School of Physiotherapy

Motor control during an active straight leg raise in pain free and chronic pelvic girdle pain subjects

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Statement of Originality

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgment has been made. This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Darren Beales
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Abstract

Aberrant motor control strategies have been identified in chronic pelvic girdle pain (PGP) subjects. It has been proposed that aberrant motor control strategies could provide a mechanism for ongoing pain and disability in these subjects. This thesis consists of a series of studies that have investigated motor control strategies during the active straight leg raise (ASLR) test, under various loading conditions, in pain free nulliparous female subjects (n=14) and female subjects with chronic PGP (n=12). Clinical examination of the chronic PGP subjects had identified the SIJ and surrounding structures as the primary source of symptoms. Heaviness of the leg (+/- pain) when the pain subjects performing the ASLR was relieved in all the pain subjects with the addition of manual pelvic compression during the ASLR, consistent with a pain disorder associated with impaired force closure mechanism.

Phase of respiration was monitored with the pneumotach. Electromyography was recorded bilaterally from internal obliquus abdominis (IO), external obliquus abdominis, rectus abdominis, anterior scaleni and rectus femoris as well as the right chest wall (CW). Intra-abdominal pressure (IAP) and intra-thoracic pressure were measured with a nasogastric catheter attached to custom-made pressure transducer equipment. Downward pressure of the non-lifted leg during an ASLR was recorded with an inflated pad linked to a pressure transducer placed under the heel. Data for these variables were collected in a custom designed data acquisition program. A separate custom designed program was used for data processing. Additionally, motion of the pelvic floor (PF) was monitored with a real-time ultrasound unit and recorded to digital video for manual processing.

Study 1: Motor control patterns during an active straight leg raise in pain free subjects

Pain free subjects demonstrated greater muscle activation of the abdominal and CW ipsilateral to the side the ASLR was performed on. This effect was most pronounced local to the pelvis in IO. This muscle pattern was associated with a small increase in

IAP. Although there was an overall commonality in the motor control patterns, individual variation was apparent. This study contradicted the theory of anterior diagonal slings for the provision of pelvic stability/force closure during the ASLR. The findings of this study highlights the flexibility of the neuromuscular system in controlling load transference during an ASLR, and the plastic nature of the abdominal cylinder.

Study 2: Motor control patterns during an active straight leg raise in chronic pelvic girdle pain subjects

In contrast to pain free subjects, chronic PGP subjects demonstrated bracing of the abdominal wall and right CW during an ASLR on the symptomatic side of the body. This was associated with higher levels of IAP and increased downward movement of the PF. Increased levels of IAP could have negative consequences and be provocative of pain. The findings from this study support the notion that aberrant motor activation patterns exist in this group of subjects.

Study 3: The effect of increased physical load during an active straight leg raise in pain free subjects

When performing an ASLR with additional physical load around the ankle, pain free subjects demonstrated increased muscle activation levels compared to an ASLR without additional load, with higher levels of IAP. Greater ipsilateral IO activation observed during an ASLR was maintained during the loaded ASLR, unlike the symmetrical bracing pattern observed in PGP subjects. This adds support to the notion that PGP subjects have aberrant motor control patterns during an ASLR, not represented solely by the increased effort of lifting the leg.

Study 4: The effect of resisted inspiration during an active straight leg raise in pain free subjects

Pain free subjects performed an ASLR while also breathing with inspiratory resistance, to simultaneously provide a stability and respiratory challenge upon the neuromuscular system. Motor activation in the abdominal wall was highlighted by a cumulative increase in motor activation when performing the ASLR with inspiratory resistance compared to performing these tasks in isolation. Despite this general increase in activation, a pattern of greater IO activity on the side of the leg lift observed during an ASLR was preserved when inspiratory resistance was added to the ASLR. Intra-abdominal pressure demonstrated an incremental increase similar to the increase in muscle activity. This confirms that pain free subjects are able to adapt to multiple demands of an ASLR and inspiratory resistance by an accumulative summation of the patterns utilised when these tasks are performed independently.

Study 5: Non-uniform motor control changes with manually applied pelvic compression during an active straight leg raise in chronic pelvic girdle pain subjects

The PGP subjects performed an ASLR with the addition of manual pelvic compression. The hypothesis that this would reduce muscle activation levels and IAP was not supported. Rather, trends for either trunk muscle facilitation or inhibition were identified. Trunk muscle facilitation was associated with higher levels of IAP, whereas motor inhibition was associated with lower levels of IAP. These findings suggest a potential for different underlying mechanism associated with the chronic PGP disorder in these subjects and variable responses to pelvic compression.

While a number of the statistical analyses were significant suggesting some consistency in motor patterns, visual inspection of the data demonstrated individual variations in the motor control strategies in both pain free and chronic PGP subjects.

Taken together, these findings demonstrate that:

- Pain free subjects adopt a predominant pattern of greater motor activation ipsilateral to the side of the leg lift during an ASLR, an ASLR with additional physical load and an ASLR performed with inspiratory resistance. Within this commonality in motor control, individual variations exist.
- Chronic PGP subjects do not demonstrate greater ipsilateral activation during an ASLR on the symptomatic side. Instead they adopt a bilateral bracing/splinting motor control pattern with increased IAP.

It is hypothesised that:

- The aberrant motor control patterns observed in these chronic PGP subjects may be maladaptive in nature. These aberrant patterns may have negative consequences on pelvic loading and stability, respiration, continence, pain and disability.

- The findings of this thesis are consistent with complex underlying mechanisms driving chronic pelvic girdle pain disorders, and suggest that multiple factors have the potential to influence motor control strategies in these subjects.
- These findings may have implications for management of chronic PGP disorders, highlighting the need for individualised programs that attempt to normalise aberrant motor control strategies.

This thesis has added substantially to the knowledge of motor control in chronic PGP disorders, a research area in its infancy compared to the investigation of motor control in the lumbar and cervical regions of the spine. Now that PGP has been recognised as a separate diagnostic entity to LBP, greater understanding of this region is essential for the identification of sub-groups within the diagnosis of PGP, and for the development of specific intervention strategies that target the underlying pain mechanisms driving these disorders.

List of Abbreviations

Abbreviations used in the text of this thesis. Additional abbreviations related to tables and figures are within the associated captions.

ASLR	active straight leg raise
ASLR+Comp	active straight leg raise with manual pelvic compression
ASLR+IR	active straight leg raise plus inspiratory resistance
ASLR+PL	active straight leg raise plus additional physical load
CI	confidence interval
CW	chest wall
EMG	electromyography/electromyographic
EO	obliquus externus abdominis
IAP	intra-abdominal pressure
ICC	intra-class correlation coefficient
IO	obliquus internus abdominis
IR	inspiratory resistance
ITP	intra-thoracic pressure
LSD	least square difference
P(di)	trans-diaphragmatic pressure
PF	pelvic floor
PGP	pelvic girdle pain
RA	rectus abdominis
RMS	root mean square
RR	respiratory rate
RS	resting supine
RSA	radiosterometric analysis
Sc	anterior scalene
SIJ	sacroiliac joint
SIJs	sacroiliac joints

Table of Contents

Chapter 1: Introduction

Pelvic girdle pain has been recognised as a separate diagnostic entity from disorders where pain emanates from the lumbar spine. For many, this condition becomes chronic, despite no identified pathology with diagnostic scans. There is good evidence that the sacroiliac joint (SIJ) can be identified as a painful structure in certain pelvic girdle pain (PGP) presentations. However, the identification of a painful structure does not necessarily reveal the mechanism(s) driving the disorder. A classification system has been proposed for so called non-specific chronic PGP. This system recognises the multifactorial nature of chronic PGP and the need to identify the underlying pain mechanism(s) so that the disorder can be managed in an appropriate and efficacious manner. There is growing evidence in support of the supposition that aberrant motor control strategies observed in chronic PGP subjects provide a mechanism for ongoing pain and disability. Improved understanding of motor control strategies in chronic PGP subjects is needed to assist classification of these disorders and to inform treatment.

1.1 Pelvic girdle pain

Pelvic girdle pain has recently been adopted as a catchall term encompassing musculoskeletal disorders of the pelvis (Vleeming, Albert, Ostgaard, Sturesson, & Stuge, 2008). Uptake of this terminology acknowledges the recognition of PGP disorders as a separate diagnostic category from disorders of the lumbar spine. This has been important as PGP disorders are often misdiagnosed as lumbar disorders, which can lead to inappropriate and ineffective management. Also, the existence of the "European guidelines for the diagnosis and treatment of pelvic girdle pain" (Vleeming et al., 2008) attests to the growing recognition of the actual existence of these disorders, as in some circles PGP is not an accepted clinical entity (Nordin, 2008; Renckens, 2000; Schofferman, 2007). The recognition of PGP disorders as distinct from lumbar disorders is based largely on clinical expertise, common sense and a large body of literature (see rest of this introduction). Future systematic reviews with methodological appraisal will help strengthen this argument.

The European guidelines have proposed the following definition for musculoskeletal PGP (Vleeming et al., 2008, pg 797):

> "Pelvic girdle pain generally arises in relation to pregnancy, trauma, arthritis and osteoarthritis. Pain is experienced between the posterior iliac crest and the gluteal fold, particularly in the vicinity of the sacroiliac joint. The pain may radiate in the posterior thigh and can also occur in conjunction with/or separately in the symphysis.
>
> The endurance capacity for standing, walking, and sitting is diminished.
>
> The diagnosis of pelvic girdle pain can be reached after exclusion of lumbar causes. The pain or functional disturbances in relation to pelvic girdle pain must be reproducible by specific clinical tests."

This definition is for musculoskeletal disorders, thereby excluding gynaecological and urological disorders (Vleeming et al., 2008).

1.1.1 Prevalence

It is estimated that between 72-84% of women develop pain in the lumbopelvic region during pregnancy (Bastiaanssen et al., 2005; Mogren & Pohjanen, 2005; To & Wong, 2003), with the point prevalence for PGP between 16-20% (Albert, Godskesen, & Westergaard, 2002; Larsen et al., 1999; Ostgaard, Andersson, & Karlsson, 1991). For most this is self limiting, resolving within three months post-pregnancy. However for 7-10% pain and disability are still present two years post partum (Albert, Godskesen, & Westergaard, 2001; Rost, Jacqueline, Kaiser, Verhagen, & Koes, 2006; Wu et al., 2004).

The development of PGP is not solely an affliction of pregnancy. Other aetiologies have been described, most notably following a traumatic event such as a fall on the buttock (Chou et al., 2004; O'Sullivan et al., 2002). A number of studies have investigated the prevalence of the SIJ as the primary source of symptoms in subjects presenting with non-specific chronic low back pain. Estimates have been of the order of 13% (Petersen et al., 2004; Schwarzer, Aprill, & Bogduk, 1995), though it could be as low as 3% (Laslett, McDonald, Tropp, Aprill, & Oberg, 2005) or as high as 30% (Schwarzer et al., 1995).

1.1.2 Specific and Non-Specific Pelvic Girdle Pain

Pelvic girdle pain is an umbrella term, in the same manner as the term low back pain is, representing a multitude of pathologies and disorders. For some subjects who present with PGP a specific diagnosis can be obtained. Examples of specific PGP disorders are ankylosing spondylitis, sacroiliitis and stress fractures. These types of disorders are identifiable from imaging studies and blood work (Johnson, Weiss, Stento, & Wheeler, 2001; Maksymowych et al., 2005). Frequently though, chronic PGP subjects present with no readily identifiable pathology based on imaging and/or blood work. These subjects are labeled as having non-specific PGP. Unfortunately this label is often associated with a poor treatment outcome (O'Sullivan & Beales, 2007b, 2007c). Enhanced understanding of chronic non-specific PGP disorders is crucial for the advancement of management strategies for these types of subjects.

An attempt has been made to catagorise non-specific PGP subjects according to the site of symptoms (Albert, Godskesen, & Westergaard, 2000; Albert et al., 2001; Albert et al., 2002). In this system, subjects are classified to one of five groups; one-sided SIJ syndrome, double-sided SIJ syndrome, symphysis pubis pain, pelvic girdle syndrome which involves all three joints, and a miscellaneous category. Indeed pain emanating from the SIJ and the surrounding ligamentous and myofascial structures is often associated with chronic PGP disorders (Albert et al., 2000; Berg, Hammar, Moller-Nielsen, Linden, & Thorblad, 1988; Damen et al., 2001; Kristiansson & Svardsudd, 1996; Laslett, Young, Aprill, & McDonald, 2003; Mens, Vleeming, Snijders, Stam, & Ginai, 1999; O'Sullivan et al., 2002; Vleeming, de Vries, Mens, & van Wingerden, 2002). By definition painful disorders of the symphysis pubis also fit under the umbrella of PGP. The identification of painful structures is an important step in diagnosing PGP disorders. However, this approach in isolation will not help to clarify the underlying pain mechanism(s) that is driving the ongoing pain state (O'Sullivan, 2005). Such a structurally based catagorisation of non-specific chronic PGP does not assist with the development of intervention programs targeted at the underlying mechanism. A better understanding of the mechanisms underlying chronic PGP is required.

