reported. Significance was set to $p<0.05$.

5.5 Results

Dancers with a history of LBP had significantly lower damping than dancers without LBP for perturbations applied in the standard condition (Interaction for Group × Condition, $F=4.97$, $p=0.03$, post hoc; $p=0.002$) (Figure 5-2). Although damping was greater in the ‘fluid’ condition than the standard condition for the dancers with a history of LBP (post hoc; $p<0.001$), this was not the case for the dancers without LBP (post hoc; $p>0.99$). In the ‘fluid’ condition there was no difference in damping between groups (post hoc; $p=0.226$). Dancers with and without a history of LBP had
greater damping when perturbed backwards than when perturbed forwards (Main effect for Direction, F=7.29, p=0.012).

![Figure 5-2 Trunk damping (mean + SD) for dancers with a history of low back pain (LBP) and without a history of low back pain (No LBP), estimated from backward and forward trunk perturbations in the standard and ‘fluid’ conditions. * - p<0.05 for comparison between LBP and No LBP groups; # - p<0.05 for comparison between conditions for the LBP group. The main effect for direction was significant.](image)

Trunk stiffness was not significantly different between the groups (Main effect for F=1.37, p=0.252). Stiffness was less for perturbations applied in the ‘fluid’ condition than in the standard condition (Main effect - F=23.69, p<0.001). Stiffness was higher when perturbed backwards than when perturbed forwards (Main effect - F=4.51, p=0.043) (Figure 5-3).
Trunk displacement was greater when perturbed forwards than when perturbed backwards (Main effect - $F=14.69$, $p=0.001$) (Table 5-1). Trunk displacement was also greater in the ‘fluid’ condition than in the standard condition (Main effect - $F=18.46$, $p<0.001$). No significant difference between groups was identified for displacement (Main effect - $F=0.09$, $p=0.768$) or the estimated trunk mass (Main effect - $F = 0.00$, $p=0.977$). Estimated trunk mass was higher during the forwards than backwards perturbations (Main effect - $F=26.53$, $p<0.001$), and was higher during the standard condition than the ‘fluid’ condition (Main effect - $F=12.25$, $p=0.002$). Differences in estimated trunk mass are most likely explained by differences in the effective mass that was perturbed as a result of changes in trunk stiffness and damping properties.
Table 5-1 Estimated trunk mass and trunk displacement.

<table>
<thead>
<tr>
<th></th>
<th>Standard Condition</th>
<th>Fluid condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Forward</td>
<td>Backward</td>
</tr>
<tr>
<td></td>
<td>No LBP</td>
<td>LBP</td>
</tr>
<tr>
<td>Estimated mass (kg)</td>
<td>21.5(4.9)</td>
<td>22.3(6.9)</td>
</tr>
<tr>
<td>Displacement (cm)</td>
<td>3.1(0.8)</td>
<td>3.0(0.6)</td>
</tr>
<tr>
<td>Estimated mass (kg)</td>
<td>20.6(5.7)</td>
<td>21.0(6.6)</td>
</tr>
<tr>
<td>Displacement (cm)</td>
<td>3.4(0.7)</td>
<td>3.2 (0.5)</td>
</tr>
</tbody>
</table>

Data are reported as mean (SD) for dancers with a history of low back pain (LBP) and without a history of low back pain (No LBP) estimated from forward and backward trunk perturbations in the standard and ‘fluid’ conditions.

5.6 Discussion

The first aim of this study was to determine whether trunk damping and stiffness differ between dancers with and without a history of LBP. The secondary aim was to assess how trunk stiffness and damping change when motor imagery is used to evoke a ‘fluid’ movement response to the perturbation, and whether the ability to adapt differs between dancers with and without a history of LBP. We showed that dancers with a history of LBP had lower trunk damping in the standard condition, but were able to increase damping by using motor imagery to respond in a ‘fluid’ manner to attain values comparable to dancers without LBP, whereas dancers without LBP had similar values of damping in the standard and ‘fluid’ conditions.

5.6.1 Trunk damping, but not stiffness is modified in dancers with a history of LBP

Reduced damping in dancers with a history of LBP in the standard condition implies a compromised ability to attenuate velocity of trunk movement after a perturbation. This finding agrees with lower damping found in non-dancers with recurrent LBP (Hodges et al. 2009) and partially confirms our hypothesis. A well-damped system returns to equilibrium rapidly when perturbed, whereas a less damped system will oscillate for a longer duration. Damping smooths movements at higher frequencies and could augment quality of trunk movement. It is probable that
higher damping observed in pain-free individuals reflects more optimal motor control. It follows that lower damping in dancers with a history of LBP may be caused by compromised ability of the nervous system to respond to perturbation. This could be mediated by compromised sensory or motor function or both, which would affect mechanisms such as reflex control (Hodges and Tucker 2011).

The deep paraspinal muscles play an important role in the control of spine motion (Kaigle et al. 1995, Wilke et al. 1995) and may contribute to compromised damping (Reeves et al. 2011). From a sensory perspective, changes in muscle spindle function could contribute (Reeves et al. 2011) to altered trunk damping. These receptors respond to changes in length of muscles, such as that induced by changes in relative orientation of body parts/vertebra (Buxton and Peck 1989) and are normally found in high density in the deep paraspinal muscles including multifidus (Nitz and Peck 1986). From a motor perspective, the multifidus muscles play an important role in fine-tuned control of spine segments (MacDonald et al. 2006, Moseley et al. 2002). Further, proprioceptive acuity is enhanced by gentle to moderate (but not intense) muscle contraction (Taylor and McCloskey 1992). Changes in the ability of the multifidus muscles to provide sensory input or generate a motor response could have consequences for damping. LBP has been associated with impaired proprioception in non-dancers (Brumagne et al. 2000) and this is related to distorted input from the multifidus muscles (Brumagne et al. 2004). Multifidus muscle activity is reduced (Sihvonen et al. 1997) and delayed (MacDonald et al. 2010) in non-dancers, and CSA is reduced in dancers with LBP (Study I). Together, these changes could underpin less optimal damping in dancers with a history of LBP. Lower damping may also reflect change in passive structures as a result of injury or a combination of compromised function of both active and passive restraints to movement. Further research is required to clarify the relative contribution of these mechanisms.

In contrast to other studies (Freddolini et al. 2014, Hodges et al. 2009) and our hypothesis, trunk stiffness was not significantly higher in dancers with a history of LBP than dancers without LBP. Increased stiffness is thought to reflect the augmented activity of superficial trunk muscles (Brown and McGill 2009, Moorhouse and Granata 2005), which is commonly reported in association with LBP (Cholewicki and Van Vliet 2002, van Dieën et al. 2003) and may be a strategy to protect the spine from pain and injury (Hodges 2013, van Dieën et al. 2003). Support for this proposal comes from modelling studies, which have identified that contraction of superficial trunk muscles increases spinal stability (Cholewicki and Van Vliet 2002, van Dieën et al. 2003). Although commonly adopted in non-dancers, augmented activity of superficial trunk muscles may not be a useful strategy for dancers with LBP as the accompanying increase in trunk stiffness may be incongruent with their required function. For instance, increased stiffness may have a negative impact on quality of movement and hence performance. This is because increased stiffness could
reduce spine movement (Mok et al. 2007), increase spinal load (Marras et al. 2001), and compromise balance control as a result of reduced potential for the spine to contribute to balance reactions (Mok et al. 2011a, Reeves et al. 2006). The severity of pain and level of dysfunction may also influence the muscle strategy used by dancers with LBP. As the dancers with a history of LBP were on full workloads and reported low levels of disability, this may have limited our participant recruitment to dancers who had only minor adaptation.

Dancers without LBP had comparable values for damping in both the standard and ‘fluid’ motor imagery conditions and less stiffness during the ‘fluid’ condition. It is unclear why these dancers did not alter damping between the two different conditions. One interpretation is that damping was already optimal in this regard, in the standard condition, and further modification would have provided no additional benefit. Alternatively, the absence of significant effect may be secondary to the statistical issue of the small sample size of pain-free dancers (see Section 5.6.3).

5.6.2 Dancers with a history of LBP can use imagery to modify trunk mechanical properties

Although dancers with a history of LBP had less damping than pain-free dancers during the standard condition, when they were instructed to use motor imagery to evoke a ‘fluid’ response to the perturbation, they demonstrated the capacity to modulate the mechanical properties of their response by increasing trunk damping to values similar to dancers without LBP. This contrasts our hypothesis that dancers with a history of LBP would have reduced ability to adapt the mechanical properties of the trunk. This observation has two implications. First, this implies that dancers were either able to improve/tune the natural strategies that modulate damping (e.g. reflex control), or find a solution to compensate for the compromised control of this mechanical property (see below). Regardless of the underlying mechanism, dancers with a history of LBP were able to change the quality of the movement response to make it more ‘fluid’ in nature and more effectively absorb energy (the outcome of improved damping) with the benefit of ‘smoother’ movement. Second, this observation implies that dancers with a history of LBP have the potential to improve the quality of trunk control and it may be possible to draw on this potential for rehabilitation.

Although the exact neural mechanisms by which motor imagery changes performance are not fully established, there is evidence that mental rehearsal can increase (Hale et al. 2003) or decrease the amplitude of H-reflexes (the electrical equivalent of a spinal stretch reflex) and is associated with cortical activation that is similar to that when movements are actually produced (Jeannerod 2001). In professional ballet dancers, motor imagery has been observed to increase hamstring muscle activation (Couillandre et al. 2008) and peak external hip rotation (Coker Girón et al. 2012) resulting in more optimal dynamic alignment during a demi-plié and sauté (a dance specific movement sequence involving bilateral knee flexion followed by a jump). In addition to changing
muscle activation and kinematics with motor imagery, here we show that dancers with a history of LBP can also modify mechanical properties of the trunk. Whether other clinical groups can achieve similar benefit with motor imagery requires investigation.

5.6.3 Methodological considerations

There are several methodological issues that warrant discussion. Motion of the pelvis and lower limb was restricted in this paradigm and the study focussed on control of the trunk (movement between the pelvis and thorax). This enabled precise estimation of the mechanical properties of this region, without the confounder of variation in strategy of hip and pelvic control. Future work should build on this data with inclusion of the lower limbs. Trunk stiffness and damping were assumed to remain constant over time and the duration was standardised. This assumption is a simplification of actual trunk control, which changes over time, however simplification is necessary to enable the estimation of trunk parameters. The validity of our estimates is strengthened by the observation that linear values of stiffness and damping were able to model actual measured trunk movement. Models that explained less than 97% of the variance of the measured trunk displacement were excluded from further analysis. This study used a convenience sample of elite classical ballet dancers and the high prevalence of LBP in professional ballet dancers limited the available sample size of pain-free dancers. This limited the statistical power of that group.

5.7 Conclusion

Dancers with a history of LBP have reduced damping when the trunk is perturbed in a standard condition and this may impact on performance. The increase in damping with ‘fluid’ motor imagery demonstrates that dancers with a history of LBP can change this mechanical property and this could have implications for rehabilitation. However, whether there is potential to induce long-term improvement and whether this has benefit for management of LBP or improved performance requires further consideration.
Chapter 6  Balance strategies of professional ballet dancers with a history of low back pain are more similar to non-dancers than dancers without low back pain (Study IV)\(^4\)

6.1 Preamble

In the previous chapter postural control in response to trunk perturbation was investigated and showed reduced damping in dancers with LBP. This chapter investigates postural control of balance in standing, as outcome measures of balance inform about use of the motor control system. The background of this thesis described (see 2.6.2) differences in the nature of balance in dancers compared to non-dancers and other athletes. Differences have been observed using linear and non-linear measures of balance, though there is limited consensus. There is considerable evidence of change in postural control strategies associated with LBP in non-dancers. Yet, little is known about control of balance in professional classical ballet dancers with LBP. Many studies on balance control in dancers fail to consider history of LBP in dancers. Therefore as data from non-dancers cannot necessarily be extrapolated to the unique population of professional classical ballet dancers this chapter investigates balance in dancers with a history of LBP compared to dancers without LBP and non-dancers. The results provide novel insight into control of balance and have implications for rehabilitation of balance in dancers with a history of LBP.

6.2 Abstract

**Purpose:** Balance is critical in ballet. LBP is common in ballet dancers and although LBP compromises balance in non-dancers, its impact on dancers’ balance is unclear. Dancers are presumed to have superior balance ability to non-dancers, however available data are conflicting and this may be due to failure to consider history of in LBP dancers. The aim of this study was to compare balance ability between professional ballet dancers with and without LBP and non-dancers, when standing with feet parallel and in the dance-specific feet turned out ‘first’ position.

\(^4\) Adapted from Gildea JE, van den Hoorn, W, Hides, JA, Hodges, PW. Balance strategies of professional ballet dancers with a history of low back pain are more similar to non-dancers than dancers without low back pain. Submitted 2015.
**Methods:** Centre-of-pressure (CoP) trajectory in the anteroposterior and mediolateral directions was analyzed using linear and non-linear measures.

**Results:** Diffusion analysis of CoP trajectories demonstrated that dancers without LBP had greater movement away from an equilibrium position than non-dancers ($p<0.01$) and moved further before correction in the short-term component of balance control ($p<0.00$) and displayed greater movement towards an equilibrium position in the long-term component of balance control than non-dancers ($p<0.00$) (parallel feet, anteroposterior direction). This observation of greater motion was supported by some linear measures. Dancers with LBP demonstrated a similar strategy to non-dancers characterized by reduced critical point distance ($p<0.02$) and greater long-term diffusion rate ($p<0.01$).

**Conclusions:** These data showed that, to control balance, dancers without LBP used more movement whereas dancers with LBP used less movement, in a manner that is more similar to non-dancers than to their LBP-free counterparts. The results imply that least movement does not define optimal balance in dancers. Furthermore, impaired balance in dancers with a history of LBP may impact performance quality.

### 6.3 Introduction

LBP is one of the most prevalent health complaints in professional ballet dancers (Allen et al. 2012, Crookshanks 1999) and has been associated with changes in postural control in non-dancers (Mazaheri et al. 2013, Mientjes and Frank 1999, Mok et al. 2007, Ruhe et al. 2011a) and elite gymnasts (Harringe et al. 2008). To successfully achieve and maintain the complex positions required in classical ballet, it is considered that professional ballet dancers require better balance ability than non-dancers (Lin et al. 2014). Data are conflicting. Dancers perform better than non-dancers on some but not all measures of balance, and not in all studies (Ambegaonkar et al. 2013, Crotts et al. 1996, Schmit et al. 2005). These results may be explained by failure to consider the LBP history of professional dancers, which is likely to influence balance, and the measures used to characterize balance. Whether postural control differs between professional ballet dancers and non-dancers when LBP is considered, and whether balance differs between professional ballet dancers with and without a history of LBP requires investigation.

Movements/moments that maintain standing balance can be broadly categorized into ankle and hip strategies (Horak and Nashner 1986), although this categorization most likely underestimates contributions from the multiple trunk segments (Hodges et al. 2002). The ankle strategy restores equilibrium, particularly in quiet stance, during small perturbations and in the anteroposterior (AP) direction, by activation of ankle plantarflexor and dorsiflexor muscles (Horak and Nashner 1986) to generate ankle moments (Winter 1995). The hip strategy involves trunk and thigh muscle activation.
to maintain postural stability when ankle torque is insufficient, such as during fast and large perturbations and in the mediolateral (ML) direction (Horak and Nashner 1986, Winter 1995). LBP should have greater impact on the hip strategy, which relies on trunk motion/moments. In support of this premise, people with LBP have difficulty initiating and coordinating the hip strategy when balancing on a short base, which limits the use of an ankle strategy ankle (Mok et al. 2004).

Dancers have shown more reliance on the hip strategy for balance control (Golomer et al. 1999a, Simmons 2005b) possibly due to dance training (Golomer et al. 1999a). A fundamental element of classical ballet training is the adoption of turned out foot positions. ‘First’ position demands external rotation of the lower limbs such that the feet are angled at 180 degrees with the heels together (Negus et al. 2005). Turned out foot positions reduce the AP radius and increase the ML radius relative to conventional bipedal stance, potentially restricting the ankle strategy and enhancing the contribution of the hip and trunk to balance control (Day et al. 1990, Winter 1995). It is reasonable to speculate that balance in this trained dance-specific position would be sensitive to differences between non-dancers and dancers with and without a history of LBP.

Body movement is continuous, even in quiet standing (Day et al. 1990, Hodges et al. 2002). In standing, pain-free individuals use small lumbar movements to compensate for balance disturbances from respiration (Hodges et al. 2002). In contrast, lumbo-pelvic movement is reduced in people with LBP in quiet standing (Mok et al. 2004), and with expected (Mok et al. 2007, Mok et al. 2011b) and unexpected perturbations (Henry et al. 2006, Mok et al. 2011a). This reduced movement relates to compromised balance control (Mok et al. 2011a) supporting the proposal that movement aids optimal postural control.

Dancers are commonly reported to have superior postural control to non-dancers based on linear measures of the CoP), such as shorter path length (Perrin et al. 2002) and smaller area (Hugel et al. 1999, Perrin et al. 2002). There is also evidence that dancers may tolerate or use greater movement than non-dancers to enhance balance ability. When maintaining equilibrium on an unstable platform, dancers have greater total spectral energy (Golomer and Dupui 2000) and higher mean velocity (Pérez et al. 2014). More experienced dancers also have greater peak difference in AP motion of the CoP and centre-of-mass (CoM) in association with superior performance on a functional balance test than less skilled dancers (Lin et al. 2014). These findings suggest movement may play an important role in the balance strategy of dancers. A history of LBP could also affect movement strategies used by dancers and this has not been previously examined.

Although linear measures provide some insight into differences in balance strategy between dancers and non-dancers, non-linear measures may be more sensitive to difference in dance experience (Schmit et al. 2005) and history of LBP (van Dieën et al. 2010a). Non-linear measures can reflect changes in movement of the CoP over time to provide richer information about balance.
control. Although promising, present results are conflicting. Young dancers exhibit less regular CoP trajectories than non-dancers (Stins et al. 2009). Yet, others show no difference with eyes open, and more regular CoP motion with eyes closed in dancers than non-dancers (Pérez et al. 2014). Conflicting results may be explained by differences in measures, methods and inclusion criteria for participants, such as history of LBP.

The aim of this study was to compare balance control between professional ballet dancers with and without a history of LBP and pain-free non-dancers using linear and non-linear measures of CoP. Based on the critical role of the trunk in ML balance with the feet parallel and in the AP direction with the feet turned out we considered measures separately for each plane (AP and ML) and each foot position (parallel and turned out). The hypothesis was that dancers without a history of LBP would use greater motion than non-dancers, and that dancers with a history of LBP would have more constrained CoP motion in conditions that require greater trunk control (turned out foot position and ML direction).

6.4 Methods

6.4.1 Participants

Thirty-two professional, classical ballet dancers (11 male; 21 female, [range and mean (SD)], age 17-32, 24 (4) years, height 155-192, 172 (10) cm, weight 41-84, 59 (13) kg) who were on tour with The Australian Ballet volunteered to participate in this study. Fifteen pain-free, age-matched non-dancers were recruited from the local community by word of mouth and digital media (Table I). The professional ranks of the ballet dancers ranged from corps de ballet to principals and all dancers were on full workloads. Total dancing experience ranged from 7-28, 18 (5) years, of which dancing professionally was 1-13, 5 (3) years. Dancers who completed the International Physical Activity Questionnaire long form (IPAQ) (n=28) all scored in the high physical activity category (Craig et al. 2003). Non-dancers had no dancing experience and were involved in intense physical activity at least three times per week scoring in the high (n=8) and moderate (n=7) categories of the IPAQ. The participants’ comfortable maximally externally rotated leg position was established by an experienced physiotherapist for use in the turned out foot condition (Negus et al. 2005).

On the basis of interviews with the dancer and the dance company’s physiotherapists, dancers were categorized into either the LBP (n=23) or LBP-free (n=9) group. Dancers were included in the LBP group if they reported a history of pain (with or without current pain) in the low back/pelvic area that required treatment or modification of class, rehearsal or performance Twenty-three dancers reported a history of LBP (pain between the lower ribs and gluteal fold) more than 6 months ago and fourteen of these dancers reported current pain or pain within the preceding 6
months. Dancers were not excluded if they reported other musculoskeletal pain unless the pain required modification of class, rehearsal or performance. Only 4 dancers reported no pain at all and some dancers reported several areas of pain. Dancers reported pain in the thoracic region (n=2), pelvic/hip region (n=9), knee (n=4), ankle (n=9) and foot (n=5), which did not limit their performance. Dancers in the LBP group completed the Roland-Morris questionnaire (Stratford et al. 1996) and the Oswestry Disability Index, version 2.0. (Fairbank and Pynsent 2000) to establish self-reported disability and recorded their average LBP level, over the previous 6 months, on a 10-cm Visual Analogue Scale anchored with 0 ‘no pain’ and 10 ‘worse possible pain imaginable’ (Table I). There was no difference between groups with respect to age, height, weight and foot length (all, $p>0.1$), whereas the dancers’ groups were different to the non-dancer group for activity level and degrees of “functional turn out” (all, $p<0.01$, One-way ANOVA, Table 6-1).

Exclusion criteria for study participants was LBP of a non-musculoskeletal etiology, spinal trauma or surgery, or any condition (other than LBP or minor musculoskeletal pathology) that might interfere with balance such as: neurological or respiratory disorders, pregnancy in the preceding 2 years, an uncorrected visual defect or use of any substance or medication which could affect balance. No volunteers were excluded based on these criteria.

The Institutional Medical Research Ethics Committee approved the study. Participants gave informed consent and the study was undertaken in accordance with the Declaration of Helsinki.
Table 6-1 Demographic and pain characteristics of the participant groups.

<table>
<thead>
<tr>
<th></th>
<th>ND (n=15)</th>
<th>LBP-free D (n=9)</th>
<th>LBPD (n=23)</th>
<th>F value</th>
<th>P value</th>
<th>LBP-freeD -ND †</th>
<th>LBP-freeD -LBPD †</th>
<th>LBPD -ND †</th>
</tr>
</thead>
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<tr>
<td>Age (years)</td>
<td>25 ± 4</td>
<td>22 ± 3</td>
<td>24 ± 4</td>
<td>2.01</td>
<td>0.15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gender per group</td>
<td>10F,5M</td>
<td>4F,5M</td>
<td>17F,6M</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Height (cm)</td>
<td>170 ± 7</td>
<td>175 ± 12</td>
<td>170 ± 9</td>
<td>1.04</td>
<td>0.36</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>64 ± 12</td>
<td>62 ± 14</td>
<td>58 ± 12</td>
<td>1.13</td>
<td>0.33</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IPAQ</td>
<td>2.5 ± 0.5</td>
<td>3 ± 0</td>
<td>3 ± 0</td>
<td>13.11</td>
<td>0.000</td>
<td>0.001</td>
<td>1.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Foot Length (cm)</td>
<td>25 ± 2</td>
<td>25 ± 2</td>
<td>25 ± 2</td>
<td>0.20</td>
<td>0.82</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Degrees of turnout</td>
<td>116 ± 17</td>
<td>143 ± 9</td>
<td>136 ± 9</td>
<td>18.22</td>
<td>0.000</td>
<td>0.000</td>
<td>0.632</td>
<td>0.000</td>
</tr>
<tr>
<td>Years Prof dance</td>
<td>0</td>
<td>3 ± 2</td>
<td>6 ± 4</td>
<td>0.08‡</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Years Dance</td>
<td>0</td>
<td>15 ± 5</td>
<td>20 ± 5</td>
<td>0.08‡</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VAS LBP (0-10)</td>
<td>0</td>
<td>0</td>
<td>3 ± 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Years LBP</td>
<td>0</td>
<td>0</td>
<td>5 ± 4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Days LBP (prior 6months)</td>
<td>0</td>
<td>0</td>
<td>35 ± 54</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R-M score (0-24)</td>
<td>0</td>
<td>0</td>
<td>1 ± 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ODI (0-100%)</td>
<td>0</td>
<td>0</td>
<td>8 ± 9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*, One-way ANOVA; †, Post hoc Bonferroni; ‡, Independent t-test. Values are represented as mean ± standard deviation.

Abbreviations: F, female; IPAQ, International Physical Activity Questionnaire; LBP, low back pain; M, male; ODI, Oswestry Disability Index; Prof, professional; R-M, Roland-Morris; VAS, visual analogue scale
ND, non-dancers; LBPF, dancers without low back pain; LBPD, dancers with low back pain

6.4.2 Procedure

All procedures and instructions were standardized. To avoid distraction from external noises data were collected in a closed room and participants wore noise-reducing headphones emitting white noise. Participants stood barefoot, centered on a force platform (Kistler Type 9286A, Kistler
Instrumente AG Winterthur, CH), facing a blank wall (2 meters away), with their arms relaxed by
their sides. The instruction given to participants was to “maintain balance” for the trial duration.
They were not asked to stand as still as possible. Data recording of 70 s were started after the
participant stood comfortably for ~3 s. Force platform data were digitized with 16-bit precision at
300 samples/s with a Micro 1401 Data Acquisition system with Spike2 software (Cambridge
Electronic Design Ltd. Cambridge, UK).

Participants were tested under two balance conditions in random order. Condition 1: In the
parallel position participants placed their feet with the midpoint of the heels separated by a distance
equal to half their foot length and externally rotated up to a maximum of 15 degrees. Condition 2:
In the dance-specific turned out position, participants placed their feet in their comfortable
maximally externally rotated leg position. Participants rested for 30 seconds between trials.

6.4.3 Data analysis

Data from 15 non-dancers, 15 dancers with LBP and 7 dancers without LBP were included in
the final analysis, as data from 10 dancers (LBP group n=8, LBP-free group n=2) were excluded
from the analysis due to calibration issues. Data were analysed in Matlab (v.8.3, MathWorks,
Natick, MA, USA). Forceplate data were resampled at 100 sample/s and then filtered with a bi-
directional 2nd order Butterworth filter at 12.5 Hz (Stins et al. 2009). CoP positions in the AP and
ML axis were derived from the forceplate’s moments (Nm⁻¹) around the y-axis and x-axis,
respectively. CoP position data were detrended and expressed in millimeters.

CoP data were analyzed in both AP and ML directions separately with descriptive linear and
non-linear measures. The linear measures were; standard deviation (SD) (mm) of the CoP signal to
quantify the amount of variability of the postural sway; path length/s (mm²/s), to quantify the amount
of movement in any direction by summing all absolute distances between consecutive samples
divided by the total time, and normalized path length/s, the CoP signal was first normalized by
dividing the signal by it’s standard deviation (unit variance) which results in a scale-free signal. A
difference in normalized path length would result from changes in the structure of the CoP signal; a
longer normalized path length is related to a larger amount of twisting and turning (Donker et al.
2007, Roerdink et al. 2011). Root Mean Square (RMS) of the time differentiated CoP signal to
quantify the amount of velocity (mm²/s), and CoP area to quantify the area (mm²) of the ellipse that
incorporates 95% of all CoP data (Prieto et al. 1996).

Non-linear measures were extracted to assess the temporal structure of the CoP signal; short-
and long-term diffusion rate (mm²s⁻¹) and exponential (Exp) short- and long-term diffusion rate,
critical point in time (CP time) (s) and critical point in distance (CP distance) (mm²) and multiscale
sample entropy (MSE). Diffusion analysis was calculated to quantify the rate at which the CoP
diffuses (spreads) over time (Collins and De Luca 1993). Balance is lost when the CoP falls outside the area of the support surface; therefore diffusion of CoP cannot always happen at the same rate in the same direction. Because of the support surface area boundary, CoP sometimes diffuses exponentially (Power law; Exp>1) until a ‘correction’ is needed to avoid a fall at which diffusion rate is lower (Power law; Exp<1) also referred to ‘open-loop’ and ‘closed-loop’ control (Collins and De Luca 1993, Collins et al. 1995). Therefore, the diffusion-time graph generally has two distinct time regions (Figure 6-1). To calculate diffusion, the average square distance between each point separated in time from 0.01 to 10 s was determined and plotted against time (Collins and De Luca 1993; Collins, De Luca et al. 1995). Short-term diffusion rate was defined as the slope of the linear fit with a correlation greater than 0.995, and long-term diffusion rate was defined as the slope of the linear fit of the remainder of the diffusion plot (van Dieën et al. 2010b). To assess whether or not diffusion rate has a ‘corrective’ nature, the diffusion rate and time were log transformed and the slope (power law) of the linear fits were determined over the same short-term and long-term time regions. If the slope was >1 an increase in CoP displacement is usually followed by another increase, whereas if the slope was <1 an increase in CoP displacement is usually followed by a decrease, i.e. more ‘corrective’ in nature. In addition, the intersection of the linear fits over the short-term and long-term regions provide information about how long (CP time) and how far (CP distance) CoP diffused before the participants changed their nature of balance control (Collins and De Luca 1993; Collins, De Luca et al. 1995). To quantify the irregularity of the CoP signals over different time scales, MSE (Costa et al. 2002, Costa et al. 2005) was calculated over six time-scales. For more detailed information about this method see Costa et al. (2002, 2005). Sample entropy is related to the information content of the signal (Peng et al. 2009) with higher entropy values related to more generation of new information. Therefore, signals with lower sample entropy values are more predictable than signals with higher sample entropy values as less new information is generated. The calculation of sample entropy is sensitive to signal non-stationarities (Peng et al. 2009), the difference signal was therefore used for analysis. Sample Entropy is defined as the negative natural logarithm of an estimate of the conditional probability that a set of consecutive samples of length M that match point-wise within a tolerance r also match at the next point (Lake et al. 2002). Signals were normalized to unit variance and the template length M and the tolerance r were determined (Lake et al. 2002). In this investigation we used M=3 and r=0.15 at each time scale. MSE was then calculated as the sum over the 6 time-scales.
Figure 6-1 Example data of CoP in AP. Data of CoP in the anteroposterior direction (AP) and diffusion plots are presented for a LBP-free dancer (top graphs), a LBP dancer (middle graphs) and a non-dancer (bottom graphs). The short- and long-term diffusion rates (Dshort and Dlong, respectively) are presented for each participant together with the coordinates, determined by the intersection of the linear fits over the short- and long-term regions (black thin lines in the diffusion plots) of the critical point in distance (y-axis diffusion plots) and the critical point in time (x-axis diffusion plots).

6.4.4 Statistical Analysis

Statistical analyses were performed with Stata (v12, StataCorp LP, USA, TX). A repeated measures ANOVA was performed for each of the outcome variables to detect whether there were any differences between the groups and conditions for AP and ML directions. Group was entered as a between subjects factor (3 levels: LBP-free dancers, non-dancers and LBP dancers) and Condition (2 levels: feet parallel and turned out) was entered as a repeated within subjects factors. Data that did not pass the Shapiro-Wilk test for normality were log transformed. When main effect of group was significant, a pair-wise comparison with Bonferroni correction for multiple comparisons was used to detect differences between the groups. When the Group × Condition interaction was significant, post hoc analysis (with Bonferroni correction for multiple comparisons) was undertaken to test whether the groups were different at each foot position and to test whether the change in foot position affected the groups differently. The corrected p-values are reported. Significance was set at p<0.05.
6.5 Results

Results of the statistical analyses are presented in Table 6-2. Post hoc analyses are reported below and presented for the AP direction in Figure 6-2 and for the ML direction in Figure 6-3.

6.5.1 Balance in the AP direction with feet parallel

Differences in balance strategy used by dancers with and without LBP, and non-dancers were mainly observed in the AP direction in the parallel foot position from non-linear analysis. Measures extracted from diffusion analysis revealed that over the short-term region, LBP-free dancers moved further (CP distance) than dancers with LBP ($p=0.02$) and non-dancers ($p=0.00$) before correcting their direction of motion. There was no difference in CP distance between dancers with LBP and non-dancers ($p=1$). All groups reached the CP distance in a similar amount of time (all, $p>0.61$). The observation that LBP-free dancers moved further in a similar time suggests greater short-term diffusion rate. Although short-term diffusion rate did not differ between dancers with and without LBP ($p=0.13$), it was greater in both dancers’ groups than non-dancers ($p<0.01$). This finding was independent of foot position. Exponential short-term diffusion rate in AP was $>1$ for all groups and was not different between groups (all, $p=1$). This suggests the short-term region was persistent in nature, i.e. not corrective. The long-term region was characterized by anti-persistent behavior (corrective), as long-term exponential diffusion rate was $<1$ in all groups. Both the long-term exponential diffusion rate and long-term diffusion rate were lower in LBP-free dancers than dancers with LBP ($p=0.05$ and $p<0.01$, respectively) and non-dancers ($p=0.00$ and $p=0.00$, respectively). Long-term exponential diffusion rate and long-term diffusion rate were not different between dancers with LBP and non-dancers ($p=0.39$ and $p=1$, respectively). This implies greater control (more corrective) in LBP-free dancers than dancers with LBP and non-dancers, most likely because LBP-free dancers moved further over the short-term region, which requires greater control over the longer term to correct for further persistent movement in the short-term. Overall, the diffusion analysis showed that dancers with LBP displayed a similar balance strategy to the non-dancers. Analysis of the measure of irregularity of CoP fluctuations (MSE) considers a different aspect of the CoP motion and provided a different outcome. MSE differed between dancers and non-dancers ($p<0.01$), but not between dancers’ groups ($p=0.42$). This finding was independent of foot position. Findings from AP linear measures of SD, RMS velocity, path length, normalized path length and CoP area (AP and ML) did not show any significant differences between the groups with parallel feet (all, $p>0.10$).
Table 6-2 Main effect of the repeated measures ANOVA.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Anteroposterior direction</th>
<th>Mediolateral direction</th>
<th>Combined anteroposterior and mediolateral directions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Group</td>
<td>Condition</td>
<td>Group × Condition</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>P</td>
<td>F</td>
</tr>
<tr>
<td>CP distance</td>
<td>3.31</td>
<td>0.05</td>
<td>0.21</td>
</tr>
<tr>
<td>CP time*</td>
<td>0.33</td>
<td>0.72</td>
<td>78.13</td>
</tr>
<tr>
<td>Dshort rate*</td>
<td>8.35</td>
<td>0.001</td>
<td>113.27</td>
</tr>
<tr>
<td>Exp Dshort rate</td>
<td>0.27</td>
<td>0.77</td>
<td>72.24</td>
</tr>
<tr>
<td>Dlong rate</td>
<td>3.14</td>
<td>0.06</td>
<td>2.92</td>
</tr>
<tr>
<td>Exp Dlong rate</td>
<td>3.96</td>
<td>0.03</td>
<td>0.37</td>
</tr>
<tr>
<td>MSE</td>
<td>5.45</td>
<td>0.01</td>
<td>92.39</td>
</tr>
<tr>
<td>SD</td>
<td>2.99</td>
<td>0.06</td>
<td>1.66</td>
</tr>
<tr>
<td>RMS velocity</td>
<td>9.95</td>
<td>0.00</td>
<td>166.47</td>
</tr>
<tr>
<td>Path length</td>
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<td>0.00</td>
<td>160.10</td>
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<td>68.53</td>
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<tr>
<td>CP distance*</td>
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<td>0.20</td>
<td>52.68</td>
</tr>
<tr>
<td>CP time*</td>
<td>1.25</td>
<td>0.30</td>
<td>3.17</td>
</tr>
<tr>
<td>Dshort rate*</td>
<td>6.29</td>
<td>0.01</td>
<td>70.28</td>
</tr>
<tr>
<td>Exp Dshort rate</td>
<td>1.20</td>
<td>0.32</td>
<td>2.16</td>
</tr>
<tr>
<td>Dlong rate*</td>
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<td>0.86</td>
<td>0.76</td>
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<tr>
<td>Exp Dlong rate</td>
<td>0.82</td>
<td>0.45</td>
<td>2.89</td>
</tr>
<tr>
<td>MSE</td>
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<td>0.002</td>
<td>17.48</td>
</tr>
<tr>
<td>SD</td>
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<td>0.37</td>
<td>47.67</td>
</tr>
<tr>
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<td>0.01</td>
<td>99.50</td>
</tr>
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<td>Path length*</td>
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<td>0.03</td>
<td>95.60</td>
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<tr>
<td>Norm path length*</td>
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<td>0.74</td>
<td>0.31</td>
</tr>
<tr>
<td>CoP Area</td>
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<td>0.10</td>
<td>13.32</td>
</tr>
</tbody>
</table>

F ratios and corresponding P-values of main effects are reported for all outcome variables. Significant Group related effects are highlighted in bold. Post-hoc P-values are reported in the Results. Variables with * were log transformed.

Abbreviations: SD, standard deviation; RMS, root mean square; norm, normalized; CP, critical point in; Dshort, short-term diffusion; Exp Dshort, exponential short-term diffusion; Dlong, long-term diffusion; Exp Dlong, exponential long-term diffusion; MSE, multiscale sample entropy.
6.5.2 Balance in the AP direction with feet turned out and the change between foot positions

In contrast to the feet parallel, outcome measures from the diffusion analysis were more similar between the dancers’ groups with the feet turned out. However, CP distance did not differ between groups (all, $p=1$) in the turned out position. In LBP-free dancers the CP distance reduced ($p=0.05$) to a similar level as the other groups with the feet turned out compared to feet parallel, whereas CP distance was not affected by foot position in the other groups (both, $p>0.52$). CP time did not differ between dancers with and without LBP ($p=0.82$), but was later in non-dancers than LBP-free dancers ($p=0.03$). Dancers with LBP did not differ from non-dancers ($p=0.29$). Both dancers’ groups reduced CP time (both, $p<0.00$) in contrast to non-dancers ($p=0.64$) from feet parallel to turned out. Short-term diffusion rate was greater in both dancers’ groups than non-dancers ($p<0.01$), independent of foot position. All groups increased short-term diffusion rate from feet parallel to turned out positions ($p<0.01$). With feet turned out, the long-term diffusion rate, long-term exponential diffusion rate and short-term exponential diffusion rate were not different between groups (all, $p>0.20$). Similar to feet parallel, the short-term region was not corrective ($>1$ all groups) in nature and was higher with feet turned out than parallel (all, $p>0.01$). The long-term region was corrective ($<1$ all groups) in nature; non-dancers reduced the exponential long term diffusion rate from feet parallel to turned out ($p=0.05$), whereas dancers’ groups were not affected by foot position (both, $p>0.38$). CoP motion in the turned out position was more regular (lower MSE) in both dancers’ groups than non-dancers ($p<0.01$), and this measure was independent of foot position. CoP motion of all groups became more regular with feet turned out, than parallel ($p<0.01$). Linear AP measures of balance with feet turned out revealed that dancers without LBP moved faster (greater RMS velocity) than dancers with LBP ($p=0.05$), and both dancers’ groups moved faster than non-dancers ($p<0.01$). All groups increased RMS velocity from feet parallel to turned out (all, $p<0.00$). In addition, dancers with and without LBP had greater path length than non-dancers in the feet turned out position ($p<0.00$), but path length did not differ between dancers with and without LBP ($p=0.20$). Path length also increased from feet parallel to turned out (all, $p<0.00$). Other linear measures (SD AP, normalized path length and CoP area (AP and ML) did not differ between groups (all, $p>0.08$). SD was not affected by foot position in any group. In contrast, normalized path length was greater with feet turned out than parallel in all groups (all, $p<0.03$) and CoP area (AP and ML) was greater with feet turned out than parallel.
Balance outcome measures in the anteroposterior direction

Critical point distance  |  Short-term diffusion rate  |  Exp short-term diffusion rate

Critical point time  |  Long-term diffusion rate  |  Exp long-term diffusion rate

RMS velocity  |  Path length  |  Normalized path length

SD  |  Multiscale sample entropy  |  CoP area

Figure 6-2 Results of the balance outcome measures in the anteroposterior direction. Mean data for each outcome measure is represented for the LBP dancers (in red), LBP-free dancers (in green) and non-dancers (in blue) for the feet parallel and feet turned out conditions. Solid brackets without # represent significant group difference based on the post-hoc of the significant Group x Foot position interaction. Coloured * (red; LBP dancers, green, LBP-free dancers, blue; non-dancers) represent a significant effect of foot position based on the post-hoc of the significant Group x Foot position interaction for that respective group. Solid brackets with # represent a significant main effect of Group. Dashed horizontal line represents a significant main effect of Foot position. Significance was set at P<0.05. Error bars represent the standard error of the mean (SEM).
6.5.3  Balance in the ML direction with feet parallel

Diffusion analysis of balance in the ML direction with feet parallel revealed that neither CP distance nor CP time differed between groups (all, \( p>0.47 \)). However, short-term diffusion rate was higher in both dancers’ groups than non-dancers (both, \( p<0.03 \)), and not different between dancers’ groups (\( p=0.21 \)). This finding was independent of foot position. Exponential short-term diffusion rate, long-term diffusion rate and exponential long-term diffusion rate were not different between the groups and were not affected by foot position. As with AP balance with feet parallel, short- and long-term diffusion were not corrective and corrective in nature, respectively. LBP-free dancers were more regular (lower MSE) than dancers with LBP in the ML direction (\( p=0.05 \)). In addition, similar to the AP direction, both dancers’ groups were more regular (lower MSE) than non-dancers (both, \( p<0.02 \)) and this was independent of foot position. Linear measures in ML revealed that both dancers’ groups moved faster (RMS velocity) than the non-dancers (both, \( p<0.04 \)), but dancers’ groups did not differ (\( p=0.30 \)). LBP-free dancers had longer path length than non-dancers (\( p<0.01 \)), whereas dancers with LBP did not different from non-dancers (\( p=0.08 \)) and LBP-free dancers (\( p=0.48 \)). Path length findings were independent of foot position. SD in ML did not reveal differences between groups.

6.5.4  Balance in the ML direction with feet turned out and the change between foot positions

CP distance was higher with feet turned out than with parallel in all groups. CP time was not different between dancers’ groups and between LBP-free dancers and non-dancers (all, \( p>0.21 \)). Short-term diffusion rate was higher in both dancers’ groups than in the non-dancers’ group. All groups increased short-term diffusion rate from feet parallel to turned out. Dancers’ groups did not alter CP time with change in foot position, whereas non-dancers increased CP time with feet turned out from parallel (\( p=0.00 \)). As observed in AP, CoP motion in ML of all groups was more regular (lower MSE) with feet turned out than with parallel feet. All groups increased SD ML, RMS velocity and path length from feet parallel to turned out. Normalized path length was lower in non-dancers with feet turned out than parallel (\( p=0.03 \)). In contrast, normalized path length increased in dancers with LBP from feet parallel to turned out (\( p=0.04 \)), whereas LBP-free dancers did not alter with the change in foot position (\( p=1 \)).
Figure 6-3 Results of the balance outcome measures in mediolateral direction. Mean data for each outcome measure is represented for the LBP dancers (in red), LBP-free dancers (in green) and non-dancers (in blue) for the feet parallel and feet turned out conditions. Solid brackets without # represent significant group difference based on the post-hoc of the significant Group x Foot position interaction. Coloured * (red; LBP dancers, green, LBP-free dancers, blue; non-dancers) represent a significant effect of foot position based on the post-hoc of the significant Group x Foot position interaction for that respective group. Solid brackets with # represent a significant main effect of Group. Dashed horizontal line represents a significant main effect of Foot position. Significance was set at P<0.05. Error bars represent the standard error of the mean (SEM).
6.6 Discussion

This study aimed to determine whether standing balance characteristics differ between professional ballet dancers with and without a history of LBP, and between dancers and non-dancers, in standing with the feet parallel and in the dance-specific turned out ‘first’ position. Most differences between dancers with and without LBP were observed in the AP direction with the feet parallel. In this condition, dancers with a history of LBP were more similar to non-dancers than LBP-free dancers. LBP-free dancers used a ‘fall and recovery’ strategy for balance, and contrasted the other groups. With feet turned out, which is familiar to dancers but not to non-dancers, dancers with and without LBP were more similar to each other than to non-dancers. Though contrary to our prediction, little additional insight was gained from analysis of the ML direction. Non-linear measures were generally more informative than simple linear measures. Taken together, findings indicate that dancers with LBP move less, and from this perspective demonstrate balance characteristics that are more like non-dancers than their LBP-free counterparts. This challenges the simple assumption that greater CoP displacement implies poorer postural control, and suggests ‘less movement’ does not define optimal postural control in ballet dancers.