Key Points:

- PGP is largely self limiting, however in a small group may become chronic, leading to ongoing pain and disability
- Improved understanding of the pain mechanisms underlying non-specific PGP are needed to better inform treatment strategies

1.2 The Sacroiliac Joint: Anatomical and biomechanical considerations

This thesis investigated motor control patterns in pain free subjects and subjects with chronic PGP. Moreover, the PGP subjects all had a clinical diagnosis consistent with the SIJ and surrounding ligamentous structures being a primary peripheral pain generator (O'Sullivan & Beales, 2007b). These structures are a potential source of nociception (Borowsky & Fagen, 2008; Fortin, Aprill, Ponthieux, & Pier, 1994; Fortin, Dwyer, West, & Pier, 1994; Szadek, Hoogland, Zuurmond, de Lange, & Perez, 2008; Vilensky et al., 2002). Prior to examining the efficacy of the diagnostic criteria for determining SIJ involvement in PGP, it is useful to understand the anatomy and biomechanics of the SIJ. This is particularly important for clinicians dealing with PGP, as there are many misconceptions about the SIJ (O'Sullivan & Beales, 2007b, 2007c). A number of review articles that include anatomical reviews of the SIJ are available (Hazle & Nitz, 2008; Oldreive, 1996; Pool-Goudzwaard, Vleeming, Stoeckart, Snijders, & Mens, 1998; Sizer, Phelps, & Thompsen, 2002), though their interpretations vary which highlights why there is some confusion about the role of the sacroiliac joints (SIJs) in chronic PGP.

1.2.1 Basic anatomical considerations

The SIJs are synovial articulations, formed between the articular surfaces of the sacrum and the ilium (Gray & Williams, 1989). Descriptions of the joint surfaces often describe the articular cartilage of the sacrum as being hyaline in nature while the iliac surfaces are fibro-cartilage (Gray & Williams, 1989). A detailed histological study has confirmed this in children (Kampen & Tillmann, 1998). By puberty though changes in the structure of the articular cartilage begin to occur. One difference is the appearance of hyaline cartilage within the iliac surface (Kampen & Tillmann, 1998). At this point in time the sacral cartilage is noticeably thicker than the iliac cartilage, while the subchondral bone of the iliac surface is thicker than that of the sacral side (Kampen & Tillmann, 1998). Further physiological changes occur during early adulthood that may be considered degenerative in nature, as they progress with advancing age (Kampen & Tillmann, 1998). These degenerative changes are more pronounced on the iliac surfaces. It is debatable as to whether or not these changes age related changes are pathoanatomical in nature (Kampen & Tillmann, 1998).

The primary function of the SIJs within the pelvis is to act as part of the kinetic chain that facilitates load transfer between the lower extremities and the trunk (Gray & Williams, 1989; Kapandji, 1982). For this reason these joints are better designed for stability rather than mobility. It is important to have a thorough understanding of the characteristics of both stability and mobility to help justify clinical decision making processes in relation to the diagnosis, classification and treatment of SIJ disorders.

1.2.2 Stability of the sacroiliac joints- form and force closure

A multitude of studies from many disciplines have led to the development and refinement of a model for pelvic stability. For extensive revision the reader is referred to review articles by Pool-Goudzwaard et al (1998) and Lee and Vleeming (2000). There are inherent similarities between this theoretical model of pelvic stability and Panjabi's model of spinal stability (Panjabi, 1992a, 1992b). An outline of this model follows.

The original model describes pelvic stability as a function of form and force closure (Pool-Goudzwaard et al., 1998). *Form closure* is essentially a function of the architecture and design of the SIJs. The major contributing factors to form closure are the wedge shape of the sacrum, the congruent ridges and depressions on the SIJ surfaces and the relatively coarse texture of the articular cartilage (Snijders, Vleeming, & Stoeckart, 1993a; Vleeming, Stoeckart, Volkers, & Snijders, 1990; Vleeming, Volkers, Snijders, & Stoeckart, 1990). The ligaments (interosseous, sacrotuberous, sacrospinous, long dorsal, iliolumbar) are also essential in the provision of passive stability/form closure (Pool-Goudzwaard et al., 2003; Wang & Dumas, 1998). For instance the interosseous ligament is perhaps the strongest ligament in the body (Wang & Dumas, 1998), consistent with its role in providing mechanical stability to the SIJ. Interestingly though, the axial interosseous ligament (which constitutes approximately 14% of the entire interosseous ligament) is relatively weak, suggesting a potential proprioceptive role for this portion of the ligament rather than a stability role (Bechtel, 2001). A proprioceptive role for ligaments in conjunction with a mechanical role is consistent with current concepts of ligament as important sensory structures (Solomonow, 2006).

Force closure refers to the complex interaction of muscles and ligaments that may, when acting in symphony, actively add compression to the pelvic ring and thereby enhancing stability of the SIJs (Snijders et al., 1993a). A multitude of theoretical (Snijders et al., 1993a; Snijders, Vleeming, & Stoeckart, 1993b), cadaveric (Pool-Goudzwaard et al., 2003; Pool-Goudzwaard et al., 2004; Snijders, Hermans, & Kleinrensink, 2006; Snijders, Ribbers, de Bakker, Stoeckart, & Stam, 1998; Vleeming, Buyruk, Stoeckart, Karamursel, & Snijders, 1992; Vleeming et al., 1996; Vleeming, Pool-Goudzwaard, Stoeckart, van Wingerden, & Snijders, 1995; Vleeming, Stoeckart, & Snijders, 1989; Vleeming, Stoeckart et al., 1990; Vleeming, Van Wingerden, Snijders, Stoeckart, & Stijnen, 1989; Vleeming, Volkers et al., 1990) and in-vivo (Damen, Spoor, Snijders, & Stam, 2002; Mens, Damen, Snijders, & Stam, 2006; O'Sullivan et al., 2002; Richardson et al., 2002; Snijders et al., 1998; van Wingerden, Vleeming, Buyruk, & Raissadat, 2004) studies lend support to this notion. For example, muscular forces across the SIJs may enhance pelvic stability by directly compressing the SIJ surfaces (Richardson et al., 2002; van Wingerden et al., 2004). Muscular forces may also increase tension within the ligamentous structures to which they attach, reducing mobility of the SIJs and further augmenting pelvic stability (Vleeming et al., 1996; Vleeming, Van Wingerden et al., 1989). The combination of form and force closure is termed the ‘self-bracing mechanism’ (Snijders et al., 1993a).

It has been proposed that the muscles that contribute to force closure may be divided into muscular slings (Mooney, Pozos, Vleeming, Gulick, & Swenski, 2001; Pool-Goudzwaard et al., 1998; Vleeming et al., 1995). The longitudinal slings are formed by lumbar multifidus, the deep layer of the thoracolumbar fascia and the long head of biceps femoris connecting into the sacrotuberous ligament (Figure 1.1). The posterior oblique slings consist of the latissimus dorsi and gluteus maximus of the opposite side acting synergistically through the thoracolumbar fascia (Figure 1.2). The anterior oblique slings are formed by the externus obliquus abdominis (EO) and contralateral internal obliquus abdominis (IO), with contribution from transversus abdominis (Figure 1.3). While a host of theoretical and cadaveric research forms the backbone of this model, only one study seems to have directly investigated the existence of these slings in-vivo. Mooney and colleagues (2001) observed synergistic activation of latissimus dorsi on one side of the body and gluteus maximus activation on the opposite side, supporting the existence of the posterior oblique slings. This finding appears entirely consistent with the tasks investigated in that study, namely walking on a treadmill and resisted trunk rotation. It remains to be seen whether this pattern occurs with other functional tasks. Consistent with their attachments to the pelvis, the pelvic floor (PF) muscles have been recognised as important contributors to pelvic stability (Pool-Goudzwaard et al., 2004; Snijders et al., 1993a).

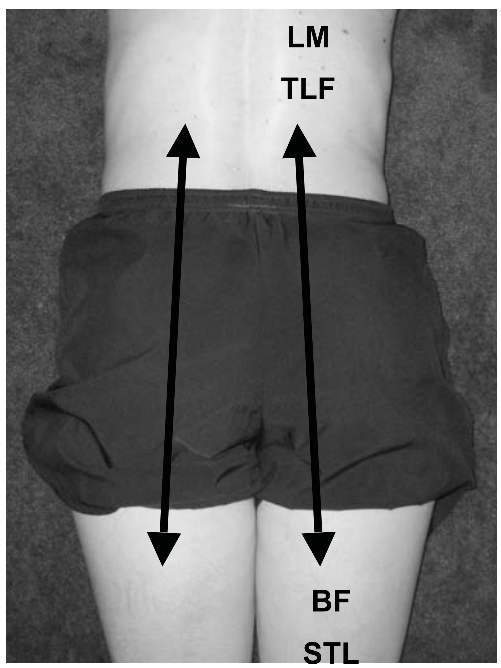

Figure 1.1 The longitudinal slings (LM = lumbar multifidus, TLF = deep layer of the thoracolumbar fascia, BF = long head of biceps femoris, STL = sacrotuberous ligament)

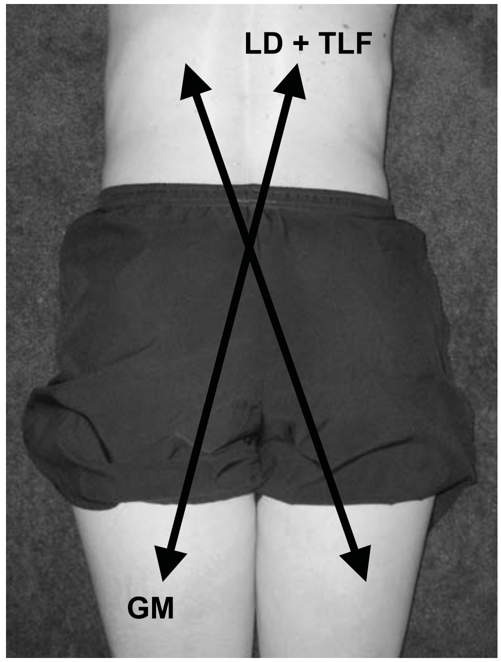

Figure 1.2 The posterior oblique slings (LD = latissimus dorsi, TLF = deep layer of the thoracolumbar fascia, GM = gluteus maximus)

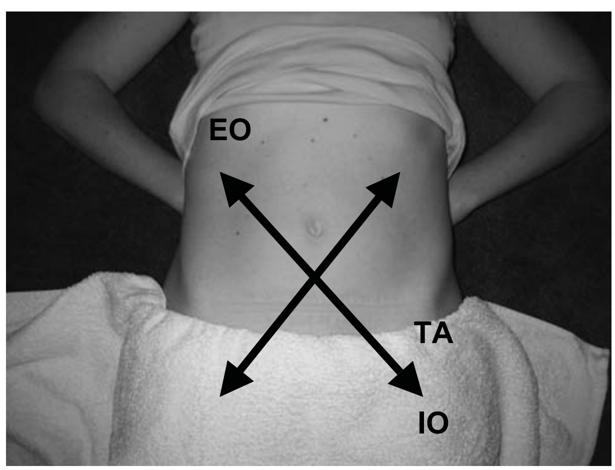

Figure 1.3 The anterior oblique slings (EO = externus obliquus abdominis, IO = internal obliquus abdominis, TA = transversus abdominis)

In addition to the role of these muscle groups in contributing to pelvic stability by enhancing compression through the pelvis these muscles contribute, usually simultaneously, to other bodily requirements. Although it is artificial to separate lumbar stability from pelvic stability, the provision of lumbar stability is also within the domain of these muscles. Through attachments to the spine, either directly or indirectly via fascia, all of the aforementioned muscles (save perhaps the PF) are able to control and stiffen the lumbar spine to enhance stability. There is an immense body of literature investigating lumbar stability, including numerous review articles as a potential starting point (McGill, Grenier, Kavcic, & Cholewicki, 2003; Panjabi, 2003; Reeves, Narendra, & Cholewicki, 2007). It is beyond the scope of this thesis to fully review the biomechanics of lumbar stability.

In addition the abdominal wall and PF, in conjunction with the diaphragm, form an abdominal canister that is capable of producing and controlling intra-abdominal pressure (IAP) (Figure 1.4). The predominant theory for the role of IAP in enhancing trunk stiffness and providing spinal stability is that IAP itself contributes to stability in conjunction with the mechanical action of these muscles on the spine (Essendrop, Andersen, & Schibye, 2002). The muscles of force closure, particularly the PF, also have roles in micturition, defecation, continence control and sexual function. Review articles highlight some of the relationships between these muscle and continence control (Grewar & McLean, 2008; Sapsford, 2004). For example, co-contraction of the PF and abdominal wall is a normal response during either PF or abdominal contraction maneuvers (Neumann & Gill, 2002; Sapsford & Hodges, 2001; Sapsford et al., 2001; Thompson, O'Sullivan P, Briffa, & Neumann, 2006). Finally, the muscles of force closure are also involved in respiration. In line with the essential role of respiration, the neuromuscular control of respiration is a highly complex and specialised task (Abraham et al., 2002; Aliverti et al., 1997; Aliverti et al., 2002) (for further review see Chapter 6- Study 4: The effect of resisted inspiration during an active straight leg raise in pain free subjects).