6.6.1 Balance characteristics in dancers without LBP compared with non-dancers

Diffusion analysis divides control of standing balance into two components; short- and long-term. Short-term control is characterized by movement away from any relative equilibrium point, whereas long-term control is characterized by movement towards an equilibrium point (Collins and De Luca 1993). Both short- and long-term components differed between LBP-free dancers and non-dancers with feet parallel (Figure 6-1). In the short-term component, LBP-free dancers moved further in a persistent manner (not-corrective) and then applied greater control (more corrective) in the long-term to maintain standing balance. Others researchers have proposed that greater short-term (not-corrective) movement constitutes poorer balance (Collins et al. 1995, Priplata et al. 2003). For example, compared with healthy young individuals, greater CP distance has been observed in elderly participants at higher risk of falls (Collins et al. 1995) and is proposed to result from age- or pathology-related sensory motor system changes (e.g. slower reflex times and diminished proprioception (Collins et al. 1995). This appears inconsistent with our data collected from professional ballet dancers who are considered balance experts with highly trained sensorimotor control (Golomer et al. 1999a, Golomer and Dupui 2000; faster response times (Simmons 2005a) and superior lower limb proprioception than non-dancers (Kiefer et al. 2013). Sensory information in standing comes from multiple sources; somatosensory, vestibular and visual systems (Massion 1992). Dancers are considered to use sensory information differently for balance control (Crotts et
al. 1996, Golomer and Dupui 2000, Simmons 2005b), including a shift in sensory weighting from visual to somatosensory information (Golomer and Dupui 2000, Simmons 2005b). Professional dancers are also thought to habituate to, or suppress vestibular input (Hopper et al. 2014, Teramoto et al. 1994). It is possible that the greater movement before active correction in LBP-free dancers is secondary to changes in sensory integration (e.g. suppression of vestibular reflexes), although how this might be mediated requires further investigation.

The observation that dancers increase use of the hip strategy for balance control (Golomer et al. 1997, Simmons 2005b) provides an alternative interpretation of greater movement before correction in LBP-free dancers. Our LBP-free dancers often moved to their limit of stability, also referred as ‘saturation point’ (Collins and De Luca 1993) early in the balance trial and then ‘diffused’ back from this limit. This was not observed in non-dancers or dancers with LBP. As the CoM approaches the limits of stability a shift in the strategy for balance control is required as corrections around the ankle are insufficient to maintain balance and corrections around the hip joint predominate (Horak and Nashner 1986, Simmons 2005b). It follows that LBP-free dancers may preferentially used the hip strategy to control balance as they move further and faster, and can rely on fast neuromuscular responses (and potentially more accurate proprioceptive information from the low back than dancers with LBP). Non-dancers appear to rely more on the ankle strategy, which dictates smaller, slower movements in standing balance. This interpretation provides a potential explanation for the similarities in diffusion measures between non-dancers and dancers with LBP. Dancers with LBP may rely more on the ankle strategy secondary to; impaired back proprioception, reduced spinal movement, or inability to initiate the hip strategy.

Long-term balance control in LBP-free dancers is characterized by greater corrective movements towards the equilibrium position (lower long-term diffusion rate) than non-dancers. Although low long-term diffusion rate is interpreted as more stable (Priplata et al. 2002) or tightly regulated (Collins et al. 1995) balance control, in the context of dancers it is likely to relate to a compensation for greater movement in the short-term component of balance control (Collins et al. 1995) as this requires increased control in the long-term to maintain balance. As non-dancers (and dancers with LBP) had less short-term movement (lower CP distance) the subsequent long-term control can be less tightly regulated. LBP-free dancers also demonstrated more anti-persistent (more corrective; lower exponential long-term diffusion rate) balance than non-dancers. This finding requires careful interpretation as there was limited linear fit in the long-term region of the log-time vs. log-diffusion relationship. Nevertheless, a low long-term diffusion rate indicates that LBP-free dancers rely on their ability to return to equilibrium and not fall. That is, they have ‘confidence’ in a good control system to maintain balance. In general, diffusion analysis suggested LBP-free dancers used a ‘fall and recovery’ balance strategy.
Linear measures of balance also implied that LBP-free dancers moved faster and further than non-dancers. Faster RMS velocity observed in dancers concurs with other observations of higher mean velocity of dancers than non-dancers (Pérez et al. 2014). In contrast, our finding of greater path length in LBP-free dancers contrasts with observations of no difference (Hugel et al. 1999) or reduced (Perrin et al. 2002) path length between dancers and non-dancers. Difference in experimental conditions (e.g. parallel feet and gaze fixation) may explain the differences.

6.6.2 Comparison of balance characteristics in dancers with and without LBP

Both linear and non-linear measures differed between dancers with and without LBP. Diffusion analysis revealed that dancers with LBP did not move as far (less CP distance) in the short-term component of balance with less corrective behavior (increased long-term and exponential long-term diffusion rate) in the long-term component of balance. Overall speed of movement (AP RMS velocity) was less in dancers with LBP with feet turned out. In the ML direction dancers with LBP were less regular (higher values of MSE). Reduced movement in the short-term component of balance might be explained by compromised lower back somatosensory information in dancers with LBP. Reduced weighting of back proprioceptive input and altered CoP motion have been reported in non-dancers with LBP (Brumagne et al. 2004). Non-dancers with LBP demonstrated increased dependence on visual input (Mientjes and Frank 1999, Mok et al. 2004) and ankle proprioception (Brumagne et al. 2000), again consistent with decreased utility of lower back somatosensory information. Although not tested for dancers, these data highlight the potential for altered somatosensory information from the lower back in dancers with LBP and thus greater dependence on ankle somatosensory information. Alternatively, differences may be explained by reduced capacity to use the back muscles for balance. Although not specifically tested here, dancers with LBP have smaller spinal muscles (Study I) and reduced trunk damping (Study III). Reduced ability to use back muscles may compel dancers with LBP to use the ankle strategy rather than the hip strategy which demands trunk moments. As the ankle strategy most effectively restores equilibrium from slow, small perturbations this may in turn, force dancers with LBP to reduce movement speed/distance to prevent loss of balance.

As anticipated, movement of dancers with LBP was more constrained (reduced RMS velocity) with feet turned out than parallel. Although some authors report increased CoP velocity in LBP (Mazaheri et al. 2013, Ruhe et al. 2011a), like our data, others confirm slower CoP motion (Mazaheri et al. 2013, Mok et al. 2004). In conjunction with lower CoP velocity, Mok et al. (2004) also reported less AP shear force when people with LBP balanced standing on a short base; which implies less contribution of the hip strategy in standing. Standing with feet turned out presents a similar challenge to standing on a short base of support; both reduce the contribution of ankle
moments to balance and emphasize the contribution of the hip and spinal regions in the AP direction (Horak and Nashner 1986, Mok et al. 2004). Lower AP RMS velocity of dancers with LBP implies lesser hip/spine contribution in dancers with LBP. Potential reduction of hip strategy in dancers with LBP did not affect balance differently to LBP-free dancers in the ML direction. This suggests either minor adaptations around the hip region or that the greater radius of support in ML relative to AP might reduce the need for control in the ML direction.

6.6.3 Regularity of balance control in dancers with and without LBP and non-dancers

The observation that CoP trajectory of dancers (without and with LBP) was more regular (lower MSE) than non-dancers, irrespective of foot position and direction contrasts the general interpretation of complexity. Reduced regularity or complexity of biological signals (e.g. neonatal heart rates) is related to less healthy systems (Pincus and Goldberger 1994). In this line of thinking, lower sample entropy values calculated from CoP motion (i.e., more regular sway fluctuations) have been related to decreased effectiveness of postural control in stroke (Roerdink et al. 2006), cerebral palsy (Donker et al. 2008) and dancers with eyes closed (Stins et al. 2009). Conversely, less regular sway fluctuations are associated with healthy balance systems (Roerdink et al. 2006). Regularity of CoP motion is also positively related to the attention given to balance control (Donker et al. 2007). Dancers are trained to cognitively attend to balance and, greater cognitive involvement might be required by LBP-free dancers, than non-dancers and dancers with LBP (significant in the ML direction), to execute the balance strategy characterized in the AP direction, by moving faster (increased RMS velocity and short-term diffusion rate) and further (increased sway path and CP distance) with increased correction to equilibrium in the long-term (lower long-term diffusion rate).

Our data concurs with the observation that undergraduate dancers are more regular than non-dancers, though only with eyes closed (Pérez et al. 2014), but contrasts data that show less regularity of young pre-professional dancers (11-14 years) than non-dancers (Stins et al. 2009). Differences in dance populations might explain the contrasting findings; postural control of dancers changes with maturation (Golomer et al. 1997) and expertise (Golomer et al. 1999b, Lin et al. 2014). The relationship between regularity and performance is also unclear as Perez et al. (2014) reported superior eyes-open balance performance with linear measures without difference in regularity in dancers versus non-dancers. Reduced regularity in elderly participants has been interpreted as less sustainable and disordered balance (Borg and Laxaback 2010). Those authors highlighted the paradox in interpretation of CoP measures of standing in that ‘chaotic’ movement may be interpreted as poor postural control or as a characteristic of a successful strategy to maintain equilibrium (Borg and Laxaback 2010). The present findings suggest interpretation of sample entropy measures is difficult in expert dancers and warrants further investigation.
6.6.4 Balance characteristics in parallel versus turned out position

Comparison of balance outcome measures between the parallel and turned out positions showed that dancers with and without LBP performed similarly in the dance-specific turned out position, and both differed from non-dancers. For example, although all groups increased CoP speed (increased RMS velocity) and moved more (increased path length) with more twists and turns (increased normalized path length) in the turned out position in the AP direction, non-dancers had less increase in speed and path length than both dancers’ groups. Increased movement in the dancers’ groups could be a reflection of familiarity with this position. Foot position affects the position of the CoM relative to the limits of stability and necessitates altered control strategies (Day et al. 1990, Henry et al. 2001, Winter 1995). The base of support is reduced by as much as two-thirds in the AP direction and increased up to twofold in the ML direction when the feet are turned out. Reduced support length in AP when turned out could account for the increased speed and path length in all groups. Poorer control in non-dancers with turned out feet is consistent with the greater use of the hip strategy and the likelihood that due to unfamiliarity, non-dancers are less effective at using a hip strategy in this position than dancers (Golomer et al. 1997, Simmons 2005b).

6.6.5 Balance characteristics in AP versus ML directions

In contrast to our hypothesis that balance in dancers with LBP would be more constrained in the ML direction, most differences between dancers with and without LBP were in the AP direction. Other authors have also reported difference in postural motion in people with chronic LBP compared healthy individuals in the AP direction (della Volpe, Popa et al. 2006; Ruhe, Fejer et al. 2011) but not the ML direction (della Volpe et al. 2006). The lack of difference in the ML direction may be explained by the foot positions used in the current investigation. The distance between the parallel feet was half a foot length (i.e. greater ML base of support than standing with the feet together) and stability in the ML direction greater with feet turned out. As greater stance width reduces body movement by increased leg-pelvic stiffness and greater support (Day et al. 1990, Henry et al. 2001) demands for trunk control in the ML direction, may have been sufficiently reduced to minimize difference between dancers with and without LBP.

6.6.6 Methodological Considerations

Some methodological issues warrant consideration. Elite classical ballet dancers incur a large number of injuries (6.8 injuries/dancer/year(Allen et al. 2012) which limited the available sample size of LBP-free dancers. Dancers were on full workloads and had no pain affecting training or performance, but several dancers indicated minor pain other than LBP. Although these issues might
influence CoP motion, to exclude these dancers would have excluded most from this LBP-free group. Balance studies of dancers generally state that dancers were “healthy” (Golomer and Dupui 2000, Golomer et al. 1999b), had “no acute articular accidents” (Hugel et al. 1999) or do not mention musculoskeletal pain or injury (Pérez et al. 2014, Stins et al. 2009). Thus, comparison of results is difficult as it is highly likely that dancers with at least a history of LBP will have been included in these studies. Limited sample size makes it impossible to consider effects of severity and duration of pain and disability. As difference in postural control characteristics have been found between people with current versus recent history of LBP (van Dieën et al. 2010a), future investigation should consider ways to increase sample size (e.g. multi-centre trials).

It is difficult to compare population specific tasks between highly trained and untrained participants, for instance, the difference in maximal turn-out between dancers and non-dancers may have impacted the results. Although we predicted greater difference may be observed in turned out standing, difference in postural control between LBP-free dancers, non-dancers and dancers with LBP was observed in standing with parallel feet, which was familiar to all participants. Although participants are often instructed to “stand as still as possible” we simply asked them to “maintain balance” for the duration of the trial. We argue this gives a better reflection of natural balance than the instruction to stand still, which has the potential to modify balance strategy (Borg and Laxaback 2010).

6.7 Conclusion

This study shows differential standing balance strategies when professional classical ballet dancers are grouped for no history of LBP and history of LBP and compared with non-dancers. Dancers without LBP used a balance strategy characterized by greater movement and speed than non-dancers. Dancers with LBP were more similar to non-dancers. The findings challenge the assumption that greater CoP motion indicates poorer postural control. Optimal postural control in ballet dancers appears to be defined by movement. LBP appears to interfere with this solution and involves smaller and slower movement. This new interpretation has important implications for assessment and rehabilitation of balance ability in dancers with LBP.
Picture 7 The Australian Ballet Bayadere Artists rehearse.
Chapter 7  Discussion and Conclusions

7.1  Main Findings of this thesis

The ability to precisely execute movements and adapt quality of movement to meet demands is a fundamental skill required by classical ballet dancers. Underlying this specialised movement are the basic necessities of dynamic stability and maintenance of functions like respiration and continence. Complex motor control strategies are critical for optimal coordination of muscle activity for the provision of dynamic trunk stability during posture and movement. Although many changes in motor control have been associated with LBP in non-dancers, until now little has been reported regarding motor control in ballet dancers and the impact of LBP. The overall objective of this thesis was to advance the understanding of the motor control of professional classical ballet dancers with and without LBP. To address this objective, studies in this thesis investigated several aspects of motor control in dancers and dancers with LBP and when possible comparison was made with non-dancers. These studies included morphology and behaviour of trunk muscles (Study I and II), dynamic properties of the trunk in response to perturbation (Study III) and standing balance (Study IV). Each of these studies revealed differences in motor control between dancers with and without LBP, and in the case of balance difference between dancers and non-dancers. Although there are limitations in the study designs related to the unique nature of this population, the findings from these studies have implications that may be relevant for strategies to prevent the development of LBP in dancers and strategies to treat LBP in dancers. The results of these studies also provide direction for future research.

7.1.1  Findings related to trunk muscle morphology and behaviour

Examining the morphology and behaviour of trunk muscles provides an indirect method of investigating motor control. Study I aimed to investigate the size and symmetry of multifidus, lumbar erector spinae, quadratus lumborum and psoas muscles by measuring their CSAs from MR images of dancers with and without LBP. Study II aimed to evaluate the resting and contracted thickness of the transversus abdominis and obliquus internus abdominis muscles as well as the lateral slide of the anterior extent of the transversus abdominis muscles (transversus abdominis slide) and reduction in total CSA of the trunk in the same dancers. The anatomical CSA of trunk muscles is closely related to torque produced by those muscles (e.g. combined area of multifidus and erector spinae muscles correlates with muscle strength in trunk extension torque (Raty et al.
In a similar manner but at the other end of the spectrum, less increase in transversus abdominis muscle thickness with contraction has been observed in people with LBP using real-time ultrasound imaging (Ferreira et al. 2004) and reduced ability to decrease the CSA of the trunk and slide the anterior abdominal fascia in athletes with LBP using MRI (Hides et al. 2008a). These parameters have been argued to primarily reflect activation of the transversus abdominis muscle and are consistent with EMG findings (Ferreira et al. 2004, Hodges et al. 2003c, Hodges and Richardson 1998). Study I and II are the first investigations to consider muscle morphology and behaviour using MRI in dancers and they provide several interesting findings.

First, the CSAs of multifidus muscles in dancers with LBP were reduced bilaterally at lumbar levels 3-5. Dancers with combined hip region pain and LBP also had reduced multifidus muscle area bilaterally at the L3 vertebral level and unilaterally at the L4 vertebral level (right side) compared with dancers without a history of LBP. These findings are consistent with studies of non-dancers and athletes, that demonstrate reduction in the size of multifidus in association with acute (Hides et al. 1994), subacute (Hides et al. 1996) and chronic LBP (Barker et al. 2004, Beneck and Kulig 2012, Danneels et al. 2000, Hides et al. 2008a), in non-dancers and athletes. Second, in our study, smaller muscle size was not affected by the side of pain. This contrasts with studies which have shown reduced multifidus muscle CSA only on the side of acute first episode LBP (Barker et al. 2004, Hides et al. 1994), but is consistent with other studies which show bilateral/symmetrical reduction of CSA in active non-dancers with chronic, unilateral back pain (Beneck and Kulig 2012). The dancers in this study were undertaking full workloads and none had acute, severe LBP. All dancers with LBP had a history of LBP or current LBP which was not limiting their ability to perform or rehearse.

It is not possible to imply causality from the present work as it is not known if the reduction in multifidus muscle CSA preceded or followed the onset of LBP in the dancers. Other researchers have found reduced multifidus muscle CSA in acute pain localised to a single level (Hides et al. 1994), whereas in chronic pain the decrease in muscle CSA can be more widespread (Danneels et al. 2000). The values for CSA of multifidus in pain-free dancers are larger than those reported in studies of non-dancers (Hides et al. 2008b, Hides et al. 1995, Lee et al. 2006, Stokes et al. 2005), thus it follows that smaller CSA may reflect a failure of hypertrophy (rather than frank atrophy) in dancers with LBP and this might be a contributing factor to the onset of LBP. However, the muscle atrophy could also be a consequence of injury. Injury to the L3-4 intervertebral disc in a porcine model induced atrophy of the multifidus ipsilateral to the lesion with the greatest loss of CSA adjacent to the L4 spinous process immediately caudal to the injured disc (Hodges et al. 2006). An alternative explanation of the reduced multifidus muscle CSA in dancers with LBP or hip and lumbar region pain is secondary to an inhibitory response to injury or LBP. Reflex inhibition, which
is the reduction of alpha motor neuron excitability due to afferent discharge from joint structures (Stokes and Young 1984) has been proposed by several authors as a potential mechanism for the multifidus muscle atrophy demonstrated in LBP (Hides et al. 1996, Hodges et al. 2006, Hodges 2013). Reduced neural drive and subsequent reduced muscle CSA are consistent with the decreased activation of the multifidus muscles (particularly the deep fibres) recorded by EMG in people with LBP (MacDonald et al. 2009, MacDonald et al. 2010). It is important to note that these changes in the multifidus muscles might contribute to altered dynamic properties of the spine e.g. the reduced damping observed in dancers with LBP (Study III). Other possible consequences of reduced CSA of the multifidus muscles include reduced ability to precisely control the orientation of spinal segments (Moseley et al. 2002) and reduced spinal robustness i.e. the capacity to change stiffness to maintain stable behaviour for both small and large perturbations (Hodges 2013, Reeves et al. 2007). Each of these possible outcomes associated with reduced CSA of the multifidus muscles has the potential to make the spine vulnerable to re-injury and thus might contribute to the high incidence of chronic LBP in dancers (Crookshanks 1999, Jacobs et al. 2012).

The results from Study II, which investigated the morphology and behaviour of the abdominal muscles, provide preliminary evidence of a reduced ability to contract and a trend for reduced lateral slide of the anterior extent of transversus abdominis muscle with contraction in dancers with LBP. Although the statistical power of this study requires consideration (due to the small number of dancers without LBP history) these changes are consistent with those found in other populations with LBP (Ferreira et al. 2004, Hides et al. 2008a) and add support to the hypothesis that LBP in dancers is associated with deficits in motor control of the trunk muscles. An interesting finding was increased thickness of the transversus abdominis and obliquus internus abdominis and increased CSA of the multifidus muscle (Study I) on the right side compared to the left side, which was unrelated to LBP. This contrasts with findings of symmetric measures in asymptomatic non-dancers (Marras et al. 2001, Springer et al. 2006), although minor asymmetry has been observed (Rankin et al. 2006). The CSA of the multifidus muscle is also relatively symmetrical in non-dancers (Hides et al. 2006a, Hides et al. 1992, Hides et al. 1994, Stokes et al. 2005) including elite rowers (McGregor et al. 2002) but larger on the side of the dominant hand in elite cricketers and other athletes (Ranson et al. 2008). In non-dancers morphology of the abdominal muscle is not affected by hand dominance (Springer et al. 2006). However, elite cricketers have thicker obliquus internus abdominis muscles on the non-dominant side (but symmetrical transversus abdominis muscles) and this is proposed to be related to the asymmetrical nature of the sport i.e. throwing, bowling and batting actions which involve trunk rotation towards the non-dominant side (Hides et al. 2008a). The majority of dancers in Study I/II nominated right hand and leg dominance and a preferred for turning to the right (pirouette en dehors or châiné), which is consistent with findings in other studies
on dancers (Kimmerle and Wilson 2007). Rotation of the thorax to the right relative to the pelvis is a primary action of the right obliquus internus abdominis and transversus abdominis muscles (Urquhart et al. 2005). It is possible that despite the emphasis on symmetrical appearance and proficiency of movement in dance (Kimmerle 2010), a bias towards the right hand side in dance teaching and practice (Farrar-Baker and Wilmerding 2006) may underlie the right-left side difference found in dancers. Asymmetry of transversus abdominis and multifidus muscles may also have implications for spinal stability. In animal studies it has been demonstrated that the mechanical effect of transversus abdominis for control of intervertebral motion is greater with bilateral than unilateral contraction of the transversus abdominis muscles (Hodges et al. 2003a). It follows that asymmetrical contraction of transversus abdominis muscles may produce asymmetrical force and be less effective in modulating intervertebral motion and stiffness. Therefore asymmetry of these deep trunk muscles has potential to be a factor in the predisposition of dancers to development of LBP.

In contrast to the smaller size of multifidus muscles and changed behaviour of the transversus abdominis muscle, the other trunk muscles examined in Studies I and II (erector spinae, obliquus internus abdominis, quadratus lumborum, and psoas) were not different between dancers without LBP and those with LBP. Results from other studies have also shown no change in CSA of the erector spinae muscles in people with chronic LBP (Danneels, Vanderstraeten et al. 2000; Beneck and Kulig 2012). Although augmented EMG activity of superficial muscles like the paraspinal erector spinae and obliquus internus abdominis muscles has been reported frequently in association with LBP, many different strategies are observed (van Dieën, Selen et al. 2003; Hodges, Coppieters et al. 2013). If increased activation of the erector spinae or obliquus internus abdominis muscles is associated with LBP in dancers, large individual variation in the pattern of increased muscle activation may explain why it was not was not reflected by a systematic increase in muscle size in the group averaged data. The finding that size of the quadratus lumborum and obliquus internus abdominis muscle were not related to LBP in dancers contrasts with the asymmetry of quadratus lumborum (Engstrom et al. 2007, Hides et al. 2008a) and obliquus internus abdominis (Hides et al. 2008a) found in elite cricketers with LBP. The finding from Study I that CSA of the psoas muscle was not reduced in dancers with pain is consistent with the some studies on non-dancers with LBP (Danneels et al. 2000) but contrasts with other studies which have shown reduced psoas CSA with chronic LBP (Parkkola et al. 1993) especially in conjunction with leg pain (Barker et al. 2004, Dangaria and Naesh 1998). Although group analysis may mask changes in specific individuals or subgroups, these data imply that quadratus lumborum and psoas muscles are normally symmetrical in dancers and not modified in the presence of LBP or hip and lumbar region pain.
7.1.2 Findings related to the mechanical properties of the trunk

Evaluation of the mechanical behaviour of the trunk in response to small perturbations provides an indirect measure of the outcome of motor control. Study III aimed to estimate the dynamic properties of stiffness, damping, mass (inertia) and displacement in dancers with and without LBP and the changes in these properties when dancers were asked to respond with a different movement quality. As motor imagery is a technique commonly used during dance training for improving qualitative and quantitative aspects of movement performance (Ryder et al. 2010) it was used to provoke a change in movement quality from a standard condition to a contrasting ‘fluid’ condition. Previous research has demonstrated that participants with recurrent LBP have reduced damping and increased stiffness in response to trunk perturbations (Hodges et al. 2009). Study III showed that dancers with LBP had lower values for damping than dancers without a history of LBP in the standard condition. When asked to respond in a fluid manner, dancers with LBP increased damping to attain values comparable to LBP-free dancers, whereas LBP-free dancers had similar damping in both conditions. These findings are consistent with previous studies which demonstrate reduced damping in people with LBP compared to healthy individuals (Hodges et al. 2009). Changes in reflex muscle activation are thought to be a major contributor to modified damping (Hodges 2013, Moorhouse and Granata 2007) and this element of motor control might explain differences in damping between dancers with and without LBP.

A well-damped system returns to equilibrium rapidly when perturbed and it is probable that higher damping observed in LBP-free dancers in the standard condition reflects more optimal motor control. Reduced damping in dancers with a history of LBP implies impaired ability to control velocity of trunk oscillations after a perturbation so that the system takes longer to return to equilibrium (Hodges et al. 2009) and this may impact on ‘smoothness’ of movement. This impaired motor control could be mediated by compromised sensory or motor function, which would affect mechanisms such as reflex control (Hodges and Tucker 2011). Multifidus muscles have an important role in control of spine motion (Kaigle et al. 1995, Wilke et al. 1995) and a potential role in compromised damping from a sensory and/or motor perspective (Reeves et al. 2011). From a sensory perspective, changes in muscle spindle function could contribute to altered trunk damping (Reeves et al. 2011). Velocity feedback is thought to be controlled primarily via muscle spindles (Buxton and Peck 1989) which are found in high density in deep paraspinal muscles like multifidus (Nitz and Peck 1986). From a motor perspective, the multifidus muscles contribute to fine-tuned control of spine segments (Kaigle et al. 1995, MacDonald et al. 2006, Moseley et al. 2002). Gentle muscle contraction is also known to enhance proprioceptive acuity (Taylor and McCloskey 1992). LBP has been associated with impaired proprioception (Brumagne et al. 2000) and this is related to
distorted input from the multifidus muscles (Brumagne et al. 2004). Reduced (Sihvonen et al. 1997) and delayed (MacDonald et al. 2010) multifidus muscle activity is present in non-dancers with LBP and Study I demonstrated reduced CSA of these muscles in dancers with LBP. Taken together it is reasonable to speculate that these changes in sensory and motor function of multifidus muscles might underpin the less optimal damping in dancers with a history of LBP. Alternatively, lower damping may reflect change in passive structures as a result of injury or a combination of impaired passive and active restraints to movement. Further research is required to clarify the relative contribution of these mechanisms.

In contrast to previous studies, trunk stiffness was not greater in dancers with a history of LBP (Freddolini et al. 2014, Hodges et al. 2009). Increased stiffness is thought to reflect augmented activity of superficial trunk muscles (Brown and McGill 2009, Moorhouse and Granata 2005) which is frequently observed in association with LBP (Cholewicki and Van Vliet 2002, van Dieën et al. 2003) and may be a strategy to increase spinal stability (Cholewicki and Van Vliet 2002, van Dieën et al. 2003) to protect the spine from pain and injury (Hodges 2013, van Dieën et al. 2003). Although activity of superficial trunk muscles is commonly augmented in non-dancers with LBP this may not be a feasible strategy for dancers with LBP as the accompanying increase in trunk stiffness may have a negative impact on quality of movement; a critical element of dance. This is because increased stiffness could reduce spine movement (Mok et al. 2007), increase spine load (Marras et al. 2001) and compromise balance control as a result of reduced potential for the spine to contribute to balance reactions (Mok et al. 2011a, Reeves et al. 2006). This latter aspect was investigated further in Study IV and is discussed in Section 7.1.3.

Two important implications arise from the finding that dancers with a history of LBP had the capacity to increase trunk damping to values similar to dancers without LBP when instructed to use motor imagery to evoke a ‘fluid’ response. First, this observation implies that dancers with LBP were either able to improve/tune the strategies that modulate damping (e.g. reflex control) or find a solution to compensate for the compromised control of this mechanical property. Although the neural mechanisms by which motor imagery changes performance are not fully established, there is evidence of change in amplitude of H-reflexes (the electrical equivalent of a spinal stretch reflex) (Hale et al. 2003) and cortical activation (Jeannerod 2001). Professional ballet dancers have the capacity to increase hamstring muscle activation (Couillandre et al. 2008) and peak external hip rotation (Coker Girón et al. 2012) by use of imagery. Regardless of the underlying mechanism, dancers with a history of LBP were able to change the quality of the trunk response to make it more ‘fluid’ in nature and more effectively absorb energy (the outcome of improved damping) with the benefit of ‘smoother’ movement. Second, this flexibility of strategy in dancers with LBP indicates it should be possible to draw on this potential for rehabilitation.
7.1.3 Findings related to balance control of the trunk

Information about the motor control strategies used to maintain postural equilibrium is gained by investigation of control of balance. Study IV aimed to investigate characteristics of CoP motion in non-dancers, and dancers with and without a history of LBP during standing, in parallel and turned out foot positions. Linear measures and non-linear balance outcome measures were used. In classical ballet, training focuses on balance control from a young age and dancers are considered to have expert balance ability (Ambegaonkar et al. 2013, Hüfner et al. 2011). Although several studies have investigated balance in dancers there is little consensus regarding this ‘superior’ ability using linear and non-linear of measures CoP motion (Golomer and Dupui 2000, Pérez et al. 2014, Perrin et al. 2002, Schmit et al. 2005, Simmons 2005b, Stins et al. 2009). Few studies on balance control in dancers consider LBP history and the inadvertent inclusion of dancers with LBP in previous studies may be one reason for conflicting data. A spectrum of change in balance control associated with LBP has been reported. One systematic review concluded that people with LBP have greater postural instability than pain-free people demonstrated by increased CoP excursion, AP displacement and CoP mean velocity (Ruhe et al. 2011a). Whereas, another contradicted this conclusion noting that although the majority of studies report increased CoP motion in people with LBP several good quality studies show no effect of LBP or decreased postural motion (Mazaheri et al. 2013). These conflicting data question the underlying assumption of most balance research (in dancers and non-dancers) that more Cop displacement equates with poorer postural control (Perrin et al. 2002, Ruhe et al. 2011a).

The results of Study IV showed that balance control of LBP-free dancers differed from that of non-dancers, but dancers with LBP were similar to non-dancers in many regards. The control strategy adopted by LBP-free dancers could be described as one characterized by ‘fall and recovery’. Non-linear outcome measures extracted from diffusion analysis showed that in the short-term component of balance control, dancers without LBP moved further away from the equilibrium (greater critical point distance) (parallel feet, AP direction) and showed greater probability of moving away from an equilibrium point (greater short-term diffusion rate) than non-dancers (irrespective of foot position and movement direction). Conversely, balance control in the long-term component of LBP-free dancers was characterized by increased corrective movements back towards the equilibrium position (lower long-term diffusion rate) and more anti-persistent (more corrective) (lower exponential long-term diffusion rate) compared to non-dancers. These long-term characteristics are likely to be a compensatory effect for the increased movement away from the equilibrium in the short-term component of balance control (Collins et al. 1995). Other studies have compared balance control in healthy young individuals with elderly individuals and demonstrated
greater critical point distance and greater short-term diffusion rate in ‘at risk elderly’ participants (Collins et al. 1995) and ‘elderly fallers’ (Laughton et al. 2003) combined with greater tendency to return to equilibrium in long-term balance in elderly participants (Collins et al. 1995, Priplata et al. 2002). The balance characteristics of these elderly participants with poorer balance control is proposed to be linked changes in the sensory motor system relating to age or pathology (e.g. slower reflex response times and diminished proprioception) (Collins et al. 1995). The proposal that strategy equates to poor balance is at odds with the observation that this strategy is adopted by young, professional dancers without LBP. The interpretation of ‘superior’ and ‘poor’ balance control is not straight forward.

Ballet dancers perform better on balance tests than non-dancers (Ambegaonkar et al. 2013, Crotts et al. 1996) and are reported to have faster and more consistent postural muscle responses (Simmons 2005a), superior sensorimotor control (Golomer et al. 1999a, Golomer and Dupui 2000), and more accurate lower limb proprioception (Kiefer et al. 2013). Dancers without LBP also demonstrated a pattern of reaching ‘saturation point’ (i.e. the limit of maximum distance or limit of support (Collins and De Luca 1993) early in the time series and then ‘diffused’ back from this point. This pattern was not observed in non-dancers. These findings from non-linear measures were supported by the linear measures of balance, which also implied that dancers without LBP moved faster (greater RMS velocity) and further (increased sway path) than non-dancers. Faster RMS velocity observed in dancers concurs with data from other studies (Pérez et al. 2014). Overall, these data challenge the assumption that greater displacement equates with poorer postural control and suggest that ‘least movement’ does not define optimal balance in ballet dancers without LBP.

One mechanism that could explain the differences in balance characteristics between LBP-free dancers and non-dancers is the adaptation of the motor control system in response to intensive and lengthy dance training. An example of this adaptation is the evidence that professional dancers habituate to, or suppress vestibular input (Hopper et al. 2014, Hüfner et al. 2011, Teramoto et al. 1994). It is possible that the greater movement before active correction in dancers without LBP is secondary to changes in sensory integration (e.g. suppression of vestibular reflexes). An alternative interpretation of greater movement before correction in LBP-free dancers is that LBP-free dancers may increase use of the hip strategy for balance control (Golomer et al. 1997, Simmons 2005b). As the CoM approaches the limits of stability a shift in the strategy for balance is required as corrections for slow, small oscillations around the ankle are not sufficient to maintain balance and corrections around the hip joint predominate (Horak and Nashner 1986, Simmons 2005b). It follows that LBP-free dancers may preferentially use the hip strategy to control balance, as they move further and faster and can potentially rely on fast neuromuscular responses and more accurate proprioceptive information from the lumbo-pelvic region.
Non-dancers appear to rely more on an ankle strategy, which dictates smaller, slower movements in standing balance. This interpretation also provides a potential explanation for the similarities in balance strategies between non-dancers and dancers with LBP. Dancers with LBP may rely more on ankle strategies secondary to impaired back proprioception, reduced spinal movement, and/or inability to initiate the hip strategy. This concurs with our observations and is consistent with the findings of Study III. As the hip strategy demands moments at the trunk in comparison to the ankle strategy which demands moments around the ankle; the evidence from Study III of altered trunk dynamics in dancers with a history of LBP suggests that tasks that involve the hip strategy (e.g. standing balance) may be compromised in this group.

Non-linear and linear measures differed between dancers with and without LBP. Diffusion analysis revealed that dancers with LBP did not move as far (less critical point distance) in the short-term component of balance with less corrective behavior (increased long-term and exponential long-term diffusion rate) in the long-term component of balance (feet parallel, AP direction). Reduced movement in the short-term component of balance might be explained by compromised low back somatosensory information in dancers with LBP. Reduced weighting of back proprioceptive input (Brumagne et al. 2004) and increased dependence on ankle proprioception (Brumagne et al. 2000) with concurrent altered CoP motion have been reported in non-dancers with LBP (Brumagne et al. 2004). These data highlight potential for altered somatosensory information from the back region in dancers with LBP and greater dependence on ankle somatosensory information. Alternatively, differences may be explained by reduced capacity to use back muscles for balance. Results from Study I imply that dancers with LBP have smaller multifidus muscles and Study III showed that dancers with LBP have reduced trunk damping. Impaired ability to use the back muscles may compel dancers with LBP to reduce movement speed/distance to prevent loss of balance.

The findings from the diffusion analysis were supported by linear measures, which demonstrated speed of movement (AP RMS velocity) was less in dancers with LBP with turned out feet. This supports the hypothesis that dancers with LBP would be more constrained with turned out feet as a result of greater requirement for trunk movement for balance in this foot position. Others studies also showed slower CoP motion in people with LBP (Mok et al. 2004, Salavati et al. 2009) although, contrasting increase in CoP velocity has also been reported (Mazaheri et al. 2013, Ruhe et al. 2011a). In conjunction with lower CoP velocity, less AP shear force (i.e. less hip strategy) was reported when people with LBP stood on a short base (Mok et al. 2004). Standing with feet turned out presents a similar challenge to standing on a short base of support; both reduce the contribution of ankle moments to balance and emphasize the contribution of the hip and spine regions in the AP direction (Horak and Nashner 1986, Mok et al. 2004). It follows that in the dance-specific turned
out position slower AP RMS velocity of dancers with LBP again implies lesser hip/spine contribution in dancers with LBP. In summary, the findings from both the diffusion analysis and linear measures of balance suggest that control of balance in dancers with LBP is impaired. Compared with dancers without LBP, the balance strategy used by dancers with LBP is characterized by reduced movement and slower movement. This new knowledge has important implications for assessment and rehabilitation of dancers with LBP.

Comparison of balance outcome measures between the ‘daily life’ parallel foot position and the dance-specific turned out foot position showed that in general dancers with and without LBP performed similarly in the trained turned out position and both dancers’ groups differed from non-dancers. For example, although all groups increased CoP speed (increased RMS velocity) and moved further (increased path length) in the turned out position (AP direction), non-dancers had less increase in speed and path length than dancers’ groups. Increased movement in the dancers’ groups is likely to be a reflection of familiarity with this position. Other studies also observe that dancers demonstrate superior postural control in dance-specific conditions (Hugel et al. 1999). These results suggest that balance control adapts in response to training (see Section 2.6.1). In contrast, unlike the present data study, Hugel et al. (1999) did not find difference between dancers and non-dancers in a ‘daily life’ position using linear measures of balance control. In Study IV the differences in postural control in the parallel foot position, between dancers with and without LBP and non-dancers also support the general motor ability hypothesis which predicts that any skill should remain observable under various conditions (Adams 1987).

The findings from Study IV that dancers (with and without LBP) had more regular (lower multiscale sample entropy) CoP trajectories than non-dancers (irrespective of foot position and direction) concurs with the finding that undergraduate dancers are more regular than non-dancers, though only with eyes closed, (Pérez et al. 2014), but contrasts data that show less regularity of young pre-professional dancers (11-14 years) than non-dancers (Stins et al. 2009). Differences in maturation (Golomer et al. 1997) and expertise (Golomer et al. 1999b, Lin et al. 2014) of dance populations might explain the contrasting results. In general, lower sample entropy values have been related to decreased effectiveness of balance control (Donker et al. 2008, Roerdink et al. 2006, Stins et al. 2009) and high sample entropy is associated with healthy balance systems (Roerdink et al. 2006). In contrast, high entropy (less regularity) in elderly participants has been interpreted to suggest less sustainable and disordered balance (Borg and Laxaback 2010). These conflicting observations highlight the paradox in interpretation of CoP measures in that ‘chaotic’ movement may be interpreted as poor postural control or as a characteristic of a successful strategy to maintain equilibrium (Borg and Laxaback 2010). Although our results showed difference in regularity between dancers with and without LBP and non-dancers and this potentially reflects differential
balance control; which is supported by the other non-linear and linear measures, interpretation of regularity of CoP motion in dancers is complex and warrants further investigation.

7.2 Limitations

Limitations for each specific experiment have been examined in the discussion of each study. Some issues that relate to the population of classical ballet dancers regarding sample size, and LBP subgrouping require further consideration.

7.2.1 Participant sample size

There are several limitations inherent in unique populations such as the professional dancers used in this series of studies. First, the elite and specialized nature of classical dance dictates a sample of convenience, which limits sample size and statistical power. For example, in Study II, the failure of reduced lateral slide of the anterior extent of transversus abdominis with contraction in dancers with LBP to reach significance is probably explained by the small number of pain free dancers available for comparison. Second, the prolonged and rigorous training involved in professional dance also make it difficult to find an appropriate comparison non-dancer group. For example, in Study IV, dancers scored in the high physical activity category on the International Physical Activity Questionnaire (Craig, Marshall et al. 2003) whereas many non-dancers scored in the moderate category despite recruitment aimed at selecting participants involved in intensive exercise at least 3 times per week. Third, some aspects of the experimental design were limited by work as a professional dancer. For example; the study methods were limited to non-invasive techniques to prevent any impact on the dancers’ performance (all professional dancers were on full workload). The timing of studies was also limited by the rehearsal and performance schedules. Despite these limitations there was sufficient statistical power to demonstrate difference between groups in the majority of analyses.

7.2.2 Classification of dancers with LBP into subgroups

Another limitation in this thesis was the difficulty to subgroup the heterogeneous group of dancers with LBP into smaller more homogeneous LBP groups. Classification of LBP into subgroups potentially facilitates meaningful comparison of findings with other studies and relevant extrapolation of findings to the clinical environment. Dancers were only classified as no-LBP/LBP-free if they had no history of LBP. There is considerable evidence of changes in motor control
persist despite remission from LBP (Hodges and Richardson 1996, Radebold et al. 2000). Exclusion of any LBP from the control group meant this group was relatively small.

Classification of dancers with LBP or a history of LBP into smaller subgroups was more difficult. The dancers who volunteered for these studies were on tour with a professional ballet company and consequently were on full performance loads. Dancers with acute or severe LBP, which affected their ability to dance, would not have been eligible to tour. Dancers with LBP or a history of LBP completed detailed injury questionnaires. In order to gauge the severity and duration of pain, these dancers reported their pain on a 10-cm Visual Analogue Scale and scored their pain during activities of daily living on the Roland-Morris (Stratford et al. 1996) and the Oswestry Disability Index (Fairbank and Pynsent 2000) disability questionnaires. In addition, the presentation of dancers who reported pain in the region of the lower back, buttock, groin or lateral pelvis was discussed with the physiotherapy team who provided ongoing care for the dancers. This was undertaken to determine if, based on comprehensive physical assessment, the source of pain was considered to be explained by the low back alone or also structures other than the low back (i.e. the hip or pelvis). This information resulted in the grouping of dancers into those with LBP or pain in the low back and hip region. This grouping was used in Studies I and II. The two pain groups were combined in Study III as dancers were semi-seated with the pelvis fixed so the influence of hip muscles was limited. The two pain groups were also combined in Study IV as preliminary analysis showed no difference in results between the two groups. The detailed information provided about the nature of LBP in this group of dancers should facilitate meaningful comparison of results with other studies.

7.3 Implications for research and clinical practice

The current thesis provides novel insight into the motor control strategies used by classical ballet dancers through a series of behavioural experiments. These findings have implications for understanding of motor control of the trunk muscles for movement and posture in healthy dancers and those with LBP. This understanding can be used to inform future development of strategies to prevent and manage LBP in classical ballet dancers.