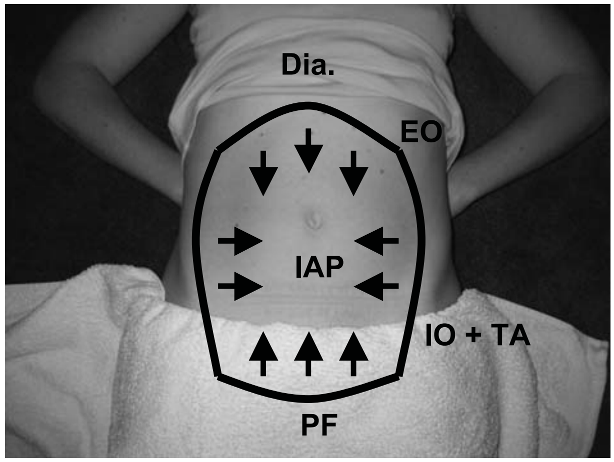

Figure 1.4 Muscles forming an abdominal canister that is capable of the production and control of intra-abdominal pressure (IAP). (Dia. = diaphragm, EO = externus obliquus abdominis, IO = internal obliquus abdominis, TA = transversus abdominis, PF = pelvic floor)

The model of form-force closure has been expanded to incorporate two further dimensions. The first of these is motor control (Lee & Vleeming, 2000; Pool-Goudzwaard et al., 1998). Deficits in motor control have been found in subjects with clinical diagnosis of PGP that is consistent with the SIJ as a peripheral source of symptoms (de Groot, Pool-Goudzwaard, Spoor, & Snijders, 2008; Hungerford, Gilleard, & Hodges, 2003; O'Sullivan et al., 2002; Pool-Goudzwaard et al., 2005) (motor control in PGP is reviewed in Section 1.5). The findings of these studies support the inclusion of this dimension in the model.

The forth component of the model is termed ‘emotion and awareness’ (Lee & Vleeming, 2000), but may also be considered under the broader label of psychosocial factors. The importance of considering these factors in chronic pain disorders is well known (Linton, 2000, 2005; Main & Watson, 1999). There is growing recognition of these factors as a contributing mechanism in chronic PGP (Bastiaenen et al., 2008; Bastiaenen et al., 2004; Bastiaenen et al., 2006; Gutke, Josefsson, & Oberg, 2007; O'Sullivan & Beales, 2007b, 2007c; Van De Pol, Van Brummen, Bruinse, Heintz, & Van Der Vaart, 2007). The direct effect of these factors on pelvic stability is yet to be ascertained. However, psychosocial factors such as stress, personality characteristics and mental processing requirements have been shown to directly affect levels of trunk muscle activity and spinal loads during lifting tasks (Davis, Marras, Heaney, Waters, & Gupta, 2002; Marras, Davis, Heaney, Maronitis, & Allread, 2000). It is reasonable to assume that the same effect would exist on loading of the pelvis.

Key Point:

- Pelvic stability, and therefore load transference through the pelvis, can be a function of form closure, force closure, motor control and the influence of psychosocial factors

1.2.3 Movement of the sacroiliac joints

Radiosterometric analysis (RSA) is the gold standard for examining joint mobility in orthopaedics (Selvik, 1989). For the measurement of motion in the SIJs the procedure firstly involves the implantation of 0.8mm tantalum balls into the sacrum and ilium (Sturesson, Selvik, & Uden, 1989). Dual x-rays are taken simultaneously which essentially allows three-dimensional analyses of position and therefore motion. Within this system SIJ motion is described in terms of rotation and translation. The error in measurement for SIJ motion using this system is reported as 0.1°-0.2° for rotation and 0.1mm for translation (Sturesson et al., 1989). The validity of using this procedure to measure SIJ movement is very high, particularly in comparison to studies using alternate measuring systems like skin markers.

Utilising RSA methodology in subjects with a clinical diagnosis of a SIJ pain disorder, it has been determined that the maximum rotation available between the end points of range in non-weight bearing is a mean of 2.5° (range 1.6° to 3.9°), with mean translation being in the order of 0.7mm (range 0.3mm to 1.6mm) (Sturesson et al., 1989). Anterior rotation of the sacrum is termed nutation, posterior rotation counter-nutation. These values are consistent with values obtained in healthy subjects by another in-vivo measurement method where Kirschner wires were inserted into the ilium and sacrum (Jacob & Kissling, 1995). They are also consistent with values obtained during biomechanical studies in cadaveric specimens (Brunner, Kissling, & Jacob, 1991; Vleeming, Buyruk et al., 1992; Vleeming, Van Wingerden et al., 1992; Wang & Dumas, 1998). Stratification for sex has revealed males to be less mobile than females (Brunner et al., 1991; Sturesson, 1997).

Once loaded in standing RSA techniques reveal less motion occurs within the SIJs in comparison to maximal non-weight bearing motion. Mean rotation of 0.2° and mean translation of 0.3mm was found in the SIJ during standing hip flexion (Sturesson, Uden, & Vleeming, 2000). This is consistent with the load transference function of the SIJs and their design for stability over mobility (Sturesson et al., 2000). Movement was equal on the loaded and unloaded side during this task, with some subjects having net nutation of the sacrum, but others net counter-nutation. The authors noted that this motion was so small that "…external detection by manual methods is virtually impossible" (Sturesson et al., 2000, pg 368)

Fibrosis leading to decreased mobility and even ossification of the SIJs has been considered a normal physiological process of aging (Gray & Williams, 1989). However, others consider this process to be pathological in nature (Kampen & Tillmann, 1998). A recent study utilising three-dimensional computed tomography scans has found SIJ fusion to be more commonly associated with advancing age in males (Figure 1.5) (Dar et al., 2008).

Key Points:

- Small movements in the sacroiliac joints in non-weight bearing are greatly reduced during weight bearing
- This is in line with the function of the SIJs to transfer load between the trunk and lower extremities

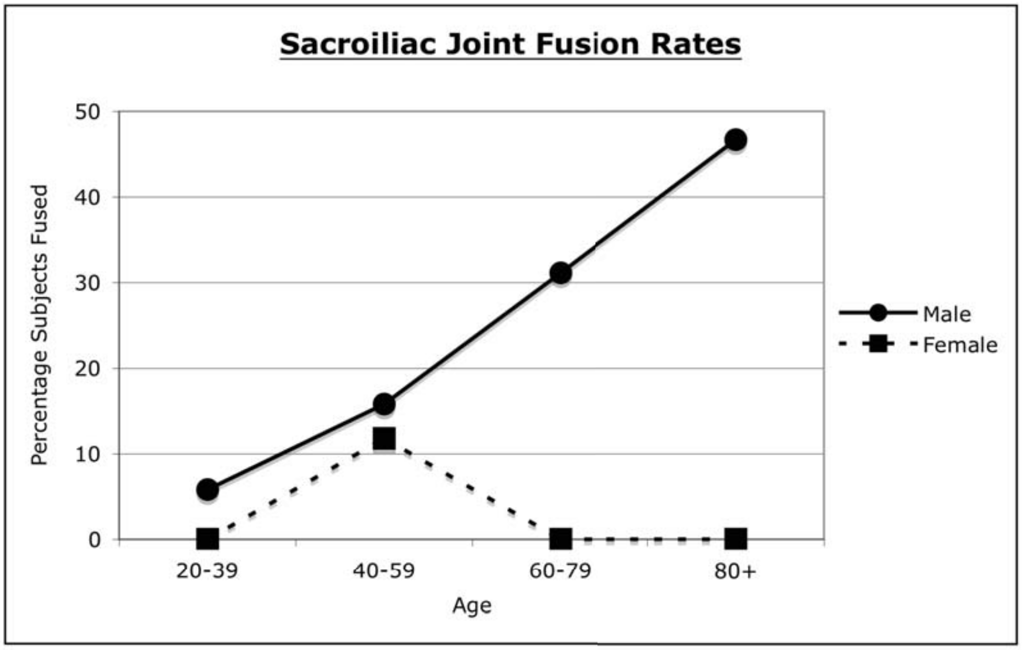

Figure 1.5 Graphical representation of sacroiliac joint (SIJ) fusion rates, compiled from data in Dar et al, "Sacroiliac joint fusion and the implications for manual therapy diagnosis and treatment" (Dar et al., 2008). Increasing age in male subjects is associated with greater incidence of SIJ fusion.

1.2.4 Is there hypermobility in sacroiliac joint pain?

A key finding from the work of Sturesson and colleagues is that in the samples of subjects with a unilateral SIJ disorder, no difference in motion could be detected between the symptomatic and asymptomatic SIJs (Sturesson, 1997; Sturesson et al., 1989; Sturesson et al., 2000). Interestingly though a small difference (less than 0.5°) has been detected comparing subjects with unilateral symptoms to those with bilateral symptoms, with the subjects having bilateral symptoms showing the greater movement (Sturesson, 1997).

Mens and colleagues have assessed pelvic ring mobility in a group of subjects with plain radiography (Mens et al., 1999). Subjects were x-rayed standing with one leg on a box with the other leg hanging passively. This was then repeated on the other side. Additionally some subjects were radiographed during an active straight leg raise (ASLR) bilaterally (for a full review of the ASLR test see Section 1.3.3). Movement in the form of a step in the symphysis pubis was measured. The authors reported a significant side to side difference in symphysis pubis movement during these tests (Mens et al., 1999). This movement in the symphysis pubis was interpreted to reflect SIJ motion. Unfortunately there was a lack of a control group for reference in this study. Also there was no evidence or rationale to explain to what degree symphysis pubis movement translates to SIJ movement.

A technique using Doppler imaging of vibrations has been developed as a non-invasive objective measure of SIJ stiffness (Buyruk, Snijders et al., 1995; Buyruk, Stam et al., 1995). In brief, vibration is measured across the SIJ with the thought that a 'looser' joint will dampen the transmission of the vibration across the joint. Studies in subjects with peripartum PGP indicate that there is no difference in SIJ stiffness overall when these subjects are compared to pain free pregnant women (Buyruk et al., 1999; Damen et al., 2001). Nor is there a difference in overall stiffness in subjects with moderate to severe symptoms compared to those with mild symptoms (Damen et al., 2001). However, subjects with moderate to severe symptoms are more likely to display asymmetrical stiffness of the SIJs (Damen et al., 2001). This finding of asymmetrical stiffness has been found to be prognostic with regard to the development of moderate to severe peripartum pelvic pain (Damen, Buyruk et al., 2002). It is important to note though that the results of studies employing the technique of Doppler imaging of vibrations must be viewed with caution as questions remain regarding the validity of the procedure (De Groot, Spoor, & Snijders, 2004).

To summarise this information, using the gold standard for joint mobility, RSA, there clearly exists a group of subjects with clinically diagnosed SIJ pain who have normal SIJ movement (Sturesson, 1997; Sturesson et al., 1989; Sturesson et al., 2000). The existence of hypermobility of the SIJs in PGP disorders remains unanswered. The RSA technique has shown that subjects with bilateral pain have slightly more mobility than those with unilateral symptoms (Sturesson, 1997). It is questionable if the magnitude of this difference (< 0.5mm) is clinically significant. Furthermore, there is not a clear relationship between hypermobility and levels of pain and disability. Findings from studies not using RSA that are also suggestive of the existence of SIJ hypermobility should be replicated with the use of RSA before clear conclusions are made.

Key Points:

- PGP can occur without any signs of SIJ hypermobility
- There may be a sub-group of PGP subjects for whom SIJ hypermobility is a factor in symptom generation, but this is yet to be validated

1.2.5 Do 'positional faults' of the sacroiliac joints exist?

In some manual therapy paradigms positional faults are presented as an underlying mechanism for PGP (Cibulka, 2002; DonTigny, 1990; Hazle & Nitz, 2008; Kuchera, 1997; Oldreive, 1998; Sandler, 1996). To the author's knowledge only one study exists which uses the gold standard of RSA to investigate changes in position of the SIJs. After clinically identifying subjects with unilateral SIJ symptoms and identified positional and movement disturbances, Tullberg and co-workers applied the technique of RSA to assess SIJ position (Tullberg, Blomberg, Branth, & Johnsson, 1998). Subjects then underwent mobilisation/manipulation and the position of the SIJs was reassessed with RSA. Clinical evaluation post-treatment found the clinically identified positional faults had normalised, however, the position of the SIJs did not alter when re-assessed with RSA (Tullberg et al., 1998). This finding seriously challenges the notion of positional faults in subjects with SIJ pain.

Key Point:

- Current evidence using the gold standard of RSA does not support the existence of positional faults in the SIJs

1.3 Identification of the sacroiliac joint as a source of pain

Assessment of the SIJs must be considered within the broader context of assessing the lower quadrant. As a link in the kinetic chain that facilitates load transference through the pelvis, this would specifically include the lumbar spine (Laslett, Aprill, McDonald, & Young, 2005; Laslett et al., 2003), symphysis pubis, the hip joints and surrounding muscles. Therefore careful consideration must be given to the factors that distinguish SIJ pain from symptoms generated in these other regions.

1.3.1 Sacroiliac joint pain is primarily over the sacroiliac joint

Radiological guided double diagnostic injections of the SIJ have been proposed as the gold standard for confirmation of this structure as a pain generator (Maigne, Aivaliklis, & Pfefer, 1996). There are varying opinions regarding the validity of this approach. One opinion is that this procedure will only test intra-articular structures, and as such may overlook the surrounding ligamentous structures that may also be an important source of symptoms (Vleeming et al., 2008). It has also been suggested that leakage of the injected material from the SIJ can affect extra-articular structures, in particular nerves but also ligaments, complicating the results of diagnostic blocks (Berthelot, Labat, Le Goff, Gouin, & Maugars, 2006). False positives may be another confounder (Berthelot et al., 2006; Schwarzer et al., 1994). It is generally agreed that with the lack of a true gold standard for identifying the SIJ as a source of pain (Saal, 2002), even when considering their limitations, there is still good utility for diagnostic blocks (Laslett, van der Wurff, Buijs, & Aprill, 2007; Saal, 2002).

Studies using two anaesthetic blocks (Maigne et al., 1996), or needle provocation of pain followed by one anaesthetic block (Dreyfuss, Michaelsen, Pauza, McLarty, & Bogduk, 1996; Young, Aprill, & Laslett, 2003), have shown that pain from the SIJ is primarily in the region of the SIJ (ie. the sacral sulcus, posterior superior iliac spine). This finding is supported by other studies that have investigated pain maps following single joint injection of the SIJ (Fortin, Aprill et al., 1994; Fortin, Dwyer et al., 1994;

Schwarzer et al., 1995; van der Wurff, Buijs, & Groen, 2006b). The SIJ may refer pain distally, with great variability in the distal referral patterns (Dreyfuss et al., 1996; Fortin, Aprill et al., 1994; Fortin, Dwyer et al., 1994; Maigne et al., 1996; Schwarzer et al., 1995; Slipman et al., 2000; van der Wurff et al., 2006b). These studies also demonstrate that the SIJ does not refer pain proximally into the lumbar region. One study would seem to refute this finding, where 72% of subjects with clinically diagnosed SIJ pain had pain in a region labeled as 'low lumbar' (Slipman et al., 2000). This area was defined as between the iliac crests and the posterior superior iliac spines, an area containing the lower lumbar segments and portions of the SIJs, which may have caused some ambiguity in the results.

Key Points:

- Pain from the SIJ is primarily over the SIJ
- The SIJ may refer distally, but does not appear to refer proximally

1.3.2 A battery of pain provocation tests for sacroiliac joint pain

Some paradigms of manual therapy evaluation of the SIJ conform to a system of motion detection and/or the identification of positional faults within the pelvis (Cibulka, 2002; DonTigny, 1990; Hazle & Nitz, 2008; Kuchera, 1997; Oldreive, 1998; Sandler, 1996). These paradigms are not presently supported by basic science literature (See Section 1.2). In addition to a lack of validity for these approaches (Freburger & Riddle, 2001; van der Wurff, Meyne, & Hagmeijer, 2000), the reliability of the manual assessment techniques purportedly utilized in the assessment of SIJ motion and positional faults has been reported as poor in systematic reviews (Freburger & Riddle, 2001; van der Wurff, Hagmeijer, & Meyne, 2000) and a number of subsequently performed studies (Albert et al., 2000; Holmgren & Waling, 2007; Riddle & Freburger, 2002; Robinson et al., 2007; van Kessel-Cobelens, Verhagen, Mens, Snijders, & Koes, 2008). Some authors have reported better reliability of movement/positional fault tests (Arab, Abdollahi, Joghataei, Golafshani, & Kazemnejad, 2008; Cibulka & Koldehoff, 1999; Hungerford, Gilleard, Moran, & Emmerson, 2007), however fail to successfully address the validity issues highlighted by the results of RSA testing (Tullberg et al., 1998).

Another approach to diagnosing SIJ involvement in PGP is through the use of pain provocation tests. Reliability of some of these tests has been reported as better than that of the tests for mobility and positional faults (Freburger & Riddle, 2001; van der Wurff, Hagmeijer et al., 2000). Yet some studies that have tried to correlate singular pain provocation tests of the SIJ with an injection criterion have found these tests to be invalid and unreliable (Dreyfuss et al., 1996; Maigne et al., 1996; Slipman, Sterenfeld, Chou, Herzog, & Vresilovic, 1998). One problem with studies of this type that the pain provocation tests will stress the SIJ and surrounding ligamentous structure, both a potential source of SIJ pain, whereas injections might neglect the extra-articular structures. Additionally, investigating singular tests for efficacy in diagnosing SIJ pain does not replicate contemporary clinical reasoning processes where all components of the subjective history, physical evaluation utilising multiple tests and other diagnostic procedures are considered before making a diagnosis (Elvey & O'Sullivan, 2005).

Extensive work has been undertaken investigating the validity of a more thorough clinical reasoning process against diagnostic SIJ injections (Laslett, Aprill et al., 2005; Laslett, McDonald et al., 2005; Laslett et al., 2003; Petersen et al., 2004; van der Wurff, Buijs, & Groen, 2006a; Young et al., 2003). When lumbar discogenic pain has been excluded and the subjects primary location of symptoms is over the SIJ, then three out of five positive pain provocation tests correlates well with the results of SIJ injections (Laslett, Aprill et al., 2005; Laslett, McDonald et al., 2005; Laslett et al., 2003; van der Wurff et al., 2006a; Young et al., 2003). These tests are depicted in Figures 1.6-1.10. As well as establishing the validity of this approach, these studies have also determined a good level of reliability for the test battery. This approach to the diagnosis of the SIJ as a painful structure has been recommended in the European guidelines for PGP (Vleeming et al., 2008). This cluster of tests has recently been found to have some utility in the identification of sacroiliitis that has been confirmed with magnetic resonance imaging (Ozgocmen, Bozgeyik, Kalcik, & Yildirim, 2008).

Figure 1.6 The Posterior Shear Test/Thigh Thrust Test/Posterior Pelvic Pain Provocation Test: With the hip at 90°, force is transmitted to the sacroiliac joint (SIJ) through the long axis of the femur. The sacrum may be stabilised at the sacral sulcus to assist the transmission of load through the SIJ. The angle of the hip joint may be varied.

Figure 1.7 Pelvic Torsion/Gaenslen's Test: One hip is placed into extension over the side of the bed as the other is moved into full flexion. This is repeated on the opposite side.

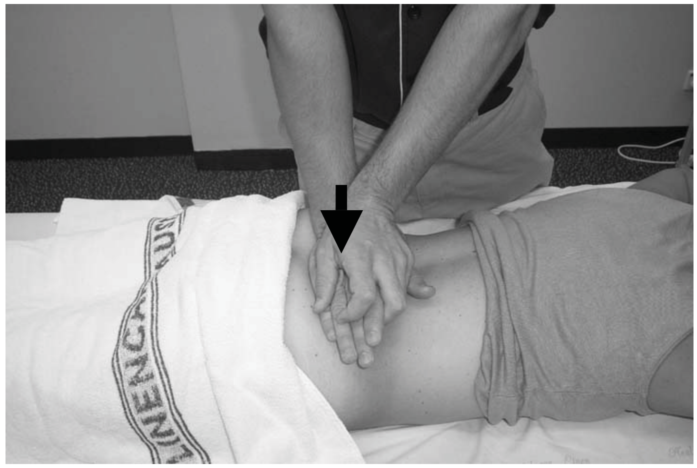

Figure 1.8 Sacral Thrust Test: Force is transmitted in a posterior to anterior direction through the sacrum. The point of contact may be moved up and down the sacrum, to the lateral aspect of the sacrum, or onto the ilium.

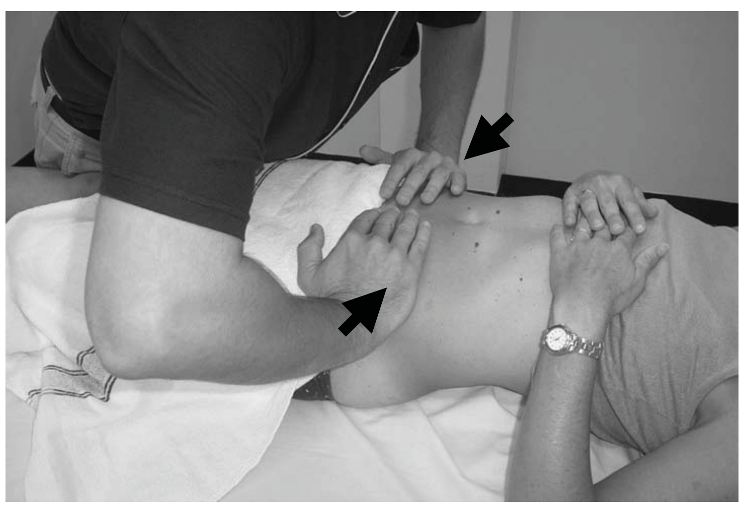

Figure 1.9 Compression: Force is directed medially through the ilia on the lateral aspect of the anterior superior iliac spines.

Figure 1.10 Distraction: Force is directed laterally through the ilia on the medial aspect of the anterior superior iliac spines.

The inclusion of compression as a pain provocation test is interesting, as some subjects with SIJ disorders are known to respond positively to manual compression (Mens, Damen et al., 2006; Mens et al., 1999; O'Sullivan et al., 2002; Ostgaard, Zetherstrom, Roos-Hansson, & Svanberg, 1994) (see Sections 1.3.3). Also, compression via a SIJ belt may be used as an adjunct to the treatment for some SIJ disorders by providing symptom control (Vleeming et al., 2008). Thus the effect of compression, either symptom provocation to symptom relieving, may differ in certain sub-groups of subjects with SIJ pain (O'Sullivan & Beales, 2007b, 2007c).

Palpation may also be used to provoke symptoms from the SIJ and surrounding ligamentous structures. Pain provocation from palpation of the long dorsal sacroiliac ligament has been shown to have utility in the diagnosis of peripartum PGP (Vleeming et al., 2002). The sacrotuberous ligament and the posterior inferior joint line may also be directly palpated. Additionally, palpation of the symphysis pubis has utility in the diagnosis of that structure as a source of pain (Albert et al., 2000). While palpation of these structures is very useful as part of a full examination of the pelvis, further research is required to validate the role of palpation in the diagnosis of PGP and to assess the reliability of pelvic palpation for pain provocation purposes.

Key Point:

- Identification of the SIJ as a source of symptoms may be reliably achieved via a clinical reasoning process were the key features are-
    - an absence of lumbar symptoms
    - the primary pain area being directly over the SIJ
    - three out of five positive pain provocation tests

1.3.3 The active straight leg raise test

The ASLR test is a non-weight bearing maneuver used in the assessment of load transference through the pelvis. Lying supine a subject lifts their leg just off the supporting surface (Figure 1.11i) (Mens et al., 1999). The primary subjective complaint will be that of heaviness of the leg that may be accompanied by pain. Aberrant changes in motor control patterns may be observed in conjunction with heaviness of the leg (for a full description of motor control during the ASLR see Section 1.5.1) (O'Sullivan et al., 2002). The test is then repeated with the addition of pelvic compression applied manually (Figure 1.11ii) or with a pelvic belt. A positive test is denoted by a reduction in the heaviness that is coupled with a decrease in associated pain (Mens, Damen et al., 2006; Mens et al., 1999; Ostgaard et al., 1994). In some subjects however the addition of compression has a negative influence on symptoms (Mens et al., 1999; O'Sullivan & Beales, 2007c), a possible representation of sub-groups of SIJ pain with different mechanisms underlying the pain disorder (O'Sullivan & Beales, 2007b).

(i)

(ii)

Figure 1.11 (i) For the active straight leg raise subjects raise their leg 10-20cm off the supporting surface. (ii) This is repeated with the addition of compression through the ilia. A positive test is denoted by a reduction of heaviness of the leg, decreased pain and improved motor control.

There is growing evidence for the validity and reliability of the ASLR test in assessing load transference through the pelvis in PGP subjects (Damen et al., 2001; Mens, Vleeming, Snijders, Koes, & Stam, 2001, 2002; Mens et al., 1999; O'Sullivan et al., 2002), although further research into all facets of this test is needed. Subjective rating of difficulty during the ASLR test correlates well with the severity of the disorder as determined by disability levels (Mens, Vleeming, Snijders, Koes et al., 2002), and can be useful in tracking the course of PGP (Mens, Vleeming, Snijders, Ronchetti et al., 2002). Use of this test is recommended in the assessment of PGP (Vleeming et al., 2008). However, the ASLR test may also be positive in groin pain (Mens, Inklaar, Koes, & Stam, 2006) and in the presence of a painful disorder of the lumbosacral junction or hip joint and/or its surrounding structures.

Key Point:

- There is a growing amount of evidence for the validity and reliability of the ASLR test in the assessment of load transference through the pelvis

1.4 The multifactorial nature of chronic pelvic girdle pain

While identification of a painful structure as a source of symptoms is important, it alone does not provide insight into the underlying mechanism(s) driving pain and disability in chronic PGP. A model for the diagnosis and classification of PGP disorders has been proposed which acknowledges the multifactorial nature of chronic PGP and highlights the importance of identifying the underlying mechanism(s) driving the chronic pain state (O'Sullivan & Beales, 2007b (Appendix 1), 2007c (Appendix 2)). This model acknowledges the various contributions of biomechanical, pathoanatomical, psychosocial, neurophysiological, hormonal and genetic factors in chronic PGP (Figure 1.12). Interaction between these factors can be complex. The challenge for researchers and clinicians alike is to identify which of these underlying factors, either individually or in unison, are driving the ongoing pain state in chronic PGP subjects.