7.3.1 Implications for motor control of the trunk (Studies I-IV)

From a broad perspective, the findings of altered motor control in dancers with LBP (demonstrated by changed muscle morphology, dynamic properties of the trunk, and balance control) have implications for prevention of LBP and other injuries. Prospective studies have demonstrated that healthy athletes with delayed muscle reflex response when the trunk is perturbed are at risk of sustaining a low back injury (Cholewicki et al. 2005) and healthy female athletes with
impaired proprioception (Zazulak et al. 2007b) or increased trunk displacement after sudden force release (Zazulak et al. 2007a) are at higher risk of developing a knee injury. These authors argue that there is a relationship between less optimal motor control of the trunk with similar deficits to those frequently reported in association with LBP (Radebold, Cholewicki et al. 2000; Cholewicki, Greene et al. 2002) and injury to the back or lower limbs. The methods used in this thesis to measure trunk muscle morphology, estimate trunk dynamic properties and analyse balance control could be utilised in prospective research to investigate the relationship between motor control and injury in dancers with the potential to identify dancers at risk of injury.

The findings also have specific implications for robustness of spinal control in dancers. Reduced size of the multifidus muscle and reduced damping suggest less optimal function of multifidus muscles in dancers with LBP. The preliminary evidence of reduced contraction thickness and trend for decreased lateral slide of the anterior extent of transversus abdominis muscles in dancers with LBP suggest that function of these muscles is also compromised. As there is consensus in the literature that these muscles contribute significantly to spinal robustness (Hodges 2013) it follows that deficits in function may contribute to injury of spinal structures or recurrent injury and LBP. In addition, as prospective studies on elite footballers have shown smaller multifidus size is predictive of lower limb injury (Hides and Stanton 2014) and associated with increased risk of hip/groin/thigh injury (Hides et al. 2011b) it is conceivable that compromised function of these muscles might predispose to injury elsewhere in the kinetic chain.

One way that the findings from this thesis might be directly implemented into clinical practice relates to use of assessment of the morphology of the trunk muscles as a screening tool. Physical screening is widely practiced in university and professional dance environments for risk management with the goal of preventing injury (Liederbach 1997; Siev-Ner, Barak et al. 1997; Solomon 1997; Gamboa, Roberts et al. 2008). As LBP in dancers often begins in adolescence (McMeeken et al. 2002, Purnell et al. 2003) prevention strategies may need to be implemented in dance schools. Although broad-based screening has been criticized for limited predictive value it does help individuals develop a personal musculoskeletal profile (Gamboa et al. 2008) and specific measurements can have prognostic importance (e.g. the relationship between small multifidus size and lower limb injury (Hides and Stanton 2014). The methodology used in this thesis for assessment of muscle morphology (i.e. MRI), provides ‘gold standard’ images and therefore is superior for research. Unfortunately, MRI is expensive, difficult to access, has a number of contraindications, and requires operational assistance from expert technicians. In contrast, real-time ultrasound imaging is inexpensive, highly portable and relatively user-friendly. Use of ultrasound imaging is ideal for the clinical environment as measurements of the deep trunk muscles (including CSA, change in thickness and slide of the anterior extent of transversus abdominis) by ultrasound
imaging correlate well to those made by MRI and also relate to EMG activity at low contraction intensities (Ferreira et al. 2004, Hides et al. 2006b, Hides et al. 1995, Hodges et al. 2003c). This suggests that ultrasound imaging could be used to measure muscle morphology in dancers in a clinical situation as a screening tool. Studies conducted on elite footballers suggests that CSA of the multifidus muscle reduces over the playing season (Hides and Stanton 2012) and that this may relate to incidence of injury (Hides et al. 2012). It follows that it may be useful to measure muscle morphology longitudinally in dancers at several key time points. Appropriate time points for a classical ballet company could be; on entry to the company to establish baseline values, prior to and after long rehearsal periods and holidays and before and after performance of a specific repertoire.

Measurement of the morphology and behaviour of trunk muscles can be used in the assessment and management of dancers with low back or lumbo-pelvic injury. Although there were small numbers of dancers, the values for muscle morphology found in LBP-free dancers provide normative data for comparison. It has been observed that recovery of multifidus muscle size is not automatic after acute low back injury (Hides et al. 1996) and it follows that targeting of these muscles could be beneficial for prevention of recurrence or the development of chronic LBP. Measurement of muscle morphology has been used extensively in the clinical setting to assess the extent of muscle atrophy and gauge the effectiveness of rehabilitation (Ferreira et al. 2010). An extension of this concept is use of real-time ultrasound imaging as a feedback tool to aid in the restoration of muscle activation and CSA in athletes with LBP (Hides et al. 2008b) or hypertrophy muscles during a training program (Hides et al. 2012). Real-time ultrasound imaging could provide a valuable tool to assist with restoring muscle size and retraining muscle behaviour as part of the rehabilitation of dancers with LBP. The findings from the studies in this thesis identified that the deep trunk muscles were the most likely to be affected by LBP in dancers. There is substantial evidence that training programs which target the transversus abdominis and multifidus muscles in people with LBP are successful in improving muscle function (Hides et al. 2009, Tsao et al. 2010a, Tsao and Hodges 2008, Unsgaard-Tøndel et al. 2012) and increasing muscle size (Danneels et al. 2001, Hides et al. 2008b). There is also evidence that exercise programs which target these muscles are associated with reduction of symptoms of LBP such as pain and disability (Ferreira et al. 2010, O'Sullivan et al. 1997, Unsgaard-Tøndel et al. 2012, Vasseljen and Fladmark 2010). Furthermore, in a sporting population (elite footballers) an intervention program focussed on the deep trunk muscles was associated with; increased multifidus CSA; improved transversus abdominis function; fewer games missed due to injury (Hides et al. 2012), and reduced risk of severe lower limb injury (Hides and Stanton 2014). Implementation of motor control intervention programs to restore deep trunk muscle function in dancers with LBP or to prevent injury in ‘at risk’ dancers would need to be
accompanied by ongoing research to assess the effectiveness of these strategies in this specific and unique population.

7.3.2 Implications for balance control of the trunk

The changes in quantitative and qualitative characteristics of balance control in dancers with LBP in Study IV have implications for rehabilitation of this group. Dancers with a history of LBP used a similar balance strategy to non-dancers which was characterised by less CoP motion. It follows that balance re-training encouraging use of movement should be included in the rehabilitation program for dancers recovering from low back injury. In addition, assessment of balance control could be utilized during rehabilitation to gauge readiness to return to training and performance. Setting up a force platform system for analysis of CoP trajectory may not be feasible in the clinical environment, and therefore, adaption of a relatively inexpensive video gaming system such as the Nintendo Wii might be possible to retrain aspects of balance control in dancers (Clark et al., Deutsch et al. 2008).

7.4 Future Research

As there is limited existing research investigating motor control in dancers, there is huge scope for future research. Several key areas for future investigations have been highlighted by the findings presented in this thesis and are outlined in this section.

Variations of the method of sudden perturbation have been used widely in non-dancer populations including people with LBP to study components of motor control including intrinsic, reflexive and voluntary muscles responses (Bazrgari et al. 2011). In this thesis, a single perturbation paradigm was used to assess a single aspect of motor control (i.e. trunk mechanical properties). Additional insight could be added to understanding of motor control and spinal stability in dancers by investigation of the response to perturbations such as sudden load release (Cholewicki et al. 2005), support surface translations (Henry et al. 1998, Mok and Hodges 2013) and limb movements (Hodges and Richardson 1997a). Although the invasive nature of fine-wire EMG makes it difficult to apply in a very active population, there is potential for its use during non-performance periods. Fine-wire EMG is particularly suited to examine the response of deep muscles like the multifidus and transversus abdominis which have shown change on MRI in this thesis. The use of surface EMG to record from the more superficial trunk muscles such as obliquus internus abdominis and erector spinae may also clarify the role of these muscles in trunk stability in dancers. Control of other trunk muscles e.g. the pelvic floor and diaphragm is also known to be important for maintenance of spinal stability (Hodges et al. 2001b, Hodges et al. 2007). Both of these muscle groups are likely to be placed under high loads in ballet. Increased voluntary respiration (Grimstone
and Hodges 2003) and urinary incontinence (Smith et al. 2007) in non-dancers with LBP has been related to compromised postural control. There is evidence of a relatively high prevalence of urinary incontinence in dancers (Pozo-Municio 2007, Thyssen et al. 2002). This could be related to jumping which places high demand on the pelvic floor muscles (Thyssen et al. 2002). Classical ballet involves frequent periods of intense physical activity (Koutedakis and Jamurtas 2004) with concurrently high respiratory demand and spinal loading. These data suggest that investigation of the contribution of the pelvic floor and respiration to spinal stability in dancers would be an important area for future research.

This thesis documents changes in motor control that are associated with LBP in dancers rather than investigating causation of LBP or predicting the risk for development of LBP. Consequently it was not possible to establish if the reduced multifidus muscle CSA observed in dancers with LBP was the result of atrophy due to muscle wasting or failure of these muscles to hypertrophy. Repeated measurement of muscle morphology over time has demonstrated predictive value in footballers (Hides and Stanton 2014) and could be used in conjunction with other readily accessible information such as injury surveillance to potentially clarify the nature of the association between reduced multifidus size and LBP in dancers.

The investigation of postural control in dancers with and without LBP raises many questions. Several particular aspects of postural control warrant further research. The findings of Study IV highlight the importance of movement (rather than movement restriction) as an integral component of balance strategy in LBP-free dancers. Collection of kinematic data with movement analysis in combination with force plate data would help quantify the precise motions of the trunk, spine, pelvis and lower limbs used for balance (Grimstone and Hodges 2003, Mok et al. 2007). Kinematic data in conjunction with EMG (Hodges et al. 1997) could be used to explore the potential relationship between reduced multifidus CSA (Study 1), reduced damping (Study III) and the reduced movement observed in balance in dancers with LBP (Study IV). Findings from this thesis imply that the balance strategy used by LBP-free dancers is the hip strategy whereas dancers with LBP preferentially use the ankle strategy. It would be informative to confirm or refute this proposition. Non-dancers with LBP have shown reduced ability to control the hip strategy on a short base (Mok et al. 2004). Investigation of balance using a similar paradigm may confirm the balance strategy favoured by dancers with and without LBP. As the interpretation of regularity of CoP motion was difficult in this dancer population further investigation of this measure with the inclusion of a cognitive task may provide more insight (Mazaheri et al. 2010, Stins et al. 2009). Findings from Study IV implied that the balance strategy used by dancers with LBP could be due to altered proprioceptive information from the trunk. Non-dancers with LBP have been reported to have compromised proprioception of the trunk (Gill and Callaghan 1998) or altered sensory
weighting (Brumagne et al. 2004). Several authors have proposed a shift from vision towards the somatosensory system in dancers (Golomer and Dupui 2000, Simmons 2005b). Together these observations suggest that investigation of the relative role of the sensory systems in dancers and dancers with LBP may reveal important information about the balance strategy used by dancers with LBP.

7.5 Conclusions

The studies described in this thesis have provided insight into the motor control of classical ballet dancers and dancers with LBP. Each of the studies showed evidence of deficits in motor control in dancers with LBP. Each finding has potential to impact on movement quality, despite the fact that dancers were performing full workloads. In summary, the findings in dancers with LBP of smaller multifidus CSA; changed contraction of transversus abdominis; reduced trunk damping; and a balance strategy characterised by less movement, provide novel evidence of factors that may underlie the high prevalence of chronic LBP in this population. The results also reveal the potential to address these motor control changes in the rehabilitation of dancers with LBP. Furthermore, improved understanding of these aspects of motor control may aid in the development and refinement of clinical intervention strategies to prevent LBP in ballet dancers.
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THE UNIVERSITY OF QUEENSLAND
Institutional Approval Form For Experiments On Humans Including Behavioural Research

Chief Investigator:  Mrs Jan Gildea
Project Title:  The Activation Pattern Of Trunk And Pelvic Muscles During Loading through the Foot In Dancers And Non-Dancers With And Without Low Back Pain
Supervisor:  Dr Julie Hides, Professor Paul Hodges
Co-Investigator(s):  Dr Julie Hides, Professor Paul Hodges
Department(s):  School of Health and Rehabilitation Sciences, Division of Physiotherapy
Project Number:  2007000935
Granting Agency/Degree:  Australian Ballet School
Duration:  31st December 2010
Comments:

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

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

Date:  1 Mar 13
Signature:
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Classical ballet dancers are a unique combination of athlete and artist who perform complex movement patterns requiring both muscle strength and control. Ballet places particularly high demands on the trunk due to the requirement for extreme range of motion and tolerance of high compressive forces. A possible sequela of these spinal loads may be low back pain (LBP), which is consistently reported to be one of the most prevalent chronic injuries in professional ballet dancers. In nondancers, LBP is associated with musculoskeletal changes, including alteration in muscle size, symmetry, and fat content. These changes include reduced cross-sectional area (CSA) of the multifidus in patients with acute, subacute, and chronic LBP. Two investigations found that people with unilateral LBP had a smaller multifidus on the side and at the spinal level of pain. These changes were associated with longer symptom duration. Another study found that people with unilateral LBP had decreased CSA of the multifidus bilaterally and symmetrically. By contrast, when the CSA of the erector spinae has been differentiated from the multifidus, changes in CSA have not been demonstrated in active people with chronic LBP.

Changes in other muscles have been identified. The CSA of the psoas muscle has been shown to be reduced bilaterally in people with chronic LBP, and this decrease in CSA has been associated with increased symptom duration on the painful side in individuals with unilateral LBP. In cricketers with LBP, when compared with pain-free cricketers, the CSAs of the psoas muscles and the number of years of professional dancing have been found to be smaller compared with pain-free cricketers, the CSA of the psoas muscle has been differentiated from the multifidus, changes in CSA have not been demonstrated in active people with chronic LBP.

Methods: Magnetic resonance imaging was performed in 14 male and 17 female dancers. The CSAs of 4 muscles (multifidus, lumbar erector spinae, psoas, and quadratus lumborum) were measured and compared among 3 groups of dancers: those without LBP or hip pain (n = 8), those with LBP only (n = 13), and those with both hip-region pain and LBP (n = 10).

Results: Dancers with no pain had larger multifidus muscles compared to those with LBP at L3-5 (P < .024) and those with both hip-region pain and LBP at L3 and L4 on the right side (P < .027). Multifidus CSA was larger on the left side at L4 and L5 in dancers with hip-region pain and LBP compared to those with LBP only (P < .033). Changes in CSA were not related to the side of pain (all, P > .05). The CSAs of the other muscles did not differ between groups. The psoas (P < .0001) and quadratus lumborum (P < .01) muscles were larger in male dancers compared to female dancers. There was a positive correlation between the size of the psoas muscles and the number of years of professional dancing (P = .03).


Key Words: dance, lumbar, MRI, muscle cross-sectional area
CSA of the quadratus lumborum muscle is smaller unilaterally\textsuperscript{26} and is proposed to be related to defects of the pars interarticularis.\textsuperscript{12} Despite the prevalence of LBP in professional dancers, changes in the CSA of the trunk muscles (eg, multifidus, lumbar erector spinae, psoas, and quadratus lumborum) have not been investigated in this group.

A key objective in ballet is the maintenance of asymmetrical body structure, with the ability to perform tasks equally on either lower extremity.\textsuperscript{26} There is evidence that healthy, nonathletic individuals have no significant right-to-left-side difference in the CSA of the multifidus, erector spinae, or psoas between sides.\textsuperscript{26} In contrast, muscle CSA differs between sides in individuals involved in sports that are predominantly asymmetrical. For instance, the lumbar erector spinae and multifidus muscles were shown to be larger on the dominant side in cricket fast bowlers.\textsuperscript{16,42} The quadratus lumborum muscle has been shown to hypertrophy on the side of the bowling arm in fast bowlers.\textsuperscript{12,16,42} The quadratus lumborum is also larger on the side of the preferred stance limb in elite Australian Football League players, whereas the CSA of the psoas muscle has been shown to be larger on the preferred kicking leg.\textsuperscript{15} Due to the asymmetrical intention of ballet, it would be predicted that trunk muscles should be asymmetrical in this group.

In addition to reduced muscle CSA, signs of muscle degeneration include increased proportions of fat and connective tissue.\textsuperscript{28,46} Several studies have found an increased CSA of fat in the multifidus\textsuperscript{26,30,37,40} (but not in the psoas\textsuperscript{40} or the erector spinae muscles\textsuperscript{37}) to be associated with chronic LBP. However, this observation is not universal, and other authors have not found increased fat in the multifidus muscles of participants with chronic LBP compared to pain-free participants matched for age and activity level.\textsuperscript{41} Age appears to be an important factor, as there is a higher incidence of fat deposits with increasing age\textsuperscript{31} and a strong association between the presence of fat deposits in the multifidus and LBP in adults but not adolescents.\textsuperscript{29} Although Parkkola et al\textsuperscript{40} reported a higher incidence in females and commented that this may be due to increased percentage of body fat, Kjaer et al\textsuperscript{29} did not show an association between fat and gender, body composition, or physical activity. At the initiation of this study, it was unclear whether fat would be present in the multifidus in a population of young, slim, highly active dancers with LBP.

There is evidence that muscle CSA differs between genders.\textsuperscript{24,33} The anatomical CSA of the lumbar erector spinae combined with the multifidus and quadratus lumborum muscles has been shown to be larger in males than in females.\textsuperscript{29} The CSA of the psoas muscles is also larger in males in both athletes and nonathletes.\textsuperscript{24,33} In these studies, some of the variability among participants can be explained by the wide range of height and weight in the sample population. As the height and weight of dancers were relatively consistent, it was anticipated that male dancers would have larger CSAs than female dancers.

On the basis of existing data of muscle CSA in elite sporting populations and

### TABLE 1

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>No Pain (n = 8)</th>
<th>LBP (n = 13)</th>
<th>Hip Pain and LBP (n = 10)</th>
<th>P Value*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>22 ± 3</td>
<td>24 ± 3</td>
<td>25 ± 5</td>
<td>.45</td>
</tr>
<tr>
<td>Gender (female), n</td>
<td>3</td>
<td>9</td>
<td>5</td>
<td>.59</td>
</tr>
<tr>
<td>Height, cm</td>
<td>176 ± 12</td>
<td>171 ± 10</td>
<td>173 ± 9</td>
<td></td>
</tr>
<tr>
<td>Female</td>
<td>164 ± 9</td>
<td>165 ± 3</td>
<td>165 ± 4</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>183 ± 7</td>
<td>185 ± 3</td>
<td>181 ± 5</td>
<td></td>
</tr>
<tr>
<td>Weight, kg</td>
<td>63 ± 13</td>
<td>58 ± 13</td>
<td>64 ± 14</td>
<td>.53</td>
</tr>
<tr>
<td>Female</td>
<td>50 ± 7</td>
<td>51 ± 4</td>
<td>52 ± 4</td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>71 ± 7</td>
<td>76 ± 3</td>
<td>77 ± 6</td>
<td></td>
</tr>
<tr>
<td>BMI, kg/m²</td>
<td>20 ± 2</td>
<td>20 ± 2</td>
<td>21 ± 2</td>
<td>.41</td>
</tr>
<tr>
<td>Female</td>
<td>18 ± 1</td>
<td>19 ± 1</td>
<td>19 ± 1</td>
<td>.33</td>
</tr>
<tr>
<td>Male</td>
<td>21 ± 1</td>
<td>22 ± 1</td>
<td>23 ± 1</td>
<td>.41</td>
</tr>
<tr>
<td>Professional dance, y</td>
<td>4 ± 3</td>
<td>5 ± 3</td>
<td>6 ± 4</td>
<td>.57</td>
</tr>
<tr>
<td>Dance, y</td>
<td>16 ± 4</td>
<td>18 ± 6</td>
<td>19 ± 4</td>
<td>.61</td>
</tr>
<tr>
<td>Spinal curve, deg</td>
<td>4 ± 4</td>
<td>2 ± 2</td>
<td>3 ± 5</td>
<td></td>
</tr>
<tr>
<td>Hypermobility score (0-9)</td>
<td>5 ± 3</td>
<td>5 ± 2</td>
<td>5 ± 2</td>
<td>.77</td>
</tr>
<tr>
<td>Turnout, deg</td>
<td>141 ± 8</td>
<td>137 ± 10</td>
<td>140 ± 11</td>
<td></td>
</tr>
<tr>
<td>VAS LBP (0-10)</td>
<td>0</td>
<td>3 ± 3</td>
<td>4 ± 2</td>
<td>.73</td>
</tr>
<tr>
<td>Roland-Morris score (0-24)</td>
<td>0</td>
<td>1 ± 2</td>
<td>1 ± 1</td>
<td>.41</td>
</tr>
<tr>
<td>Oswestry Disability Index (0-100), %</td>
<td>0</td>
<td>8 ± 10</td>
<td>4 ± 2</td>
<td></td>
</tr>
<tr>
<td>VAS hip (0-10)</td>
<td>0</td>
<td>0</td>
<td>5 ± 2</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: BMI, body mass index; LBP, low back pain; VAS, visual analog scale.

*Values are mean ± SD unless otherwise indicated.

†Between-group comparison.
people with LBP, we developed a number of hypotheses. The primary hypothesis was that dancers with LBP would have decreased CSA of the multifidus, psoas, and quadratus lumborum muscles, but unchanged CSA of the erector spiniae muscles. We predicted that there would be no fatty infiltrate in dancers with LBP compared to pain-free dancers. Further, we hypothesized that the multifidus, erector spiniae, psoas, and quadratus lumborum muscles would be symmetrical in healthy ballet dancers and larger in male dancers than in female dancers.