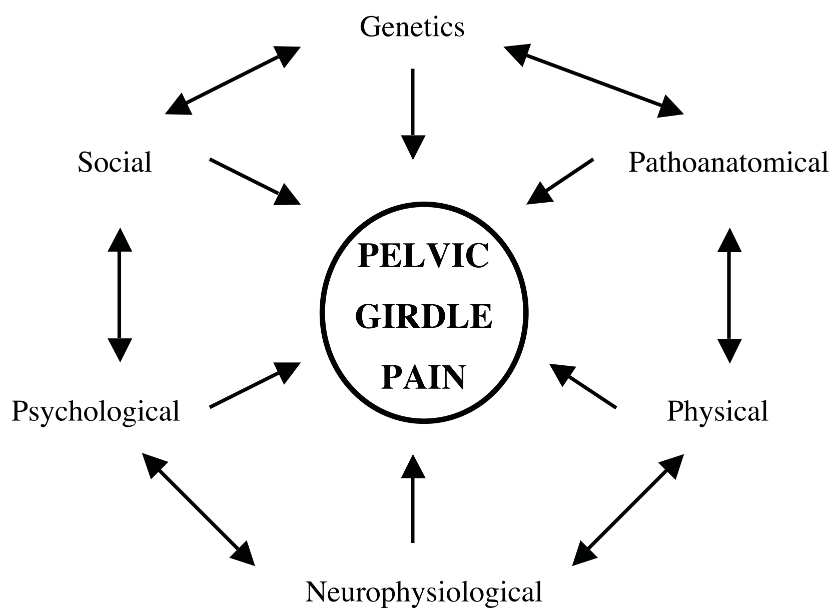

Figure 1.12 Factors contributing to the multifactorial nature of chronic pelvic girdle pain, adapted from O'Sullivan and Beales, "Diagnosis and classification of pelvic girdle pain disorders, Part 1: a mechanism based approach within a biopsychosocial framework" (O'Sullivan & Beales, 2007b).

1.4.1 Genetics and pelvic girdle pain

Little is known of the role that genetics play in non-specific PGP disorders, though its potential influence must be recognised. Subjects with PGP are more likely to have a mother or sister who also has PGP (Larsen et al., 1999; Mogren & Pohjanen, 2005). This may implicate a genetic link, although social and behavioural influences may also mediate this effect. Also a genetic predisposition for altered action of relaxin in PGP patients has been proposed as a mechanism of genetic influence on PGP (MacLennan and MacLennan, 1997). Genetic factors could potentially influence other factors within this model. For example genetic factors may influence pain neurophysiology (Buskila, 2007; Lacroix-Fralish & Mogil, 2008) and structural degenerative changes (Battie, Videman, & Parent, 2004). Further research into genetic influences on PGP is required.

1.4.2 Neurophysiological and psychosocial factors

Central nervous system sensitisation and/or glial cell activation are accepted mechanisms in the maintenance of chronic pain states (Hansson, 2006; Woolf, 2004). Central nervous system sensitisation may be initiated by a peripheral pain source, but can continue long after the peripheral injury has resolved. Chronic PGP is no exception, possibly being mediated partly or entirely via the central nervous system (O'Sullivan & Beales, 2007b, 2007c). Central sensitisation is also modulated by the forebrain (Zusman, 2002), and as such can be closely related to psychosocial factors.

As with central sensitisation, it is accepted that chronic pain disorders are commonly mediated by psychosocial and cognitive impairments (Linton, 2000, 2005; Main & Watson, 1999). The importance of these factors in chronic PGP is gaining greater recognition (Albert, Godskesen, Korsholm, & Westergaard, 2006) (Bastiaenen et al., 2008; Bastiaenen et al., 2004; Bastiaenen et al., 2006; Gutke et al., 2007; O'Sullivan & Beales, 2007b, 2007c; Van De Pol et al., 2007). Faulty beliefs, fear avoidance behaviour, stress, elevated anxiety levels, passive coping strategies and depression may amplify pain via the central nervous system and promote high levels of disability associated with the pain disorder. As an example, high levels of stress, poorer relationship with ones spouse, lower job satisfaction and no history of vocational training or professional education have been associated with an increased risk of developing pregnancy related PGP (Albert et al., 2006). Alternately positive beliefs and active coping strategies can assist in the management of these disorders.

1.4.3 Hormonal factors in pelvic girdle pain

Hormonal factors have the potential to contribute to PGP on a number of levels. Traditionally the effect of hormones in PGP has been viewed from within the physical domain. This simplistic view has revolved around the theory that increased relaxin levels during pregnancy leads to pelvic hypermobility and pain. However, pelvic mobility does not correlate with pain (see Section 1.2.4) and studies investigating relaxin levels in late pregnancy in subjects with and without PGP symptoms fail to demonstrate a difference between these groups (Albert, Godskesen, Westergaard, Chard, & Gunn, 1997; Bjorklund, Bergstrom, Nordstrom, & Ulmsten, 2000). However there is evidence that subjects who develop peripartum PGP have higher serum levels of progesterone and relaxin in early pregnancy, concurrently with increased levels of propeptide of type III procollagen (an indicator of collagen turnover) (Kristiansson, Svardsudd, & von Schoultz, 1999). Thus a complex interaction of hormones, rather than a single hormone, may affect the tolerance to loading of ligamentous structures in the pelvis during pregnancy, predisposing those individuals to the development of PGP. Further research is required into the effect of hormones on the physical factors contributing to PGP.

The effect of hormones may extend beyond the physical domain. There is ample evidence that sex hormones are active in neurophysiological processes, with the potential to either amplify or dampen pain (Aloisi & Bonifazi, 2006). Sex hormones can also influence the inflammatory process in inflammatory pain disorders, with estrogen generally acting in a pro-inflammatory role and androgens acting in an anti-inflammatory role (Schmidt et al., 2006). Further research is needed to clarify the role of hormones in different presentations of PGP.

1.4.4 Physical and lifestyle factors in pelvic girdle pain

Physical and lifestyle factors may contribute to the development and maintenance of a chronic pain state in PGP. Literature investigating these factors can be contradictory, which may result from differences in diagnosis and classification between studies. From a physical perspective, increased body weight before or during pregnancy, or a failure to return to pre-pregnancy body weight following delivery, have all been associated with increased risk of developing chronic PGP (Albert et al., 2006; Mogren, 2006; Mogren & Pohjanen, 2005; To & Wong, 2003; Wu et al., 2004). As an example of the contradictory nature of the literature in this area though, it has also been reported that body weight is not a factor in chronic PGP (Larsen et al., 1999; Vleeming et al., 2008). Increased maternal age could be a physical factor contributing to chronic PGP (Gutke, Ostgaard, & Oberg, 2008; Mogren, 2006; Mogren & Pohjanen, 2005). General articular hypermobility has also been associated with chronic pregnancy related PGP (Mogren, 2006; Mogren & Pohjanen, 2005), though general pelvic laxity is not (Buyruk et al., 1999; Damen et al., 2001). However, asymmetrical SIJ laxity may be a physical factor for subjects with higher levels of pain and disability (Damen et al., 2001; Damen, Buyruk et al., 2002) (see Section 1.2.4 Is there hypermobility in sacroiliac joint pain?). Decreased endurance of the back muscles could also be a physical factor in some subjects (Gutke et al., 2008). From a muscle perspective, aberrant motor control patterns have received increasing attention as a physical factor in chronic PGP (see Section 1.5 Aberrant motor control as a mechanism for chronic pelvic girdle pain).

Two lifestyle factors appear to have the strongest association with chronic PGP. Strenuous, more physically demanding employment can be associated with greater risk of developing PGP (Larsen et al., 1999; Wu et al., 2004). Secondly, lower general exercise levels have been associated with chronicity in PGP (Larsen et al., 1999), while higher exercise levels prior to pregnancy are associated with lower risk of chronicity (Mogren, 2005). Additionally increased parity (Albert et al., 2006; Larsen et al., 1999; Mogren & Pohjanen, 2005) and smoking (Albert et al., 2006; Wu et al., 2004) may also contribute to chronicity in PGP.

Key Point:

- The underlying mechanism driving chronic PGP disorders are a complex interaction of biomechanical, pathoanatomical, psychosocial, neurophysiological, genetic and hormonal factors

1.5 Aberrant motor control as a mechanism for chronic pelvic girdle pain

There is growing evidence for sub-groups of chronic non-specific PGP subjects who have primary peripherally mediated (nociceptive) pain (eg SIJ pain), where physical factors appear to be clearly linked to the physical impairments of the subjects. There is growing evidence that aberrant motor control patterns play an important role within this domain. While motor control has been extensively investigated in relation to lumbar spine disorders, there are relatively few studies that have specifically examined motor control in PGP subjects.

1.5.1 Motor control in pelvic girdle pain subjects during an active straight leg raise

Motor control patterns during the ASLR test have been investigated in SIJ pain subjects and pain free controls (O'Sullivan et al., 2002 (Appendix 3)) (further information in Section 2.1). Decreased diaphragmatic excursion, altered respiratory patterns and depression of the PF were observed in the SIJ pain subjects during the ASLR. These changes were normalized when manual pelvic compression was applied during the ASLR (O'Sullivan et al., 2002). Another study utilised an ASLR to investigate motor activation and strength in pregnant subjects both with and without pregnancy related lumbar and PGP (de Groot et al., 2008). Increased bilateral activation of the EO was observed during the ASLR in the pain subjects. They also reported increased bilateral activation of psoas major, though having used surface electrodes to record activity from this muscle there is serious doubt over this reported finding. The pain subjects also developed less hip flexor force during resisted ASLR (de Groot et al., 2008).

1.5.2 Motor control in pelvic girdle pain subjects in other tasks

Muscle onset during transition from double leg to single leg stance has been compared in SIJ pain subjects and pain free subjects (Hungerford et al., 2003). Pain subjects had delayed onset of IO, multifidus and gluteus maximus on the symptomatic side, while there was early onset of biceps femoris. Another study has reported characteristics of increased PF activation during voluntary PF maneuvers in PGP subjects compared to pain free controls (Pool-Goudzwaard et al., 2005). Also an inability to consciously elevate the PF, as observed with real time ultrasound, has been reported in SIJ pain subjects (O'Sullivan & Beales, 2007a (Appendix 4)).

Lumbosacral posture and movement patterns during forward bending have been compared between pain free subjects, chronic low back pain subjects and chronic PGP subjects (van Wingerden, Vleeming, & Ronchetti, 2008). The PGP group demonstrated greater posterior pelvic tilt in standing. The PGP subjects had greater limitation of hip movement during forward bending compared to the low back pain subjects, and had greater lumbar motion in the initial stage of bending. The results of this study could be oversimplifying lumbopelvic movement patterns as it has been shown that sub-groups of chronic low back pain subjects can demonstrate different movement patterns during forward bending (Dankaerts, 2005). For example van Wingerden and colleagues noted diminished lumbar motion in all low back pain subjects during forward bending (van Wingerden et al., 2008). Dankaerts also found reduced lumbar motion during forward bending, but only in a sub-group of low back pain subjects with an 'active extension pattern' compared to 'flexion pattern' and pain free subjects (Dankaerts, 2005). Similar differences in lumbopelvic control have been proposed in sub-groups of PGP subjects (O'Sullivan & Beales, 2007b, 2007c). More research is required into the body postures and movement patterns in PGP subjects.

1.5.3 Motor control as a mechanism for ongoing pain and disability

The mere existence of aberrant motor control in PGP disorders is not sufficient to implicate this as a underlying mechanism contributing to the pain disorder. However, from a theoretical stand point at least, aberrant motor control patterns may contribute to suboptimal loading of pelvic structures which; (i) potentially provokes nociceptive output from peripherally sensitised tissue such as the SIJs and/or the surrounding ligamentous and myofascial structures, and (ii) contribute to ongoing tissue microtrauma (Mens, Vleeming, Stoeckart, Stam, & Snijders, 1996; O'Sullivan & Beales, 2007a; O'Sullivan et al., 2002; Vleeming et al., 1996; Vleeming, Volkers et al., 1990). Aberrant motor control strategies may contribute to increased IAP (O'Sullivan & Beales, 2007a). Increased IAP acting to overload pelvic ligaments has been theorised as a potential pain mechanism in non-specific PGP (Mens, Hoek van Dijke, Pool-Goudzwaard, van der Hulst, & Stam, 2006). No studies to date have investigated the control of IAP specifically in subjects with PGP though. Studies investigating IAP are warranted given that aberrant motor control strategies identified in PGP subjects involve the muscles that control IAP.

Studies investigating treatment strategies for chronic PGP support the notion of aberrant motor control strategies as a primary pain mechanism in sub-groups of PGP subjects. An exercise program that appeared to reinforce aberrant motor control strategies was found to be unsuccessful in the management of PGP (Mens, Snijders, & Stam, 2000). Twenty-five percent of the subjects in the intervention group had to cease their exercise program secondary to increased pain. On the other hand, interventions that focus on normalising aberrant motor control have been successful in achieving reductions in pain and disability in chronic PGP subjects (O'Sullivan & Beales, 2007a; Stuge, Laerum, Kirkesola, & Vollestad, 2004; Stuge, Veierod, Laerum, & Vollestad, 2004). Motor relearning intervention within a biopsychosocial framework is also able to reverse aberrant motor control strategies observed in subjects with chronic SIJ pain (O'Sullivan & Beales, 2007a). Not all subjects respond to the same intervention though (Stuge, Morkved, Haug Dahl, & Vollestad, 2006), which may be indicative of different motor control strategies in those subjects that didn't respond or may reflect a situation where the motor control impairment is not the primary or sole mechanism underlying the pain disorder (O'Sullivan & Beales, 2007b, 2007c).

Key Point:

- There is growing evidence for the existence of sub-groups of PGP subjects for whom aberrant motor control strategies represent a primary mechanism for ongoing pain and disability

1.6 Summary statement

In the majority of cases, a specific PGP diagnosis cannot be made. A multifactorial model for the mechanisms underlying non-specific PGP has been proposed. It has been suggested that subjects with non-specific chronic PGP may be sub-grouped according to these underlying mechanisms. One sub-group appears to be related to deficits in motor control, where aberrant motor control patterns and increased IAP contribute to ongoing pain and disability. The ASLR is an important test of load transference in these subjects, during which signs of aberrant motor control may be observed. To date though, motor activation patterns and IAP have not been directly investigated in PGP subjects, during the ASLR test or functional tasks. The premise of this thesis was to begin addressing this gap in the literature.

1.7 References: Chapter 1

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Chapter 2: Genesis of the Thesis Topic

2.1 An answer provides more questions

In 2002 we published a study that investigated trunk motor control during the active straight leg raise (ASLR) test in pain free subjects and chronic pelvic girdle pain (PGP) subjects who exhibited features consistent with sacroiliac joint (SIJ) pain (O'Sullivan et al., 2002 (Appendix 3)). In comparison to the pain free subjects, during an ASLR subjects with SIJ pain had:

- Altered respiratory patterns with features such as changes in respiratory rate and breath holds, with noticeable individual variation
- Higher minute ventilation, mediated primarily by an increased respiratory rate
- Decreased diaphragmatic excursion, with seven of 13 subjects completely splinting their diaphragm
- Descent of the pelvic floor (PF) measured by trans-abdominal real time ultrasound.

These motor control strategies were found to normalise with the addition of manual compression through the ilia during the ASLR. It was proposed that the aberrant motor control strategies exhibited by the SIJ pain subjects were an attempt by the neuromuscular system to compensate for an impairment in the ability to effectively load transfer through the pelvis. Additionally it was proposed that this inability to effectively load transfer was most likely related to inadequate form and/or force closure mechanisms. It was proposed that the addition of pelvic compression augmented form and/or force closure, facilitating more efficient load transfer, and as such resulted in normalisation of the aberrant motor control patterns.

An interesting finding from this study was that these aberrant motor control strategies were not only related to poor load transference through the pelvis. There was also evidence of altered kinematics of the PF and disruption of the respiratory system concurrent to performing an ASLR. There is clearly a role for the muscles of the abdominal cavity in the provision of lumbopelvic stability, the control of intra-abdominal pressure (IAP), the maintenance of continence and in respiration. The neuromuscular system must attend to these various body functions and demands simultaneously. The findings of this study highlighted disruption of this control during the ASLR test in these subjects.

The motor control patterns observed in the pain subjects appeared to represent a bracing/splinting strategy through the trunk muscles. It was theorised that this could be associated with an increase in IAP. While the study documented clinical observations of subjects performing the ASLR test, it was beyond the scope of that study to monitor electromyographic (EMG) activity of the abdominal muscles and IAP directly. Hence the foundations for this thesis were informed.

2.2 The research questions

This thesis investigated motor control strategies during the ASLR, expanding the scope of the previous study to incorporate muscle activation patterns, as well as monitoring IAP and intra-thoracic pressure (ITP). The five major studies undertaken as part of this project evolved from questions that arose from the original study.

2.2.1 Study 1: Motor control patterns during an active straight leg raise in pain free subjects

Study 1 (Chapter 3) Research Question: What motor control patterns do pain free subjects exhibit during an active straight leg raise? The aim of this study was to investigate patterns of trunk muscle activation and IAP in pain free subjects during an ASLR. Knowledge of this in pain free subjects would provide a foundation and point of comparison for the investigation of chronic PGP subjects.

2.2.2 Study 2: Motor control patterns during an active straight leg raise in chronic pelvic girdle pain subjects

Study 2 (Chapter 4) Research Question: How do motor control patterns during an active straight leg raise differ in chronic pelvic girdle pain? The purpose of this study was to investigate the observation of apparent bracing/splinting motor strategy in PGP subjects with a positive ASLR, during an ASLR. It was hypothesised that this strategy would result in increased global abdominal wall motor activation with a concurrent increase in IAP.

2.2.3 Study 3: The effect of increased physical load during an active straight leg raise in pain free subjects

Study 3 (Chapter 5) Research Question: How do pain free subjects adapt to increased physical load during an active straight leg raise? During a positive ASLR test the primary complaint is one of heaviness of the leg, with subjects often reporting a sensation akin to having a heavy weight tied to their leg while trying to raise it. This study was designed to investigate the motor control patterns of pain free subjects during a low load ASLR (weight of the leg only) compared to a high load ASLR (extra physical loading in the form of a weight around the ankle). It was hypothesised that the high load motor control strategy would represent similar patterns observed in chronic PGP subjects during a positive ASLR test.

2.2.4 Study 4: The effect of resisted inspiration during an active straight leg raise in pain free subjects

Study 4 (Chapter 6) Research Question: How do pain free subjects co-ordinate an active straight leg raise when under a concurrent respiratory load? Respiratory changes were noted in our initial study during the ASLR test in subjects with PGP. This study was performed to investigate how pain free subjects co-ordinate the physical load of an ASLR with a simultaneous respiratory challenge.

2.2.5 Study 5: Non-uniform motor control changes with manually applied pelvic compression during an active straight leg raise in chronic pelvic girdle pain subjects

Chapter 7 Research Question: What effect does manual pelvic compression have on motor control strategies in pelvic girdle pain subjects during an active straight leg raise? Given the positive effect of manual pelvic compression during an ASLR in PGP subjects in the initial study, it was a natural progression for this thesis to investigate the effect of manual pelvic compression on trunk motor control.

2.3 References: Chapter 2

O'Sullivan, P. B., Beales, D. J., Beetham, J. A., Cripps, J., Graf, F., Lin, I. B., et al. (2002). Altered motor control strategies in subjects with sacroiliac joint pain during the active straight-leg-raise test. *Spine, 27*(1), E1-8. (Appendix 3)

Chapter 3: Study 1. Motor control patterns during an active straight leg raise in pain free subjects

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3.1 Abstract

Study Design

Repeated measures.

Objective

To investigate motor control patterns of normal subjects during the low level physical load of the active straight leg raise (ASLR).

Background Data

Aberrant motor control patterns, as observed with the ASLR test, are considered to be a mechanism for ongoing pain and disability in subjects with chronic musculoskeletal pelvic girdle pain (PGP). These patterns may not only affect the provision of lumbopelvic stability, but also respiration and the control of continence. Greater understanding of motor control patterns in pain free subjects may improve the management of PGP.

Method

Fourteen pain free nulliparous females were examined during the ASLR. Electromyography of the anterior abdominal wall, right chest wall and the scalene, intra-abdominal pressure (IAP), intra-thoracic pressure (ITP), respiratory rate, pelvic floor kinematics and downward leg pressure of the non-lifted leg were compared between a left and right ASLR.

Results

There was greater activation of obliquus internus abdominis and obliquus externus abdominis on the side of the ASLR. The predominant pattern of activation for the chest wall was tonic activation during an ipsilateral ASLR, and phasic respiratory activation lifting the contralateral leg. Respiratory fluctuation of both IAP and ITP didn't differ lifting either leg. The baseline shift of these pressure variables in response to the physical demand of lifting the leg was also the same either side. There was no difference in respiratory rate, pelvic floor kinematics or downward leg pressure.

Conclusion

Pain free subjects demonstrate a predominant pattern of greater ipsilateral tonic activation of the abdominal wall and chest wall on the side of the ASLR. This was achieved with minimal apparent disruption to IAP and ITP. The findings of this study demonstrate the plastic nature of the abdominal cylinder and the flexibility of the neuromuscular system in controlling load transference during an ASLR.

3.2 Introduction

Pelvic girdle pain (PGP) is common during pregnancy, with 72-84% of pregnant women reporting symptoms in this region (Bastiaanssen et al., 2005; Mogren & Pohjanen, 2005; To & Wong, 2003). For most this is self limiting, resolving within three months post-partum. However in 7-10% of cases symptoms become chronic, persisting beyond two years (Albert, Godskesen, & Westergaard, 2001; Rost, Jacqueline, Kaiser, Verhagen, & Koes, 2006; Wu et al., 2004). This condition is not limited to pregnancy, with other aetiologies such as trauma also responsible for the development of chronic PGP (Chou et al., 2004; O'Sullivan et al., 2002).

The underlying mechanisms that drive chronic PGP are complex and multifactorial. These may include hormonal and genetic factors, neurophysiological factors such as peripheral or central sensitisation, pathoanatomical changes and biomechanical factors, and psychosocial influences to varying degrees (O'Sullivan & Beales, 2007b). Recently research has focused on alterations of motor control as a potential mechanism for an ongoing peripheral drive of symptoms in chronic PGP. Evidence for the effectiveness of a motor learning approach in the management of chronic PGP (O'Sullivan & Beales, 2007a; Stuge, Veierod, Laerum, & Vollestad, 2004) supports that motor control deficits may underlie some of these disorders.

Several studies have documented alterations of motor control in PGP subjects (Table 3.1) (de Groot, Pool-Goudzwaard, Spoor, & Snijders, 2008; Hungerford, Gilleard, & Hodges, 2003; O'Sullivan & Beales, 2007a; O'Sullivan et al., 2002; Pool-Goudzwaard et al., 2005). Altered motor control patterns could contribute to the maintenance of a chronic pain state via mechanical provocation of pain sensitised structures within the pelvis. An interesting outcome from some of these investigations has been the documentation of changes in the function of multiple body systems. Alterations of motor control in response to the primary musculoskeletal disorder of PGP

Table 3.1 Findings of altered motor control in subjects with pelvic girdle pain. (ASLR = active straight leg raise, EO = obliquus externus abdominis, IO = obliquus internus abdominis, PF = pelvic floor)

	Activity	**Altered Motor Control Strategies**
De Groot et al (2008)	ASLR	• Increased bilateral EO activity
Hungerford et al (2003)	Standing Hip Flexion	• Delayed onset of IO and multifidus bilaterally • Delayed onset of gluteus maximus on the symptomatic side • Early activation of biceps femoris on the symptomatic side
O'Sullivan et al (2002)	ASLR	• Decreased diaphragmatic excursion • Altered respiratory patterns • Descent of the PF
O'Sullivan and Beales (2007)	Voluntary PF Contraction	• Depression of the PF
Pool-Goudzwaard et al (2005)	Voluntary PF Maneuvers	• Increased PF activation

have been linked to changes in function of the respiratory system (O'Sullivan et al., 2002). There is also a link between changes in pelvic floor (PF) function with changes in the control of continence (O'Sullivan et al., 2002; Pool-Goudzwaard et al., 2005).

These findings should not be surprising given that the lumbopelvic muscles, diaphragm and PF are involved in assisting lumbopelvic stability, as well as controlling respiration, intra-abdominal pressure (IAP) and continence. To date no study has investigated these systems in detail during the active straight leg raise (ASLR).

The aim of this study was to investigate motor control strategies employed by pain free subjects during low level load transference through the pelvis. The ASLR is a valid and reliable test for assessing load transference through the pelvis in PGP subjects (Damen et al., 2001; Mens, Vleeming, Snijders, Koes, & Stam, 2001, 2002; Mens, Vleeming, Snijders, Stam, & Ginai, 1999; O'Sullivan et al., 2002). The methodology included simultaneous observation of trunk muscle activation, IAP and intra-thoracic pressure (ITP), variables not measured in our previous work in this area (O'Sullivan & Beales, 2007a; O'Sullivan et al., 2002). Patterns of motor control related to lifting one leg versus the other were compared in order to elucidate neuromuscular system coordination during an ASLR. It was hypothesised that pain free subjects would demonstrate a local motor strategy with minimal change in IAP.

3.3 Materials and Methods

3.3.1 Subjects

Fourteen pain free, nulliparous females were recruited from the Perth metropolitan region (average age 28.9±5.9 years, average body mass index 23.0±2.1kg/m^2, average adductor strength (Mens, Vleeming, Snijders, Ronchetti, & Stam, 2002) 167.1±35.4N). Exclusion criteria were: history of a musculoskeletal pain disorder in the last 6 months, surgery in the last year, current neurological or inflammatory disorders or a history of a significant respiratory disorder. Written informed consent was obtained from all subjects. Ethical approval was granted by the Human Research Ethics Committee of Curtin University of Technology.