**METHODS**

**Participants**

Thirty-one dancers (14 male, 17 female) from The Australian Ballet volunteered from a possible 49 dancers present on tour for the Brisbane season of the production of *Giselle*. From this sample, dancers with and without LBP were identified. The mean ± SD age, height, and weight was 23.7 ± 3.6 years, 172.9 ± 10.1 cm, and 61.5 ± 12.9 kg, respectively (Table 1). The length of time dancing ranged from 7 to 28 (mean ± SD, 17.7 ± 5) years, including dancing professionally for 1 to 13 (mean ± SD, 5.2 ± 3.4) years. Their positions ranged from corps de ballet to principals. All dancers who completed the physical activity questionnaire (n = 27) scored in the high physical activity category. The majority of the dancers indicated that they were right-hand dominant (94%) and preferred to kick a ball with their right leg (97%). One dancer indicated left-hand and left-leg dominance. Demographic data, including age, gender, years of dance, limb dominance, and anthropometric measures, were recorded from each participant. Hypermobility scores, site and degree of spinal curvature, leg-length difference, and functional lower-leg turnout were measured by an experienced physiotherapist.

LBP was investigated in a number of ways. Participants completed the International Physical Activity Questionnaire long form and questionnaires related to general health and injury, the latter of which included a body chart on which the dancers were to indicate the area of pain. Dancers who indicated that they had pain (current or previous) in the region of the lower back, buttock, or hip (groin or lateral hip) were asked to complete a more detailed questionnaire related to their condition. Presentation was discussed with the physiotherapy team, who provided care for the dancers to determine, on the basis of their detailed physical assessment, whether the pain was reproduced by provocation of the low back only or by provocation of structures other than the low back (ie, the hip or pelvis). As 10 dancers were reported to have hip-region pain in addition to LBP, and there were no cases of hip-region pain without LBP, dancers were divided into 3 groups for comparison: dancers without hip-region pain or LBP (no-pain group, n = 8), dancers with LBP only (LBP group, n = 13), and dancers with both hip-region pain and LBP (hip pain and LBP group, n = 10). This grouping was considered necessary because preliminary analysis of muscle measures indicated that the presence of hip-region pain influenced the relationship between LBP and muscle CSA. Severity of pain in the low back and hip was measured using a 10-cm visual analog scale. Participants with LBP also completed the Roland-Morris disability questionnaire and Oswestry Disability Questionnaire. Except for pain, there was no difference in demographic data among groups (analysis of variance) (Table 1).

Dancers were excluded if they had LBP of a nonmusculoskeletal etiology, or if they had neurologic or respiratory disorders, a history of surgery to the spine, or contraindications to magnetic resonance imaging (MRI). Only 1 dancer was excluded, due to pregnancy. All of the dancers were on full workloads. The number of participants in the study was determined by availability rather than by power analysis. The Medical Research Ethics Committee of The University of Queensland approved the study. Participants gave informed consent, and the study was undertaken in accordance with the Declaration of Helsinki.

**Magnetic Resonance Imaging**

After a medical screening for MRI contraindications, the participants were positioned in supine, with their hips and knees resting in slight flexion on a wedge. MRIs from L2 to the lesser trochanter were made using a 1.5-T MAGNETOM Sonata magnetic resonance system (Siemens AG, Erlangen, Germany). A true fast imaging with steady-state precession sequence, using 28 × 8-mm and 12 × 4-mm contiguous slices centered on the L3-4 disc, was employed for the static images.

MRI images were digitally archived for later analysis and deidentified prior to measurement. The CSAs of the multifidus, lumbar erector spinae, psoas, and quadratus lumborum muscles were measured by manually tracing around the muscle borders using ImageJ Version 1.42q (National Institutes of Health, Bethesda, MD) (Figure 1). All measurements were made by the same person, who was blinded to participant grouping. The CSAs of the multifidus and lumbar erector spinae muscles were measured bilaterally at the lumbar levels L2 through L5 from images taken at the level of the intervertebral disc, where the lumbar zygapophyseal joints and muscle borders were clearly identified. The CSAs of the quadratus lumborum muscles were measured bilaterally at the level of the L3-4 disc, and the psoas muscles were measured at the L4-5 disc. These vertebral levels represent the greatest CSA of these muscles, which is thought to be related to the greatest force generated by the muscles. Noncontractile tissue that could be distinguished from muscle tissue was excluded from the calculation of CSA. Repeatability and reliability of CSA measurements of trunk muscles from MRI scans have been reported previously. Presence of fat in the multifidus muscles was graded by visual inspection and, when present, its
 CSA was measured using the following criteria: “normal” for estimates of 0% to 10% fat in the muscle, “slight” for 10% to 50% fat, and “severe” for greater than 50% fat.  

Statistical Analysis

STATISTICA Version 9 (StatSoft Pacific Pty Ltd, Melbourne, Australia) was used for data analysis. The alpha level was set at P<.05. Preliminary analysis was conducted to reduce the large range of potential variables that could be included. As the cohort involved a mix of participants with unilateral and bilateral pain, it was not intended to include the side of pain in the analysis (LBP group: unilateral pain, n = 3 and bilateral pain, n = 10; hip-region pain and LBP group: unilateral LBP, n = 5 and bilateral LBP, n = 5; unilateral hip-region pain, n = 7 and bilateral hip-region pain, n = 3). However, to confirm that this decision was valid, an analysis of covariance was used to determine whether the side of back or hip-region pain was related to multifidus or lumbar erector spinae muscle CSA. The analysis revealed that there was no difference between the CSAs of the multifidus and erector spinae if the back or hip-region pain was right, left, or bilateral (all, P>.05). Hypermobility score, range of “functional turnout,” years of dance training, leg-length difference, and site and degree of spinal curvature were eliminated from the analysis, as they did not influence muscle CSA in a preliminary analysis of covariance (all, P>.05). As all the dancers were of slim build, height provided the main variance across subjects, and weight and body mass index (BMI) were not included in the analysis.

For the main analysis, separate analyses of covariance using a general linear model were conducted to compare the CSAs of the multifidus and lumbar erector spinae muscles (at levels L2-L5), the psoas major (at levels L4-L5), and the quadratus lumborum (at levels L3-L4) between the right and left sides (repeated measures) and between the 3 groups. Age, height, gender, and years of professional dance were the factors included as covariates in the analysis. Post hoc analysis was undertaken using the Bonferroni test for multiple comparisons.

RESULTS

Analysis of multifidus CSA revealed a significant difference between groups (main effect for group, P = .049). Multifidus CSA at lumbar levels L3, L4, and L5 on both sides was larger in dancers with no pain compared to those with LBP (post hoc for all, P<.024) (FIGURE 2). The CSA of the multifidus muscle at L3 on both sides and L4 on the right was also larger in the no-pain group compared to the hip pain and LBP group (post hoc for all, P<.027). Furthermore, multifidus CSA on the left side at L4 and L5 was larger for the hip pain and LBP group compared to the LBP group (post hoc for all, P<.033). There was a similar pattern on the right side, which

FIGURE 1. MRI analysis. Transverse MRI image at the L3-4 intervertebral disc level showing the borders of the multifidus, erector spinae, psoas, and quadratus lumborum muscles on the left side (ie, right side of body according to MRI convention). Abbreviation: MRI, magnetic resonance imaging.

FIGURE 2. Cross-sectional area of the multifidus muscles at each lumbar level on the left and right sides of the body for the 3 participant groups: no pain, LBP, and hip pain and LBP. Data are shown as mean ± SD. *P<.05. Abbreviation: LBP, low back pain.
did not reach significance at L5 ($P = .06$) or L4 ($P = .27$). Multifidus CSA did not differ between groups at L2 (post hoc for all, $P > .44$). There was no difference between dancers in the no-pain group and those with pain (LBP and hip pain and LBP), or between the 2 pain groups (LBP and hip pain and LBP), for erector spinae CSA (main effect for group, $P = .10$) (FIGURE 3), psoas CSA (main effect for group, $P = .55$), or quadratus lumborum CSA ($P = .70$). Fat was only evident in the multifidus muscles of 5 participants (4 females and 1 male, all in pain groups), and all were graded “normal,” as the total CSA of fat was less than 10% in the muscles.

CSAs of the psoas (main effect for gender, $P < .0001$) and quadratus lumborum muscles (main effect for gender, $P = .01$) were larger in male compared to female dancers (FIGURE 4), but not the erector spinae and multifidus. There was a significant effect of years of professional dancing on psoas CSA (main effect for years of professional dance, $P = .03$). A linear regression fitted to the relationship between psoas CSA and years of professional dance indicated increasing CSA with greater number of years of professional dance.

**DISCUSSION**

This study found asymmetry in multifidus CSA between sides in classical ballet dancers. The results also demonstrate that LBP is associated with a smaller multifidus CSA in dancers. Dancers with current LBP or a history of LBP had a smaller CSA of the multifidus muscles at the lower lumbar levels, and this was not affected by dominance or gender or side of back or hip-region pain. The apparent atrophy of the multifidus was present in this young and highly athletic population, despite the dancers operating at full function and reporting low disability. Thus, high levels of physical activity are not sufficient to maintain properties of this muscle.

Consistent with our primary hypothesis and data from other populations, the CSA of the multifidus muscles was decreased in dancers with LBP.11,12,40 Dancers with combined hip-region pain and LBP also had significantly smaller multifidus muscles at L4 and L5 compared to dancers without LBP, but the difference in size compared to pain-free individuals was less than those with only LBP. The presence of hip-region pain may be associated with different lumbo pelvic muscle function compared to that associated with isolated LBP. Alternatively, the difference between groups may be due to the potential for some of the individuals with combined hip-region pain and LBP to have primary pathology in the hip, with compensatory spinal loading and subsequent LBP. Future investigation of CSAs of hip-region muscles in dancers with both hip pain and LBP may prove informative. In addition, as changes in control of the abdominal muscles are commonly reported in association with LBP in athletes,16,18 further examination...
of CSAs of these muscles in dancers could be valuable.

Although several authors have reported higher fat content in the multifidus in people with LBP, qualitatively, our dancer population had very little fat in any of the muscles studied. This is consistent with our null hypothesis and with observations from other groups that have compared people with LBP to age- and activity-matched participants and have not found an association between fat and chronic LBP. The explanation for the contrasting observations is unclear. The age range of the present population of dancers (17-32 years) is between the ages investigated by Kjaer et al., who showed no association between fat infiltration and LBP in 13-year-olds and a strong association in 40-year-old participants. Thus, age may explain the absence of fat deposits. Body composition has also been suggested as a factor by some authors but disputed by others. The BMI of the dancers with LBP was lower (mean, 20 kg/m²) than that of populations studied by authors who did not observe fat in the multifidus muscle (mean, 23 kg/m²; mean, 24 kg/m²) and those who did (mean, 24 kg/m²; mean, 27 kg/m²). BMI does not appear to fully explain the differences in fat content reported in association with atrophy of the multifidus muscle in some studies.

Whether the smaller size of the multifidus in dancers with LBP indicates atrophy of the muscles or is due to hypertrophy of the multifidus muscles in the dancers without pain is unclear. The size of the multifidus muscles has been shown to be decreased in nondancers with acute/subacute and chronic LBP bilaterally, on the side of pain, and at the level of pain provocation, and is related to the duration of symptoms. In human cross-sectional studies, it is not possible to determine whether the reduction in size precedes or follows the onset of pain. However, in a porcine model, Hodges et al demonstrated that injury to the L3-4 intervertebral disc induced atrophy of the multifidus ipsilaterally, with the greatest loss of CSA adjacent to the L4 spinous process immediately caudal to the injured disc. Complicating the issue in dancers, the multifidus muscles appeared to be larger in dancers with no pain than in the general population (TABLE 2), although a specific comparative study of matched subjects has not been conducted and some of the differences between studies may relate to differences in methodology (eg, identification of muscle boundaries). It is possible that larger multifidus muscles in dancers are protective of LBP and may be related to the specific functional demands of dance (eg, spinal posture or sustained and repetitive lumbar and hip extension). It follows that failure of hypertrophy could contribute to the onset of LBP and account for the smaller CSA of the multifidus muscles seen in dancers with LBP. The alternative explanation is that the smaller multifidus in dancers with LBP (relative to dancers without pain) could be due to an inhibitory mechanism similar to that proposed to explain the smaller

### TABLE 2

Lumbar Multifidus Morphometry, Anatomic Cross-sectional Area at L3-L5 Averaged Between Right and Left Sides, and Demographics for Healthy Populations of Males and Females

<table>
<thead>
<tr>
<th>Gender/Study</th>
<th>Group</th>
<th>Age, y</th>
<th>Height, cm</th>
<th>Weight, kg</th>
<th>CSA Measurement Method</th>
<th>L3, cm²</th>
<th>L4, cm²</th>
<th>L5, cm²</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>
</tr>
<tr>
<td>Current study</td>
<td>Dancers (n = 5)</td>
<td>23 ± 3</td>
<td>183 ± 7</td>
<td>71 ± 6</td>
<td>MRI supine: disc/LZJ</td>
<td>5.96 ± 1.3</td>
<td>9.5 ± 0.91</td>
<td>8.78 ± 1.15</td>
</tr>
<tr>
<td>McGill et al</td>
<td>Nondancers (n = 15)</td>
<td>25 ± 4</td>
<td>176.1 ± 6.8</td>
<td>81.5 ± 10.7</td>
<td>MRI supine: disc center</td>
<td>4.6 ± 2.7</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>Lee et al</td>
<td>Nondancers (n = 19)</td>
<td>42 ± 5</td>
<td>NR</td>
<td>NR</td>
<td>US prone: lamina</td>
<td>NR</td>
<td>765 ± 1.34</td>
<td>72 ± 1.83</td>
</tr>
<tr>
<td>Hides et al</td>
<td>Nondancers (n = 21)</td>
<td>(18-35)</td>
<td>178.9 ± 7.5</td>
<td>72.8 ± 13.7</td>
<td>US prone: lamina</td>
<td>NR</td>
<td>6.15 ± 0.93</td>
<td>NR</td>
</tr>
<tr>
<td>Stokes et al</td>
<td>Nondancers (n = 52)</td>
<td>40 ± 13</td>
<td>178 ± 0.0</td>
<td>82.8 ± 11.0</td>
<td>US prone: lamina</td>
<td>NR</td>
<td>7.87 ± 1.85</td>
<td>...</td>
</tr>
<tr>
<td>Hides et al</td>
<td>Nondancers (n = 45)</td>
<td>39 ± 13</td>
<td>177 ± 0.1</td>
<td>82.5 ± 10.4</td>
<td>US prone: lamina</td>
<td>NR</td>
<td>...</td>
<td>8.91 ± 1.68</td>
</tr>
<tr>
<td>Hides et al</td>
<td>Cricket (n = 14)</td>
<td>21 ± 2</td>
<td>182.7 ± 5.7</td>
<td>84.0 ± 17.7</td>
<td>US prone: lamina</td>
<td>4.32 ± 1.48</td>
<td>6.49 ± 2.18</td>
<td>8.01 ± 1.75</td>
</tr>
<tr>
<td><strong>Female</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current study</td>
<td>Dancers (n = 3)</td>
<td>21 ± 2</td>
<td>164 ± 9</td>
<td>50 ± 7</td>
<td>MRI supine: disc/LZJ</td>
<td>4.14 ± 0.08</td>
<td>7.24 ± 0.52</td>
<td>6.57 ± 0.44</td>
</tr>
<tr>
<td>Hides et al</td>
<td>Nondancers (n = 27)</td>
<td>(18-35)</td>
<td>167.3 ± 6.2</td>
<td>60.2 ± 8.1</td>
<td>US prone: lamina</td>
<td>NR</td>
<td>5.6 ± 0.8</td>
<td>NR</td>
</tr>
<tr>
<td>Hides et al</td>
<td>Nondancers (n = 10)</td>
<td>26</td>
<td>NR</td>
<td>NR</td>
<td>MRI supine: disc/LZJ</td>
<td>3.29 ± 0.77</td>
<td>4.99 ± 1.09</td>
<td>7.15 ± 0.58</td>
</tr>
<tr>
<td>Stokes et al</td>
<td>Nondancers (n = 68)</td>
<td>34 ± 13</td>
<td>165 ± 0.1</td>
<td>62.9 ± 8.9</td>
<td>US prone: lamina</td>
<td>3.33 ± 0.85</td>
<td>4.87 ± 1.22</td>
<td>7.12 ± 0.68</td>
</tr>
<tr>
<td>Stokes et al</td>
<td>Nondancers (n = 15)</td>
<td>32 ± 12</td>
<td>166 ± 0.1</td>
<td>61.8 ± 7.2</td>
<td>US prone: lamina</td>
<td>NR</td>
<td>5.55 ± 1.28</td>
<td>...</td>
</tr>
</tbody>
</table>

Abbreviations: CSA, cross-sectional area; LZJ, lumbar zygapophyseal joint; MRI, magnetic resonance imaging; NR, not reported; US, real-time ultrasound imaging.

*Values are mean ± SD.
†Value is range.
muscle size in LBP/injury for nondancers and animals. Further research is needed to resolve this question.

We predicted that LBP in dancers would be associated with decreased CSA of the multifidus, psoas, and quadratus lumbarum muscles, but that the CSA of the erector spinae muscles would be unchanged. In contrast to our hypothesis, the CSAs of the psoas and quadratus lumbarum muscles did not differ between dancers without pain, those with LBP only, or those with both hip-region pain and LBP. This is consistent with data of Danneels et al\textsuperscript{21} who compared the CSA of the psoas in people with LBP to that in matched healthy controls and found no difference between groups. However, it contrasts the findings of other authors who reported decreased psoas CSA in individuals with LBP,\textsuperscript{3,30,40} especially in conjunction with leg pain.\textsuperscript{3,30} Asymmetry of the quadratus lumbarum has been associated with LBP in elite cricketers and may be related to asymmetrical activities\textsuperscript{32,33} but was not evident in this population of dancers. Although no differences were apparent in the group analysis, specific differences might have been present in individuals or subgroups. This would be consistent with evidence of changes in psoas muscle CSA in the specific subgroup of people with LBP associated with sciatica.\textsuperscript{3,10} The finding that the CSA of the erector spinae did not differ between dancers without pain, with LBP only, or with both hip-region pain and LBP was consistent with our hypothesis and is supported by data from other studies.\textsuperscript{4,31} Danneels et al\textsuperscript{21} found no difference in the CSAs of the erector spinae between people with LBP and healthy controls. Similarly, Beneck and Kulig\textsuperscript{4} found no decrease in the volume of erector spinae muscles in people with chronic LBP compared to healthy individuals. The absence of significant asymmetry of the erector spinae, psoas, and quadratus lumbarum muscles in dancers with pain could be due to the symmetrical demands of dance or other factors.

In contrast to our prediction of symmetrical multifidus CSAs in healthy dancers, the CSA of the multifidus muscle was larger on the right side compared to the left for both the pain-free and LBP groups. This is similar to observations in other populations, such as elite cricketers\textsuperscript{32,33} and other athletes,\textsuperscript{42} who have larger multifidus CSA, erector spinae CSA, and/or combined multifidus and erector spinae CSA on the side of the dominant arm, and contrasts observations in nondancers\textsuperscript{7,23,32} and rowers,\textsuperscript{36} who have symmetrical CSAs of these muscles. It is notable that, despite the aspiration in ballet of equal proficiency on either leg, there is evidence for limb preference in dance tasks and lateral bias in teaching, which is typically toward the right side.\textsuperscript{28,29} The majority of dancers in the current study indicated that they were right-limb dominant. The findings of a larger right multifidus coincide with the dancers’ dominant side and may be related to this laterality preference.

The larger CSA of the psoas and quadratus lumbarum muscles in male compared to female dancers concurs with data from nondancers.\textsuperscript{33} However, unlike our data, Marras et al\textsuperscript{32} also reported larger multifidus/erector spinae CSA in males. Although male dancers do more lifting than females, both genders perform a range of other actions that place large demands on the spine (eg, repetitive holding of leg extension and prolonged trunk extension). This latter point may account for the similarity in paraspinal muscle size relative to height between male and female dancers.

It is difficult to directly compare the muscle CSAs recorded in our pain-free group with other populations, due to the small number of dancers who have never experienced LBP and to variation in methods and data analysis between studies (eg, many studies have combined the multifidus and erector spinae). It could be reasoned that dancers would have larger CSAs of spinal extensor muscles than nondancers due to higher values of peak extension torque recorded in this group compared to nondancers,\textsuperscript{6} and to the correlation between the combined multifidus and erector spinae CSA and extension torque.\textsuperscript{43} From the limited data available, male dancers appear to have larger multifidus CSA at L3,\textsuperscript{35} L4,\textsuperscript{19,31} and L5\textsuperscript{21} than healthy nondancers (Table 2). They also had larger multifidus muscles at L2-L5 than elite cricketers with a similar mean age and height but greater mean weight.\textsuperscript{21} Female dancers also had larger multifidus CSA at L2,\textsuperscript{35} L3,\textsuperscript{19} and L4\textsuperscript{20,44} compared with nondancers, but not at L5.\textsuperscript{20,44} Healthy dancers also had larger multifidus muscles at L4 compared to L5. This finding is consistent with some authors\textsuperscript{31}; however, other authors report that the multifidus muscle is usually larger at L5 than L4.\textsuperscript{16,20,44} No comparable data could be found for the CSA of the lumbar erector spinae.

The increase in the CSA of the psoas muscles with advancing years of professional dancing is an interesting finding. Peltonen et al\textsuperscript{41} also found a correlation between physical training time, psoas CSA, and trunk flexion force in a group of adolescent female ballet dancers, gymnasts, and figure skaters. The correlation between the size of the psoas muscles and years of professional dancing may reflect the high use of the psoas muscles in ballet, supporting the proposed role of the psoas muscles as hip and trunk flexors.\textsuperscript{3}

A limitation of this study was the small sample size, which was due to the elite nature of the professional classical ballet population. This might have affected some of the analyses. For example, there is evidence that the prevalence of scoliosis is associated with asymmetry of the size of the multifidus muscles.\textsuperscript{37} The small number of dancers in this study with spinal curves greater than 10° (n = 4) may explain the failure of this relationship to reach significance. The small number of dancers without LBP and the necessity to divide the pain group into LBP only and both hip-region pain and LBP may also impact the conclusions that may be drawn from the results.
CONCLUSION

The results of this study demonstrate asymmetry of multifidus CSA in dancers. The study also provides evidence that LBP and combined hip-region pain and LBP in classical ballet dancers are associated with smaller size of the multifidus muscles. Clinical trials are necessary to determine whether this change in muscle size can be reversed with specific treatment strategies and whether this is associated with changes in LBP symptoms.

KEY POINTS

FINDINGS: The multifidus muscles were larger in dancers without pain than in those with LBP only and with hip-region pain and LBP. The size of the erector spinae, psoas, and quadratus lumborum muscles was the same in dancers with and without LBP and in those with hip-region pain and LBP. The psoas and quadratus lumborum muscles were larger in male dancers than in female dancers, but there was no difference in the size of the multifidus and erector spinae between genders. The psoas muscle size increased with the number of years of professional dancing.

IMPLICATIONS: As the CSA of trunk muscles in dancers with LBP and hip-region pain and LBP is different from the CSA of trunk muscles in dancers without pain and LBP, it is possible that these differences may be associated with changes in LBP symptoms. Further research is needed to investigate the relationship between the size of these muscles and the incidence of LBP in dancers.

CAUTION: The elite nature of professional classical ballet limited the sample size available for this study.

ACKNOWLEDGEMENTS: The authors sincerely thank the staff of The Australian Ballet, who assisted with scheduling and recruitment, and the dancers from The Australian Ballet who generously participated in the study. We also thank Warren Stanton, who provided statistical expertise, and The University of Queensland Centre for Advanced Imaging, particularly Steve Wilson and Mark Strudwick.

REFERENCES

Original research

Morphology of the abdominal muscles in ballet dancers with and without low back pain: A magnetic resonance imaging study

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Abstract

Objectives: To evaluate the morphology of transversus abdominis and obliquus internus abdominis muscles and the ability to “draw in” the abdominal wall, in professional ballet dancers without low back pain, with low back pain or both hip region and low back pain.

Design: Observational study.

Methods: Magnetic resonance images of 31 dancers were taken at rest and during voluntary abdominal muscle contraction. Measurements included the thickness of transversus abdominis and obliquus internus abdominis muscles, lateral slide of the anterior extent of the transversus abdominis muscles (transversus abdominis slide) and reduction in total cross sectional area of the trunk.

Results: The transversus abdominis and obliquus internus abdominis muscles were thicker in male dancers and the right side was thicker than the left in both genders. There was no difference in muscle thickness as a proportion of the total thickness, between dancers with and without pain, although there was a trend for female dancers with low back pain only to have a smaller change in transversus abdominis muscle thickness with contraction than those without pain. Transversus abdominis slide was less in female dancers than in male dancers. When gender was ignored, the extent of transversus abdominis slide was less in dancers with low back pain only. Reduction in trunk cross sectional area with contraction was not different between genders or groups.

Conclusions: This study provides evidence that the abdominal muscles (transversus abdominis and obliquus internus abdominis) are asymmetrical in dancers and although the abdominal muscles are not different in structure (resting thickness) in dancers with LBP, there is preliminary evidence for the behavioural change of reduced slide of transversus abdominis during the ‘draw in’ of the abdominal wall.

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1. Introduction

Despite the effortless grace of classical ballet there is a high prevalence and incidence of low back pain (LBP). The spine is the most common site of chronic pain in professional dancers with the majority of injuries occurring in the lumbar region. Abdominal muscle weakness has been cited as a contributing factor to LBP in professional dancers. However in dancers, peak trunk flexion torque is not correlated with LBP and the association between abdominal endurance and LBP in athletes (including dancers) is weak. Abdominal muscle strength is also a poor predictor of risk for development of LBP in athletes. In contrast, morphology and behaviour of the abdominal muscles has been suggested to have a more consistent relationship to LBP.

In non-dancers with LBP, altered motor control of abdominal muscles has been observed. Electromyography (EMG) recordings have demonstrated delayed activation and reduced amplitude of activity in transversus abdominis (TrA) muscles in people with LBP. Consistent with EMG changes, a smaller increase in TrA muscle thickness with contraction has also been observed with ultrasound imaging.

Delayed and reduced activation of the TrA muscle may compromise spinal control. The TrA muscle contributes to spinal control via its attachment to the thoracolumbar fascia, and by modulation of intra-abdominal pressure. Changes in cross-sectional area (CSA) of the trunk, observed with ultrasound and magnetic resonance imaging (MRI) during the voluntary task of “drawing-in” the abdominal wall has been used as a clinical muscle test of
the TrA muscle. During this manoeuvre, as the muscle bellies of TrA thicken and shorten, there is an associated lateral slide of the anterior extent of the TrA muscle (TrA muscle slide) and reduced trunk CSA. These actions are consistent with descriptions of TrA muscle function from anatomical studies. Less TrA muscle slide and smaller reduction in trunk CSA have been observed in people with LBP than those without LBP. Reduced ability to decrease the CSA of the trunk by “drawing-in” the abdominal wall has also been observed in elite cricketers and footballers with LBP. These parameters have been argued to primarily reflect TrA activation.

Studies of trunk muscle geometry have reported symmetry of the abdominal muscles between sides in participants without LBP, irrespective of hand dominance or gender. Bilateral contraction is argued to have a greater effect on spine control than unilateral contraction. Asymmetry of the TrA muscle slide has been observed in cricketers with LBP. Cricketers also had larger resting thickness of the OI muscle on the side of the non-dominant hand and there was a non-significant tendency for greater OI muscle thickness in those with LBP than those without LBP.

Maintenance of an aesthetically symmetrical body structure and equal ability to perform tasks on either leg and to either side is a key objective in ballet. The symmetrical emphasis of classical ballet would be predicted to encourage symmetrical abdominal muscle development in dancers, although an asymmetrical bias in teaching and some specific dance tasks has been observed. As changes in muscle morphology, symmetry and behaviour are related to LBP in non-dancers it is possible that dancers with LBP could also have changes in these trunk muscle parameters.

This study aimed to investigate, in professional ballet dancers, the size and symmetry of the TrA and OI muscles and the lateral slide of the anterior extent of the TrA muscle, changes in thickness of TrA and OI muscles, and trunk CSA with voluntary contraction of the abdominal muscles. A second aim was to compare these parameters between dancers with and without LBP.

2. Methods

Seventeen female dancers aged 23(3) years, weighing 51(4)kg with heights of 165(4) cm; and 14 male dancers aged 24(4) years, weighing 74(6)kg, with heights of 183(5) cm volunteered from 49 dancers on tour for The Australian Ballet production of Giselle in Brisbane, Australia. All dancers, including corps de ballet to principals were on full workloads. The majority of the dancers nominated that they were right hand (94%) and right leg (97%) dominant. Demographic data, hypermobility scores, site and degree of spinal curvature and functional lower leg turnout were collected by an experienced physiotherapist. Dancers completed a general health and injury questionnaire (which included a body chart), the International Physical Activity Questionnaire long form and a laterality profile. All dancers who completed the physical activity questionnaire (n = 27) scored in the ‘high’ physical activity category. Dancers were excluded if they had LBP of non-musculoskeletal aetiology, neurological or respiratory disorders, a history of spinal surgery, or contraindications to MRI (magnetic resonance imaging). One dancer was excluded due to pregnancy. The number of participants in the study was determined by availability rather than by a power analysis.

LBP was investigated several ways. Dancers who indicated on the body chart that they had pain in the region of the lower back, pelvis or hip completed a detailed questionnaire. Presentation was discussed with the physiotherapy team who provided ongoing care for the dancers, to determine whether, based on comprehensive physical assessment, pain was reproduced by provocation of the low back only or structures other than the low back i.e. the hip or pelvis. As 10 dancers were reported to have hip region pain in addition to LBP, and there were no cases of hip region pain without LBP, dancers were divided into three groups for comparison: no history of hip region or LBP (n = 8); history of or current LBP (n = 13); history of or current hip region and LBP (n = 10). Severity of pain in both the low back and hip regions was measured using a 10 cm Visual Analogue Scale (VAS). Participants with LBP also completed a Roland-Morris Disability questionnaire and Oswestry Disability questionnaire. Except for pain, there was no difference in demographic data among groups (ANOVA).

The Institutional Medical Research Ethics Committee approved the study. Participants gave informed consent and the study was undertaken in accordance with the Declaration of Helsinki.

After a medical practitioner had screened the participants for MRI contraindications they were positioned in supine with the hips and knees resting in slight flexion on a foam wedge. Measures were made at rest and during abdominal muscle contraction. Dancers were instructed to gently “draw-in” the abdominal wall without moving the spine and without breathing. Dancers were familiar with this manoeuvre from their dance training. Images were taken at rest and after completion of the contraction (which was cued by the operator) with the subject holding the breath at mid expiration. Images were made using a Siemens Sonata MR system (1.5 T) with true fast imaging and a steady-state precession (TrueFISP) sequence of 14 mm × 7 mm contiguous slices centred on the L3–4 disc. MRI images were saved for later analysis and de-identified prior to measurement.

Measurements were made from the MRI images using Image J (version 1.42q, http://rsb.info.nih.gov/ij) (Fig. 1). In all measurements the cursor was placed at the inside edge of the fascia. Measures were: thickness of the TrA and OI muscles on the right and left sides at the muscle’s widest point at rest and at the same location during contraction; the CSA of the entire trunk excluding skin and subcutaneous fat at rest and during contraction; and the lateral slide of the anterior extent (defined as the point at which the muscle attaches to the anterior fascia) of the TrA muscle with contraction, on both sides. Repeatability and reliability of measurements of trunk CSA from MRI scans have been reported.

STATISTICA, Version 9 (StatSoft Pacific Pty Ltd.) was used for data analysis. Preliminary analysis was conducted to reduce the large range of potential variables. The mix of participants with unilateral and bilateral pain precluded investigation of the side of pain in the analysis. This decision was validated by the absence of main effect for side of back or hip region pain on the muscle parameters. Age, height, hypermobility score, range of ‘functional turnout’, years of dance training, years of professional dancing, leg length difference and site and degrees of spinal curvature were eliminated from the analysis as they did not influence muscle thickness, trunk CSA or TrA muscle slide in a preliminary ANCOVA (all: p > 0.05). As all the dancers were of slim build, height provided the main variance across participants so weight and body mass index were not included in the analysis.

For the analysis of change in muscle thickness with contraction, ANCOVAs using a general linear model were undertaken separately to compare the proportional change from rest to after contraction in the linear measurements of TrA and OI muscle thickness between right and left sides (repeated measure) and between the three groups. One-way ANOVAs were used to compare the TrA muscle slide, and the CSA of the entire trunk between rest and contraction. Post hoc analysis was undertaken using Duncan’s test. Significance was set at p < 0.05.

3. Results

At rest the thickness of OI was larger than that of TrA (main effect – muscle: p < 0.01). Male dancers had thicker TrA (interaction...
– muscle × gender: \( p = 0.002 \), post hoc \( p < 0.001 \)) and OI muscles \( (p < 0.001) \) than female dancers. OI and TrA muscles were thicker on the right than the left in both genders (main effect – side: \( p = 0.01 \)) (Fig. 2).

The increase in TrA muscle thickness with contraction was greater than that for the OI muscle (main effect – muscle: \( p < 0.001 \)). There was a tendency, although non-significant, for an interaction between muscle, group and gender \( (p = 0.069) \). Exploration of this finding revealed a tendency for a smaller change between the contracted and resting TrA muscle thickness in females with LBP only. The failure to reach significance is likely explained by the small number of females without LBP \( (n = 3) \).

Lateral slide of the anterior extent of the TrA muscle was less for females than males on both sides (interaction – gender × side: \( p < 0.03 \), both sides \( p < 0.05 \)) (Fig. 3). Although the primary analysis, which included consideration of gender, failed to show a difference between groups (main effect group \( p = 0.085 \)), because of the small sample size we undertook an additional analysis in which data were analysed without consideration of gender, and compared between pain groups with an ANOVA. This analysis showed a significantly smaller TrA muscle slide in dancers with LBP only than those without pain (main effect – group: \( p < 0.001 \); post hoc \( p = 0.015 \)) and those with hip region and LBP (post hoc: \( p = 0.025 \)). There was no difference in this parameter between the pain free, and hip region and LBP groups (post hoc: \( p = 0.74 \)).
There was no significant difference in reduction of trunk CSA with contraction between groups (main effect group \( p = 0.62 \)) or between genders (main effect gender \( p = 0.26 \)).

4. Discussion

These data show that thickness of TrA and OI at rest and with contraction is asymmetrical in dancers but did not differ between dancers with and without LBP or combined hip region and LBP. Other factors with the potential to affect asymmetry for example spinal asymmetry due to scoliosis and variance in physical activity levels were eliminated as these factors did not affect results. Although our primary analysis showed no group difference in measures of TrA contraction in dancers with LBP, the additional exploratory analysis that ignored gender revealed a smaller lateral slide of the anterior extent of the TrA muscles in dancers with LBP only (but not combined hip and LBP pain), which is consistent with the trend for female dancers with LBP only to show less increases in TrA muscle thickness with contraction. This finding justifies the necessity to conduct a larger study of professional ballet dancers. This would be likely to require a multi-site study, as there is only a small population of dancers who have not experienced LBP.

Asymmetry of the morphology of the abdominal muscles in dancers contrasts with findings in non-dancers, who are generally symmetrical between the sides.\(^{[18,19]}\) Asymmetry in OI muscle thickness has been reported in elite cricketers. Cricket involves considerable trunk rotation away from the dominant hand with throwing, bowling and batting actions. In that group the larger OI muscle is on the side of the non-dominant arm.\(^{[16]}\) This contrasts the larger muscle on the side of the dominant hand in dancers, but is probably explained by the specific kinematic demands of bowling/throwing in cricket and rotating (pirouettes) in dance. A further difference between dancers and cricketers is that dancers had larger TrA on the right side unlike the symmetry of the muscle in cricketers.\(^{[16]}\) In this study, as in previous studies on dancers\(^{[22]}\) the majority of dancers nominated right hand and leg dominance. There was also a right bias in preferred turning side. All dancers (except one) preferred to pirouette en dehors or chârîn to the right. Rotation of the thorax to the right relative to the pelvis is a primary action of the right OI and TrA.\(^{[22]}\) Other authors have observed a right turning bias in university dance students\(^{[22]}\) and bias towards the right hand side in dance teaching which results in 26% higher prevalence of repetitions to the right.\(^{[21]}\) Despite the emphasis in training on achieving and maintaining the appearance of body symmetry and equal proficiency of tasks to both sides,\(^{[20]}\) the impact of side dominance in teaching and practice may underlie the right−left side differences reported here. It is possible that a focus on restoration of symmetry of morphology of the abdominal muscles could be advantageous to optimise the desired symmetry of structure and movement that is demanded in classical ballet.

Male dancers had larger abdominal muscles and greater TrA muscle slide than female dancers, even when height was accounted for as a covariate in the analysis, and this agrees with gender differences in the non-dance populations.\(^{[18,19,28]}\) Absolute resting thickness of TrA muscles in male dancers is similar to the absolute thickness found in non-dancers using ultrasound measurements\(^{[18,28]}\) but thinner than values reported in elite cricketers.\(^{[16]}\) However, the resting thickness of TrA in female dancers appears to be less than in non-dancers.\(^{[19,28]}\) This may be related to the lower body weight of the female dancers compared to the non-dancers. The absolute resting thickness of OI muscles in dancers is intermediate between thinner muscles in non-dancers\(^{[28]}\) and thicker muscles in elite cricketers.\(^{[16]}\)

Unlike elite cricketers, Australian League Footballers\(^{[15,17]}\) and other non-dancers with LBP,\(^{[15]}\) the ballet dancers with LBP did not have a compromised ability to reduce the abdominal CSA during the “draw-in” manoeuvre, when compared to the pain free dancers. The only difference in behaviour of abdominal muscle activation observed in the present study was a reduced TrA muscle slide in dancers with LBP, but not combined hip region and LBP, when gender was excluded from the analysis. The main impact of removal of the gender factor was the increase in sample size particularly in the pain free group (only 3 females had not experienced LBP). Although not related linearly, TrA muscle slide provides an indication of muscle activity. Thus limitation to muscle shortening is consistent with reports of reduced TrA activation.\(^{[8]}\) There was also a non-significant tendency for female, but not male, dancers with LBP only to have reduced increase in TrA thickness from rest to contraction. Reduced change in TrA muscle thickness with contraction has been reported in non-dancers with LBP,\(^{[9]}\) but not cricketers. The non-significant tendency implies that either difference in muscle activation changes between groups is small, or that it presents variably in dancers. Ballet places very different demands on the trunk than cricket. These physical demands may account for the differences in muscle morphology associated with LBP in these two populations.

The absence of changes in the dancers with hip region and LBP highlights that these presentations are unique and the muscle changes are specific to primary LBP. The lack of the overall change in abdominal CSA in dancers, unlike other elite athletic populations,\(^{[14,15]}\) could be explained by the training of the dancers. The action of narrowing the waist, similar to the “draw-in” manoeuvre used here, is a routine component of ballet training and a fundamental aspect of ballet posture. It is possible that familiarity with this task as a result of training might counteract any differences in performance mediated by pain. Evaluation of abdominal muscle activation during other tasks such as automatic response to limb movements\(^{[5]}\) and perturbations to the spine\(^{[2]}\) may provide additional insight.

There are several methodological issues that require consideration. With respect to the aforementioned familiarity of the participant group with voluntary contraction of the muscles under investigation, future work should include evaluation of automatic activation of the muscles. However, this may preclude use of MRI to measure activation as a result of limitation to tasks that can be performed in a confined space. A further limitation of this study is that the elite nature of classical ballet limits the available sample size. The small number of females without LBP may explain why the relationship between TrA muscle thickness and LBP did not reach significance.

Reduced lateral slide of the anterior extent of TrA muscles during the voluntary “drawing-in” task may have implications for spine health and treatment selection. Earlier studies have shown a relationship between activation of TrA in the voluntary task of “drawing-in” the abdominal wall and compromised automatic function of TrA, such as that tested in association with arm movement.\(^{[8]}\) As this muscle provides a contribution to control of the spine and pelvis,\(^{[11,12,29]}\) this will be likely to have an impact on the robustness of spine control. Further, poor TrA muscle slide is a predictor of responsiveness to a motor control training intervention in non-dancers with pain.\(^{[10]}\) Thus, identification of such deficit may contribute to decision making in planning intervention for LBP. This requires testing in clinical trials.

5. Conclusion

The results of this study suggest that resting thickness of the TrA and OI muscles are asymmetrical in ballet dancers regardless of presence of LBP. Asymmetry may relate to limb dominance and subsequent bias in the training of dancers. The preliminary evidence of compromised behaviour of TrA muscles in LBP provides a
foundation upon which treatments may be developed and tested for dancers with pain.

Practical implications

- Addressing the asymmetry of the abdominal muscles found in dancers may facilitate the aim of classical ballet for symmetry of body shape and movement.
- In the assessment and treatment of dancers with LBP the lateral slide of the anterior extent of the TrA muscle may contribute to guidance for treatment.
- Male dancers have larger abdominal muscles and greater TrA muscle slide than female dancers.

Acknowledgements

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jsams.2013.09.002.

References

Appendix V Study III
Trunk Dynamics Are Impaired in Ballet Dancers with Back Pain but Improve with Imagery

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The authors have read and concur with the content in this manuscript. We declare that we have no financial or personal relationships that can inappropriately influence our work. The results of the present study do not constitute endorsement by ACSM.

Running title: Trunk dynamics in ballet dancers
ABSTRACT

Purpose Trunk control is essential in ballet and may be compromised in dancers with a history of low back pain (LBP) by associated changes in motor control. This study aimed to compare trunk mechanical properties between professional ballet dancers with and without a history of LBP. As a secondary aim we assessed whether asking dancers to use motor imagery to respond in a “fluid” manner could change the mechanical properties of the trunk, and whether this was possible for both groups.

Methods Trunk mechanical properties of stiffness and damping were estimated with a linear second order system, from trunk movement in response to perturbations, in professional ballet dancers with (n=22) and without (n=8) a history of LBP. The second order model adequately described trunk movement in response to the perturbations. Trials were performed with and without motor imagery to respond in a “fluid” manner to the perturbation.

Results Dancers with a history of LBP had lower damping than dancers without LBP during the standard condition (P=0.002) but had greater damping during the “fluid” condition (P<0.001) with values similar to dancers without LBP (P=0.226). Damping in dancers without LBP was similar between the conditions (P>0.99). Stiffness was not different between dancers with and without a history of LBP (P=0.252) but was less during the “fluid” condition than the standard condition (P<0.001).

Conclusion Although dancers with a history of LBP have less trunk damping than those without LBP, they have the capacity to modulate the trunk’s mechanical properties to match that of pain-free dancers by increasing damping with motor imagery. These observations have potential relevance for LBP recurrence and rehabilitation.

Keywords: spine; motor control; damping; stiffness; rehabilitation
INTRODUCTION

Classical ballet dancers have the ability to change the quality of their movement to portray a particular character, convey an emotion or meet the requirements of the choreographer, dance style or musical accompaniment. A key component is motor control of the trunk (2), which evolves in response to dance training and results in more accurate, efficient and repeatable movement patterns (30). For instance, in the execution of a développé arabesque (moving the gesture leg from the ground to an elevated position behind the body) differences in lumbo-pelvic control (kinematics) account for most of the variance between expert and less skilled dancers (2). On the basis of data from non-dancers (17, 39) it is reasonable to speculate that trunk control, including the ability to regulate movement quality, might be modified in ballet dancers with a history of low back pain (LBP).