3.3.2 Equipment and set-up

Respiratory, electromyographic (EMG), pressure and kinematic data were collected concurrently during the ASLR. The phase of respiration was recorded via the pneumotach of a Benchmark Pulmonary Exercise System (P.K. Morgan Instruments, Inc., Andover, Massachusetts), which was modified with an external output.

Electromyographic data were collected from the following muscles:

- bilateral rectus abdominis (RA): 1cm above and 2cm lateral to the umbilicus (Ng, Kippers, & Richardson, 1998)
- bilateral obliquus externus abdominis (EO): just below the rib cage on a line connecting the inferior costal margin with the contralateral pubic tubercle (Ng et al., 1998)
- bilateral lower fibres of obliquus internus abdominis (IO): just medially and inferior to the anterior superior iliac spine (Ng et al., 1998)
- the right chest wall (CW): at the sixth and seventh intercostal spaces, 2cm lateral to the mid clavicular line (Allison, Kendle et al., 1998; Gross, Grassino, Ross, & Macklem, 1979; Sharp, Hammond, Aranda, & Rocha, 1993)
- bilateral anterior scalene (Sc): over the anterior Sc adjacent to the lower third point of a line between the mastoid and the sternal notch (Falla, Dall'Alba, Rainoldi, Merletti, & Jull, 2002)

  bilateral rectus femoris: mid way between the anterior superior iliac spine and the superior border of the patella (Perotto, 1994) (as a marker for when the leg was lifted, not otherwise analysed).

The skin was lightly abraded and cleaned so that impedance was $<5k\Omega$ (Gilmore & Meyers, 1983). Disposable Ag/AgCl electrodes (ConMed Corporation, Utica, New York) were placed in situ with an intra-electrode distance of 2.5cm. Two Octopus Cable

Telemetric units (Bortec Electronics Inc., Calgary, Canada) were utilised, one for each side of the body, earthed to the anterior superior iliac spine of the corresponding side. Data were sampled at 1000Hz, at a bandwidth of 10 to 500Hz, with a common mode rejection ratio of >115dB at 60Hz, and pre-amplified and amplified at an overall gain of 2000.

Intra-abdominal pressure and ITP were recorded with a custom made silicone nasogastric catheter (Dentsleeve International Ltd, Mississauga, Canada). Saline solution was passed at high pressure through tiny lumen in the catheter. Changes in the rate of flow through the lumen that occur in response to changes in pressure were monitored using custom built pressure transducer equipment. The system was calibrated against pressure measurements at known depths of water. Correct location of the catheter in the thorax and abdomen was confirmed with opposite pressure changes in both channels during respiration (Hodges & Gandevia, 2000).

To monitor any compensatory downward pressure of the leg not being lifted, an inflated pad linked to a pressure transducer was placed under the heel. Respiratory, EMG and pressure variables were collected simultaneously on a computer running LabVIEW v6.1 (National Instruments, Austin, Texas). Concurrently kinematics of the PF were monitored using a Capesee SSA-220A ultrasound unit (Toshiba Corporation, Tochigi, Japan) (O'Sullivan et al., 2002; Sherburn, Murphy, Carroll, Allen, & Galea, 2005; Thompson & O'Sullivan, 2003; Thompson, O'Sullivan, Briffa, Neumann, & Court, 2005; Walz & Bertermann, 1990). The probe was positioned trans-abdominally, angled inferiorly, to view the bladder. Trials were recorded to digital video.

3.3.3 Data Collection and Processing

For normalisation 3s of EMG data was collected for three repetitions of a crook lying double leg raise with cervical flexion as a sub-maximal reference contraction (Allison, Godfrey, & Robinson, 1998; Allison, Kendle et al., 1998; Dankaerts, O'Sullivan, Burnett, Straker, & Danneels, 2004; O'Sullivan, Twomey, & Allison, 1998). The average root mean square (RMS) was used. Data was then collected during 60s in resting supine. Initially the subjects were asked to cough, producing movement on the ultrasound which acted as a marker to synchronise PF video with the rest of the data. Then data were collected during the ASLR. Approximately 5s after coughing, subjects were asked to raise their leg 10cm. After approximately 45s the subjects were then instructed to lower their leg and data collection was ceased a further 10s later. This was repeated twice per leg to allow for repeatability analyses.

A custom designed data processing program was used to prepare the data for analysis. The EMG was inspected for contamination by heartbeat and other artifact. Data were then demeaned, band pass filtered from 4 to 400Hz with a 4^{th} order Butterworth filter with zero lag and normalised. The RMS for 500ms during the middle of the inspiratory and expiratory phases of three breath cycles was calculated. This allowed investigation of phasic EMG changes in relation to respiration versus tonic EMG changes in response to physical loading related to the ASLR. Pressure change over the breath cycle was calculated for both IAP and ITP during each breath cycle by subtracting the minimum from the maximum pressure value during that breath. This allowed investigation of the normal phasic change in these measures associated with respiration. Pressure change related to physical loading was ascertained by calculating a baseline shift. Baseline shift equaled the average minimum pressure value of the three breath cycles during an ASLR minus that of resting supine.

Respiratory rate (RR) was calculated from the respiratory traces during the ASLR. The average pressure exerted downward by the non-lifted leg was calculated over the breath cycle. Movement of the PF was obtained by capturing two frames of video: a) slightly before and after the leg lift to ascertain bladder motion secondary to the ASLR, and b) at the maximum and minimum points of excursion over each of the three breath cycles to observe motion in response to respiration. These frames were overlaid to measure the distance the PF moved.

3.3.4 Data Management and Analyses:

Data from the three breath cycles were averaged and analysed with a two (*Side*: left ASLR, right ASLR) by two (*Respiration*: inspiration, expiration) repeated measures analysis of variance. A separate model was constructed for each muscle. Paired t-tests were used for post-hoc analyses. Intra-abdominal pressure, ITP, RR, leg pressure and the PF motion variables were compared lifting one leg versus the other with paired t-tests. This was complimented with visual inspection of the motor patterns.

To examine consistency of the motor patterns intra-class correlation coefficients and corresponding 95% confidence intervals were calculated for all variables over two sequential leg lifts. Analysis was performed with SPSS 14.0 for Windows (SPSS Inc., Chicago, Illinois), with a critical p value of 0.05.

3.4 Results

3.4.1 Internal obliquus abdominis

Activation of IO was greater during an ipsilateral ASLR compared to a contralateral ASLR (left IO: *side* p=0.004; right IO: *side* p=0.001) (Figure 3.1). Activation was tonic in nature (left IO: *respiration* p=0.919; right IO: *respiration* p=0.307), regardless of which side the ASLR was on (left IO: *side by respiration* p=0.426; right IO: *side by respiration* p=0.464) (Figure 3.1). This indicates a response in IO to the physical load of the leg lift which was not overtly influenced by the respiratory cycle. An example of this pattern is visible on the EMG trace in Figure 3.2.

3.4.2 Externus obliquus abdominis

Visual examination of the EO EMG traces revealed the same pattern of greater tonic activation during an ipsilateral ASLR as the IO muscles (Figure 3.1 and 3.2). For the left EO this did reach statistical significance (*side* p=0.028, *respiration* p=0.418, *side by respiration* p=0.886), while it did not for the right (*side* p=0.068, *respiration* p=0.442, *side by respiration* p=0.204) (Figure 3.1).

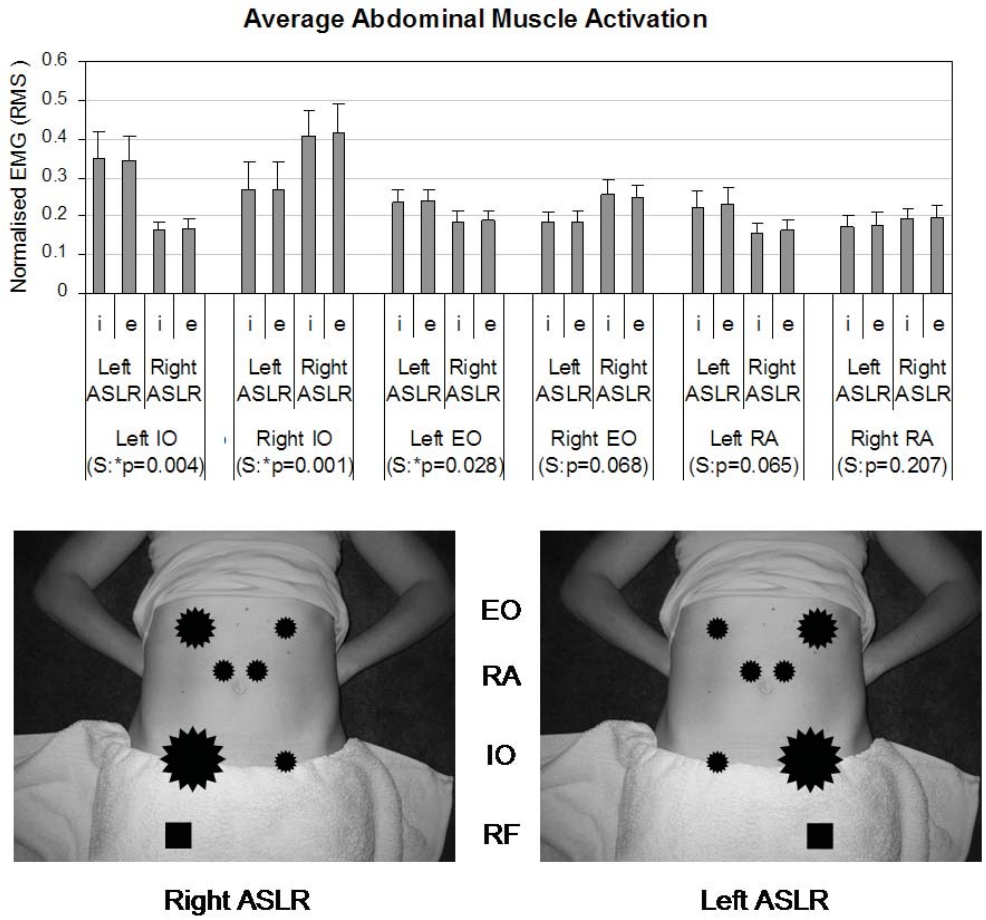

Figure 3.1 Activation patterns via group averages (standard error of the mean) of root mean square (RMS) electromyographic (EMG) values for obliquus internus abdominis (IO), obliquus externus abdominis (EO) and rectus abdominis (RA) bilaterally, with a pictorial representation of the graphical data. The muscle markers represent relative activation for the purpose of visualising the overall motor pattern, and are not to any particular scale. A clear pattern is discernable for a higher level of activation of IO lifting the ipsilateral leg. A similar pattern exists for EO. (i = inspiration, e = expiration, ASLR = active straight leg raise, RF = rectus femoris, S=Side)

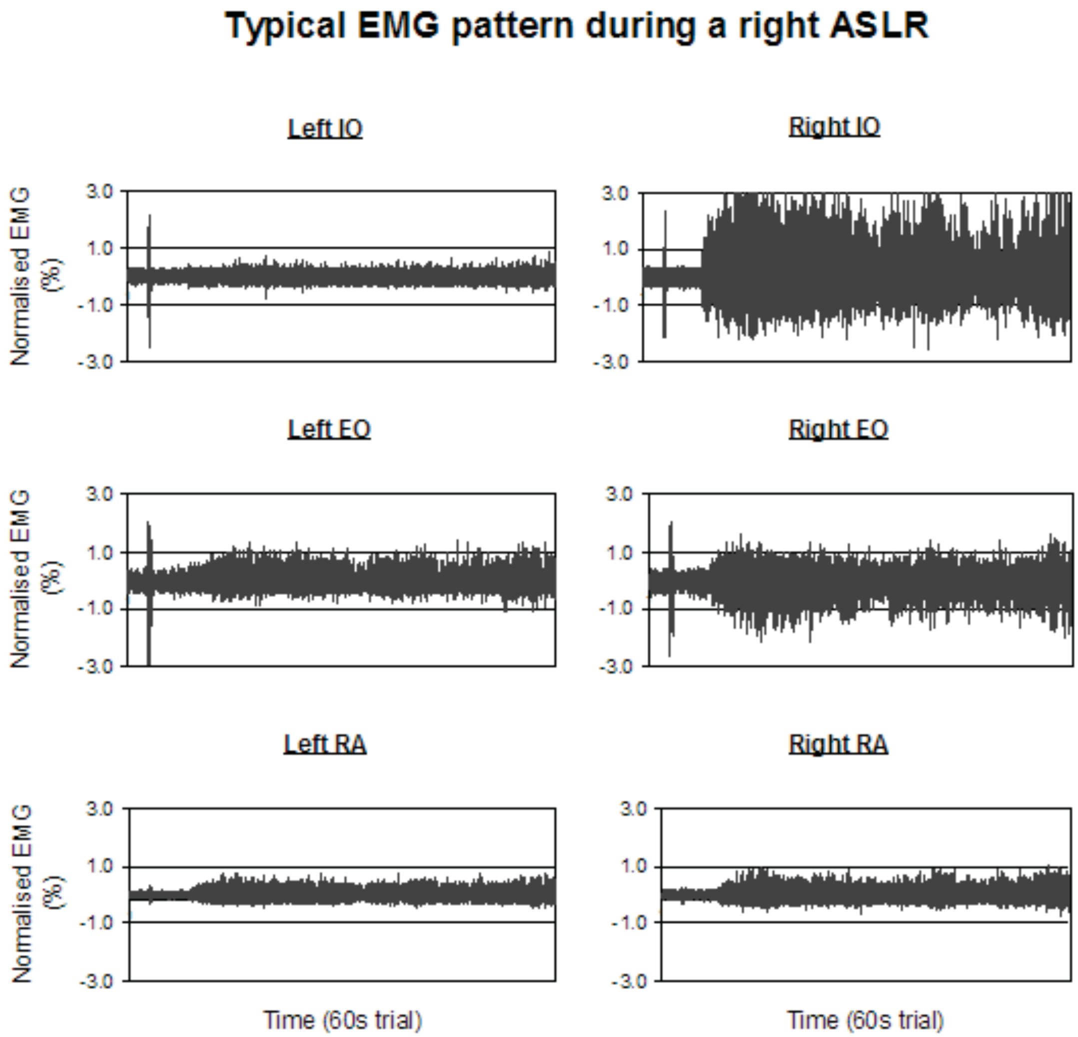

Figure 3.2 Demeaned and normalised electromyographic (EMG) traces during a right active straight leg raise (ASLR). The spike at the beginning of the traces is a cough. Subject A displays the typical pattern of increased obliquus internus abdominis (IO) activation on the ipsilateral side of the leg being lifted. Increased activation of the ipsilateral obliquus externus abdominis (EO) is also discernable. Activation of rectus abdominis (RA) appears more symmetrical. All muscle activation appears primarily tonic in nature in response to lifting the leg. Note: Right IO appearance of being clipped at the top is simply for scaling purposes to allow clear comparison.