Changes in the recruitment of trunk muscles have been reported in association with LBP and this has implications for control of the spine (16). Electromyography (EMG) recordings of the trunk muscles commonly reveal a pattern of compromised activity of the deeper trunk muscles including multifidus (22) and transversus abdominis (17) and augmented activity of the larger, more superficial trunk muscles such as obliquus externus abdominis (32). Consistent with EMG findings, measurement of deep trunk muscle morphology using magnetic resonance imaging has demonstrated that LBP in dancers is associated with smaller cross sectional area of the multifidus muscles (13) and reduced shortening with contraction of the transversus abdominis muscles (12). It has been hypothesized that altered recruitment and morphology of trunk muscles underlies changes in the mechanical behavior of the trunk in people with recurring episodes of LBP (15). However, whether trunk mechanical behavior is altered in ballet dancers with a history of LBP is unknown.
Although movement quality incorporates many components, viewed simply, the dynamic behavior of the trunk depends on its inertia, damping and stiffness properties (11, 27). Estimation of trunk mechanical properties from the response to small perturbations may yield information about trunk control in ballet dancers with and without a history of LBP. Stiffness (Nm\(^{-1}\)) is the resistance to trunk displacement (28) and is dependent on muscle activity (e.g. co-contraction) and passive constraints (3, 28). Damping is the resistance to trunk velocity (Nsm\(^{-1}\)) (1) and prevents unwanted oscillations in a system. As damping smooths movement at higher frequencies, change in damping has the potential to affect the quality of trunk movement, which could be an important feature in dance. Estimation of the dynamic properties of the trunk has identified greater stiffness and less damping in people with recurrent LBP than pain-free individuals (15). Trunk dynamics have not been studied in dancers.

Evaluating the change in mechanical behavior of the trunk in different conditions may provide insight into how dancers modulate movement quality. Dance training frequently employs mental practice including motor imagery, as a technique to change both qualitative and quantitative aspects of movement performance (8, 9, 35). For example, when using motor imagery, professional dancers can improve the quality of a dance-specific movement sequence by changing muscle activity level (9) and kinematics (8). Kinesthetic motor imagery simulates the “felt” experience of performing movement (8) and produces similar cortical activation to actual movement (19). Whether dancers can change basic mechanical properties of the trunk with motor imagery, and whether this can also be achieved by dancers with a history of LBP remains unclear. For the current study, a standard and a “fluid” motor image were developed in conjunction with dance experts to evoke movement responses with different qualities that would be likely to influence the properties of stiffness and damping.
This study had two aims. The first aim was to determine whether dynamic properties of the trunk (i.e. stiffness and damping), as estimated from responses to small perturbations applied to the trunk; differ between dancers with and without a history of LBP. The second aim was to investigate whether these properties could be modified by motor imagery. This was achieved by comparison of the mechanical responses to perturbations with a standard instruction with the responses when dancers employed the motor image of using their body in a “fluid” manner. We hypothesized that dancers with a history of LBP would have less damping and greater stiffness of the trunk than those without pain, and a reduced ability to modulate these properties in the “fluid” condition.

MATERIALS AND METHODS

Participants

Thirty professional classical ballet dancers with and without a history of LBP (11 male, 19 female, mean (SD): 24 (4) years, 172 (10) cm, 60 (13) kg) volunteered for this study. Participants were recruited from a group of dancers on full workloads (n=49) who were on tour with The Australian Ballet. Dancers of all ranks were included and the participants’ dancing experience ranged from 7-28 years, of which 1-13 years was professional. Participants were excluded if they presented with LBP at the time of testing or LBP of a non-musculoskeletal etiology, spinal trauma or surgery, major postural abnormality (e.g. severe scoliosis), neurological or respiratory disorders or pregnancy in the preceding 2 years.

Dancers were categorised into either no LBP or LBP groups on the basis of interview with the dancer and the dance company’s physiotherapists. Dancers were included in the LBP group if they reported a history of pain in the low back/pelvic area that required treatment or
modification of class, rehearsal or performance. Dancers were not excluded if they also reported pelvic/hip region pain. Of the 30 dancers, 22 dancers reported pain in the lower back or pelvic/hip region. Fourteen dancers reported back pain (pain between the lower ribs and gluteal fold) within the preceding 6 months and 8 dancers reported pain prior to that (range 0.5-13y). Nine of these dancers also reported pelvic/hip region pain (pain from the top of the pelvis to upper thigh) within the preceding 6 months. To gauge self-reported disability, the LBP group completed the Roland-Morris questionnaire, (Scoring range 0-24 - (mean (SD) 1(2)) and the Oswestry Disability Index (version 2.0)(Scoring range 0-100% - (8(9)%)). They also recorded their LBP level over the previous 6 months, on a 10cm Visual Analogue Scale anchored with 0 ‘no pain’ and at 10 ‘worse possible pain imaginable’ (mean(SD): 3(3) out of 10). There was no difference between groups for age, height, weight and years of dancing (t-test for independent samples: all P>0.07). Procedures were approved by the institutional Medical Research Ethics Committee and were undertaken according to the Declaration of Helsinki. Participants provided written informed consent prior to participation.

**Experimental Procedure**

Participants sat in a semi-seated upright position with their arms held relaxed by their sides and their head maintained in a neutral position (Fig. 1). The pelvis was fixated with a belt to minimize movement. A harness was tightly fitted around the thorax for attachment of cables at the front and back at the level of the 9\textsuperscript{th} thoracic vertebrae, the approximate location of the trunk’s centre of mass (15, 32). The cables passed over low friction pulleys to weights (7.5 \% body weight) attached by an electromagnet. As the front and back weights were equal, minimal muscle activity was required to hold the trunk upright. Force transducers (Futec, LSB300, USA,
Irvine, CA) were placed in series with the cable between the weights and the trunk to measure the force applied to the trunk. Either the front or back weight was released at random by switching off the electromagnet at unpredictable times to induce a trunk perturbation. After each perturbation the weight was reattached after ~5s. Force data were collected at 2000 samples/s using a Micro1401 data acquisition system (Cambridge Electronic Design Limited, UK) and Spike 2.6 software (Cambridge Electronic Design, Limited UK).

Participants were tested under 2 conditions. The aim was to use verbal cues to create a motor image to elicit a different movement response in each condition. The instructions for these conditions were devised in conjunction with dance experts. Instruction given for the standard condition was; “think of yourself sitting upright in a relaxed manner then respond as if you are sitting on a bus and the driver hits the brakes when you are not expecting it and you right yourself as quickly as possible.” This condition was repeated for 21 front and 21 back weight drops, in random order. Instruction for the second condition aimed to elicit a “fluid” response. It was; “think of yourself as fluid in your movements and respond in a fluid manner; think of holding yourself in a gentle lifted way by sustaining yourself through a gentle humming inside your body.” This condition was repeated for 5 front and 10 back weight drops in random order. The number of repetitions was less for the front weight drops as these were initially only included so the participant could not predict the direction of the perturbation, however, we subsequently elected to include these trials in the analysis. The standard condition was always performed first and not randomized as it was considered that the training of the “fluid” imagery condition could modify the movement response and carry over to the standard condition if it was performed second.
Data analysis (Modeling procedures and analyses)

Force data were analyzed offline in Matlab (Mathworks, U.S.A., Natick, MA). Trunk parameters were assumed to be constant over time and were estimated with a second order linear model for each perturbation.

\[ F = m\ddot{x} + B\dot{x} + Kx \]  

(1)

\( F \) (N) is the resultant force acting on the trunk \((F_{\text{front}} - F_{\text{back}})\), \( m \) (kg) the trunk mass, \( B \) (Nsm\(^{-1}\)) trunk damping, and \( K \) (Nm\(^{-1}\)) the trunk stiffness. Trunk linear displacement, velocity and acceleration are represented by \( x, \dot{x}, \ddot{x} \) respectively, and were calculated from the force transducer attached to the weight that remained attached during a perturbation (i.e. opposite side to the released weight). The cable attached to the weight and the force transducer remained tensioned during the perturbations, as participants did not accelerate more than gravitational acceleration. As the perturbation weight and force were known (7.5% of body weight) trunk acceleration was determined by dividing the force by the mass. Trunk velocity and displacement were derived by numerically integrating acceleration once and twice over time, respectively. To increase robustness of the estimation of the trunk parameters, both sides of equation 1 were integrated twice over time (38). As the participants did not move at the time of the weight drop, initial values of displacement and velocity for the integration procedure were set to zero.

\[ \int_{t_0}^{t_1} \int_{t_0}^{t_1} F \, dt = mx + B\int_{t_0}^{t_1} x \, dt + K\int_{t_0}^{t_1} \int_{t_0}^{t_1} x \, dt \, dt \]  

(2)

The moment the weight dropped was \( t_0 \) and \( t_1 \) was 0.329 s later. The time duration of the model was held constant between conditions and between participants to avoid bias of the estimated trunk parameters related to differences in model duration between conditions (1) and was set to 0.329 s. This duration reflected the common mode of all trials across all participants. The unknown variables of the trunk \( m, B \) and \( K \) were estimated by minimizing the least squares
differences between the trunk displacement derived from the second order linear model and the actual trunk displacement. The $R^2$ between the measured trunk displacement and the modeled trunk displacement was calculated. Trunk parameter estimates that explained more than 97% variance of the measured trunk displacement were accepted. In total, 2.4% of all trials were discarded. The amount of trunk displacement was assessed at $t=0.329\text{s}$.

**Statistical analysis**

Statistics were performed with Stata (v12, StataCorp LP, USA, TX). Outcome variables (trunk $m$, $B$, $K$) were averaged across the forward and backward perturbations within each condition (standard and “fluid”). A repeated measures analysis of variance (ANOVA) was performed for each of the outcome variables ($m$, $B$, $K$, trunk displacement) to detect whether there were any differences between the groups, conditions and perturbation direction. Group was entered as a between subjects factor (2 levels: no LBP and LBP dancers) and Condition (2 levels: standard and “fluid” responses) and Direction (2 levels: forward and backward perturbations) were entered as repeated within subjects factors. Stiffness values did not pass the Shapiro-Wilk test for normality and were log transformed. When significant interaction was identified related to group, post-hoc comparisons were undertaken with Bonferroni correction for multiple comparisons to evaluate group differences. Because of the smaller number of front weight drop (backward perturbation) trials we undertook an additional analysis with data from the first five repetitions in each direction. This did not change the outcome with respect to differences between direction and the original analysis was included. The corrected $P$-values are reported. Significance was set to $P<0.05$. 
RESULTS

Dancers with a history of LBP had significantly lower damping than dancers without LBP for perturbations applied in the standard condition (Interaction - Group × Condition; F=4.97, P=0.03, post-hoc; P=0.002) (Fig. 2). Although damping was greater in the “fluid” condition than the standard condition for the dancers with a history of LBP (post-hoc; P<0.001), this was not the case for the dancers without LBP (post-hoc; P>0.99). In the “fluid” condition there was no difference in damping between groups (post-hoc; P=0.226). Dancers with and without a history of LBP had greater damping when perturbed backwards than when perturbed forwards (Main effect - Direction; F=7.29, P=0.012).

Trunk stiffness was not significantly different between the groups (Main effect – F=1.37, P=0.252). Stiffness was less for perturbations applied in the “fluid” condition than in the standard condition (Main effect - F=23.69, P<0.001). Stiffness was higher when perturbed backwards than when perturbed forwards (Main effect - F=4.51, P=0.043) (Fig.3).

Trunk displacement was greater when perturbed forwards than when perturbed backwards (Main effect - F=14.69, P=0.001) (Table 1). Trunk displacement was also greater in the “fluid” condition than in the standard condition (Main effect - F=18.46, P<0.001). No significant difference between groups was identified for displacement (Main effect - F=0.09, P=0.768) or the estimated trunk mass (Main effect - F = 0.00, P=0.977). Estimated trunk mass was higher during the forwards than backwards perturbations (Main effect - F=26.53, P<0.001), and was higher during the standard condition than the “fluid” condition (Main effect - F=12.25, P=0.002). Differences in estimated trunk mass are most likely explained by differences in the effective mass that was perturbed as a result of changes in trunk stiffness and damping properties.
DISCUSSION

The first aim of this study was to determine whether trunk damping and stiffness differ between dancers with and without a history of LBP. The secondary aim was to assess how trunk stiffness and damping change when motor imagery is used to evoke a “fluid” movement response to the perturbation, and whether the ability to adapt differs between dancers with and without a history of LBP. We showed that dancers with a history of LBP had lower trunk damping in the standard condition, but were able to increase damping by using motor imagery to respond in a “fluid” manner to attain values comparable to dancers without LBP, whereas dancers without LBP had similar values of damping in the standard and “fluid” conditions.

Trunk damping, but not stiffness is modified in dancers with a history of LBP

Reduced damping in dancers with a history of LBP in the standard condition implies a compromised ability to attenuate velocity of trunk movement after a perturbation. This finding agrees with lower damping found in non-dancers with recurrent LBP (15) and partially confirms our hypothesis. A well-damped system returns to equilibrium rapidly when perturbed, whereas a less damped system will oscillate for a longer duration. Damping smooths movements at higher frequencies and could augment quality of trunk movement. It is probable that higher damping observed in pain-free individuals reflects more optimal motor control. It follows that lower damping in dancers with a history of LBP may be caused by compromised ability of the nervous system to respond to perturbation. This could be mediated by compromised sensory or motor function or both, which would affect mechanisms such as reflex control (18).

The deep paraspinal muscles play an important role in the control of spine motion (20, 40) and may contribute to compromised damping (34). From a sensory perspective, changes in
muscle spindle function could contribute (34) to altered trunk damping. These receptors respond to changes in length of muscles, such as that induced by changes in relative orientation of body parts/vertebra (6) and are normally found in high density in the deep paraspinal muscles including multifidus (31). From a motor perspective, the multifidus muscles play an important role in fine-tuned control of spine segments (23, 29). Further, proprioceptive acuity is enhanced by gentle to moderate (but not intense) muscle contraction (37). Changes in the ability of the multifidus muscles to provide sensory input or generate a motor response could have consequences for damping. LBP has been associated with impaired proprioception in non-dancers (4) and this is related to distorted input from the multifidus muscles (5). Multifidus muscle activity is reduced (36) and delayed (21) in non-dancers, and cross sectional area is reduced in dancers with LBP (13). Together, these changes could underpin less optimal damping in dancers with a history of LBP. Lower damping may also reflect change in passive structures as a result of injury or a combination of compromised function of both active and passive restraints to movement. Further research is required to clarify the relative contribution of these mechanisms.

In contrast to other studies (10, 15) and our hypothesis, trunk stiffness was not significantly higher in dancers with a history of LBP than dancers without LBP. Increased stiffness is thought to reflect the augmented activity of superficial trunk muscles (3, 28), which is commonly reported in association with LBP (7, 39) and may be a strategy to protect the spine from pain and injury (16, 39). Support for this proposal comes from modelling studies, which have identified that contraction of superficial trunk muscles increases spinal stability (7, 39). Although commonly adopted in non-dancers, augmented activity of superficial trunk muscles may not be a useful strategy for dancers with LBP as the accompanying increase in trunk
stiffness may be incongruent with their required function. For instance, increased stiffness may have a negative impact on quality of movement and hence performance. This is because increased stiffness could reduce spine movement (26), increase spinal load (24), and compromise balance control as a result of reduced potential for the spine to contribute to balance reactions (25, 33). The severity of pain and level of dysfunction may also influence the muscle strategy used by dancers with LBP. As the dancers with a history of LBP were on full workloads and reported low levels of disability, this may have limited our participant recruitment to dancers who had only minor adaptation.

Dancers without LBP had comparable values for damping in both the standard and “fluid” motor imagery conditions and less stiffness during the “fluid” condition. It is unclear why these dancers did not alter damping between the two different conditions. One interpretation is that damping was already optimal in this regard, in the standard condition, and further modification would have provided no additional benefit. Alternatively, the absence of significant effect may be secondary to the statistical issue of the small sample size of pain-free dancers (see below).

**Dancers with a history of LBP can use imagery to modify trunk mechanical properties**

Although dancers with a history of LBP had less damping than pain-free dancers during the standard condition, when they were instructed to use motor imagery to evoke a “fluid” response to the perturbation, they demonstrated the capacity to modulate the mechanical properties of their response by increasing trunk damping to values similar to dancers without LBP. This contrasts our hypothesis that dancers with a history of LBP would have reduced ability to adapt the mechanical properties of the trunk. This observation has two implications.
First, this implies that dancers were either able to improve/tune the natural strategies that modulate damping (e.g. reflex control), or find a solution to compensate for the compromised control of this mechanical property (see below). Regardless of the underlying mechanism, dancers with a history of LBP were able to change the quality of the movement response to make it more “fluid” in nature and more effectively absorb energy (the outcome of improved damping) with the benefit of “smoother” movement. Second, this observation implies that dancers with a history of LBP have the potential to improve the quality of trunk control and it may be possible to draw on this potential for rehabilitation.

Although the exact neural mechanisms by which motor imagery changes performance are not fully established, there is evidence that mental rehearsal can increase (14) or decrease the amplitude of H-reflexes (the electrical equivalent of a spinal stretch reflex) and is associated with cortical activation that is similar to that when movements are actually produced (19). In professional ballet dancers, motor imagery has been observed to increase hamstring muscle activation (9) and peak external hip rotation (8) resulting in more optimal dynamic alignment during a demi-plié and sauté (a dance specific movement sequence involving bilateral knee flexion followed by a jump). In addition to changing muscle activation and kinematics with motor imagery, here we show that dancers with a history of LBP can also modify mechanical properties of the trunk. Whether other clinical groups can achieve similar benefit with motor imagery requires investigation.
Methodological considerations

There are several methodological issues that warrant discussion. Motion of the pelvis and lower limb was restricted in this paradigm and the study focussed on control of the trunk (movement between the pelvis and thorax). This enabled precise estimation of the mechanical properties of this region, without the confounder of variation in strategy of hip and pelvic control. Future work should build on this data with inclusion of the lower limbs. Trunk stiffness and damping were assumed to remain constant over time and the duration was standardised. This assumption is a simplification of actual trunk control, which changes over time, however simplification is necessary to enable the estimation of trunk parameters. The validity of our estimates is strengthened by the observation that linear values of stiffness and damping were able to model actual measured trunk movement. Models that explained less than 97% of the variance of the measured trunk displacement were excluded from further analysis. This study used a convenience sample of elite classical ballet dancers and the high prevalence of LBP in professional ballet dancers limited the available sample size of pain-free dancers. This limited the statistical power of that group.

Conclusion

Dancers with a history of LBP have reduced damping when the trunk is perturbed in a standard condition and this may impact on performance. The increase in damping with “fluid” motor imagery demonstrates that dancers with a history of LBP can change this mechanical property and this could have implications for rehabilitation. However, whether there is potential to induce long-term improvement and whether this has benefit for management of LBP or improved performance requires further consideration.
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Conflict of Interest

The authors have read and concur with the content in this manuscript. We declare that we have no financial or personal relationships that can inappropriately influence our work. The results of the present study do not constitute endorsement by ACSM.
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Figure Legend

**Fig. 1** Methods. Participants sat in a semi-seated position with the pelvis fixated. Equal weights were attached to front and back so that no force acted on the trunk and minimal trunk muscle activity was required to maintain an upright posture. The weight was released from one side of the trunk by release of an electromagnet. Force transducers placed in series with the cable measured the force applied to the trunk.

**Fig. 2** Trunk damping (mean + SD) for dancers with a history of low back pain (LBP) and without a history of low back pain (No LBP), estimated from backward and forward trunk perturbations in the standard and “fluid” conditions. * - $P<0.05$ for comparison between LBP and No LBP groups; # - $P<0.05$ for comparison between conditions for the LBP group. The main effect for direction was significant.

**Fig. 3** Trunk stiffness (mean + SD) for dancers with a history of low back pain (LBP) and without a history of low back pain (No LBP), estimated from backward and forward trunk perturbations in the standard and “fluid” conditions. * - $P<0.05$ for comparison between conditions for both groups. The main effect for direction was significant.
Figure 1
Figure 2

![Graph showing Damping (Nsm^-1) for Backward and Forward movements]

- **Backward**: Standard vs. Fluid
  - No LBP: Lower damping
  - LBP: Higher damping
- **Forward**: Standard vs. Fluid
  - No LBP: Lower damping
  - LBP: Higher damping

Legends:
- *: Significant difference
- #: Trend towards significance

Damping (Nsm^-1)

Standard Fluid Standard Fluid
Figure 3

![Graph showing stiffness (Nm⁻¹) for backward and forward movements with standard and fluid conditions. The graph compares stiffness with and without LBP (low back pain).]

- Backward:
  - Standard: Open circle (No LBP) and solid circle (LBP)
  - Fluid: Open circle (No LBP) and solid circle (LBP)

- Forward:
  - Standard: Open circle (No LBP) and solid circle (LBP)
  - Fluid: Open circle (No LBP) and solid circle (LBP)

* indicates a statistically significant difference.
Table 1. Estimated trunk mass and trunk displacement.

<table>
<thead>
<tr>
<th></th>
<th>Standard Condition</th>
<th>Fluid condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Forward</td>
<td>Backward</td>
</tr>
<tr>
<td>Trunk</td>
<td>No LBP</td>
<td>LBP</td>
</tr>
<tr>
<td>Estimated mass (kg)</td>
<td>21.5(4.9)</td>
<td>22.3(6.9)</td>
</tr>
<tr>
<td>Displacement (cm)</td>
<td>3.1(0.8)</td>
<td>3.0(0.6)</td>
</tr>
</tbody>
</table>

Data are reported as mean(SD) for dancers with a history of low back pain (LBP) and without a history of low back pain (No LBP) estimated from forward and backward trunk perturbations in the standard and “fluid” conditions.