3.4.3 Rectus abdominis

Activation of RA was no different performing a left or right ASLR (left RA: *side* $p=0.065$; right RA: *side* $p=0.207$) (Figure 3.1). Although the main effect for respiration was significant for the left RA (*respiration* $p=0.049$; *side by respiration* $p=0.877$) this was not supported by the post-hoc tests (inspiration versus expiration: $p=0.096$). There was no effect for respiration for the right RA (*respiration* $p=0.079$, *side by respiration* $p=0.893$) (Figure 3.1). Visual inspection confirmed a very consistent pattern of equal tonic activation lifting either leg (Figure 3.2).

3.4.4 Right chest wall

Overall, activation at the right CW did not differ lifting either leg (*side* $p=0.111$, *respiration* $p=0.073$, *side by respiration* $p=0.743$) (Figure 3.3). Visual inspection of the EMG traces demonstrated some discrete patterns that may be confounding this analysis. The predominant pattern (8/14 subjects) was of phasic activity lifting the contralateral leg, but a shift towards tonic activation lifting the ipsilateral leg (Figure 3.4). However two subjects demonstrated predominant phasic activity lifting either leg, while four displayed predominant tonic activation lifting either leg (Figure 3.4).

3.4.5 Anterior scaleni

There was phasic inspiratory activation of both (left Sc: *respiration* $p=0.024$; right Sc: *respiration* $p=0.012$) lifting either leg (left Sc: *side* $p=0.919$, *side by respiration* $p=0.462$; right Sc: *side* $p=0.902$, *side by respiration* $p=0.043$) (Figure 3.3).

3.4.5 Intra-abdominal pressure and intra-thoracic pressure

Respiratory fluctuation in IAP ($p=0.372$) and ITP ($p=0.266$) were the same lifting either leg (Figure 3.5). There was a slight rise in IAP from a resting supine baseline level during an ASLR, but this IAP baseline shift was not significantly different ($p=0.17$)

performing a left or right ASLR (Figure 3.5). There was no difference for the baseline shift in ITP (p=0.712) lifting either leg (Figure 3.5).

3.4.6 Respiratory rate

Respiratory rate was comparable during either ASLR (left ASLR: 15.6(1.3)breaths/min; right ASLR: 15.0(1.3)breaths/min; p=0.414).

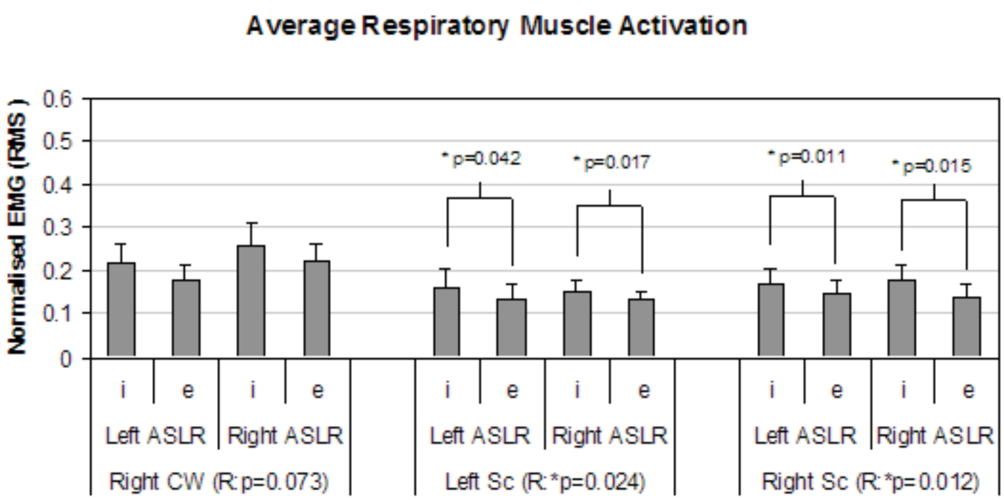

Figure 3.3 Average (standard error of the mean) root mean square (RMS) electromyographic (EMG) values for the right chest wall (CW) and anterior scalene (Sc) muscles. Inset p values on graph are from post hoc t-tests, denoting phasic activation of the Sc lifting either leg. (i = inspiration, e = expiration, ASLR = active straight leg raise, R = respiration)

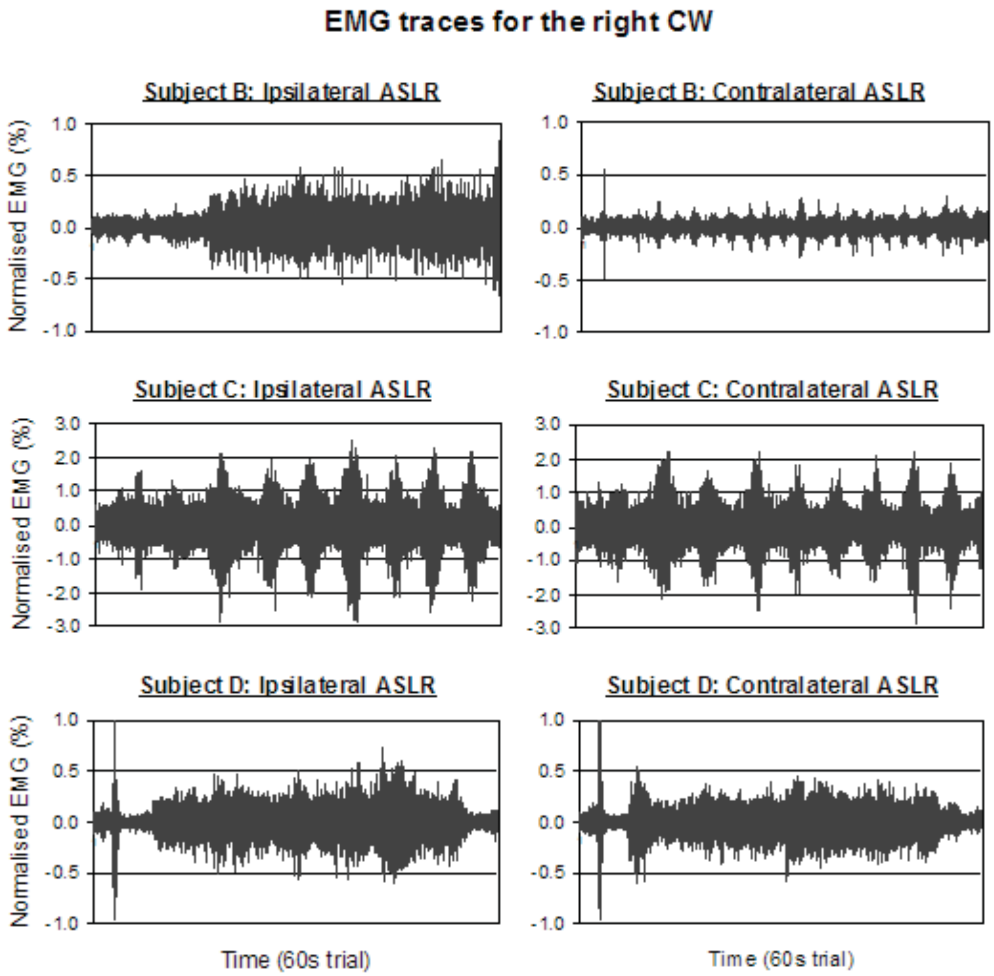

Figure 3.4 In these electromyographic (EMG) traces of demeaned and normalised EMG, Subject B demonstrates the typical pattern of tonic right chest wall (CW) activation lifting the contralateral leg compared to phasic activation lifting the ipsilateral leg. Subject C demonstrates phasic activation maintained lifting either leg. Subject D demonstrates predominant tonic activity lifting either leg. (ASLR = active straight leg raise)

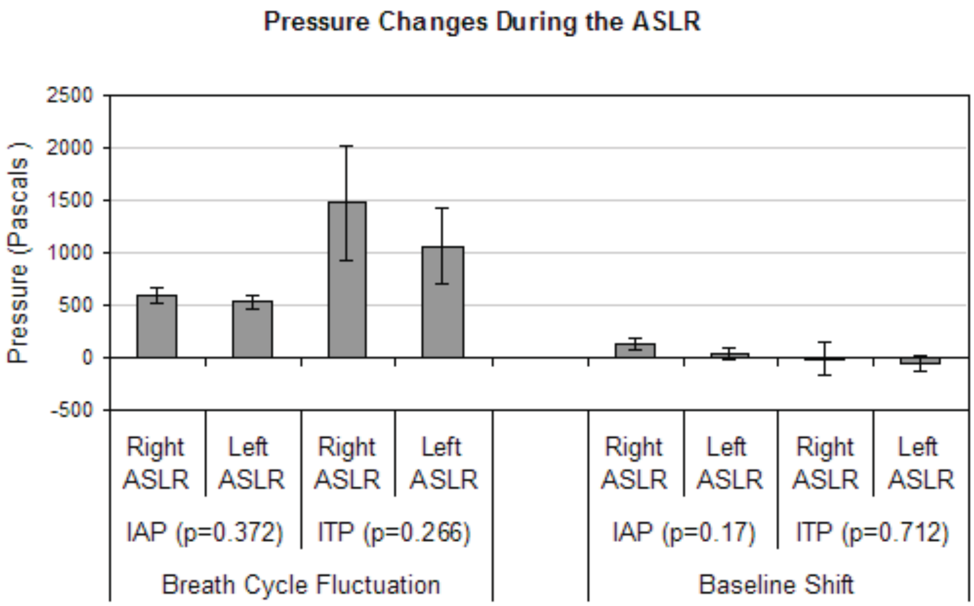

Figure 3.5 Pressure changes (mean, standard error of the mean) for intra-abdominal pressure (IAP) and intra-thoracic pressure (ITP). Measurements didn't differ over the respiratory cycle and baseline shift lifting either leg. (ASLR = active straight leg raise)

3.4.7 Pelvic floor movement

There was no difference in PF movement during an ASLR lifting either leg (p=0.1), with a mean(standard error of the mean) downward movement of 3.7(0.5)mm lifting the left leg and 3.4(0.6)mm lifting the right. Interestingly one subject elevated the PF during the ASLR of either side, while three subjects displayed depression lifting one side and elevation lifting the other. Respiratory motion of the PF was comparable lifting either leg (left ASLR: 2.7(1.0)mm; right ASLR: 4.0(1.0)mm; p=0.801).

3.4.8 Contralateral leg downward pressure

Downward pressure with the non-lifted leg was comparable during either ASLR (left ASLR: 59.04(7.65)N; right ASLR: 57.47(8.04)N; p=0.801).

3.4.9 Consistency of patterns

Repeatability over two trials was good to very good for all variables except for the baseline shift of IAP which displayed more variability (Table 3.2).

3.5 Discussion

This study documents motor patterns observed in pain free, nulliparous female subjects during a low level physical load of an ASLR in supine. The findings were consistent with the hypothesis of a predominant local motor strategy with minimal change in IAP.

3.5.1 Muscle activation

The abdominal wall demonstrated a pattern of increased activation in IO and EO on the side of the ASLR (Figure 3.1). This was most pronounced in IO (Figure 3.2), representing a consistent strategy to recruit muscles local to the pelvis, in an apparent role to assist efficient load transference. This corresponds with other in-vivo EMG studies in pain free subjects which have reported an important role for IO in providing pelvic stability in various standing positions (Snijders, Ribbers, de Bakker, Stoeckart, & Stam, 1998) and during sitting (Snijders et al., 1995). In contrast to our findings, a symmetrical pattern of EO activation in pain free subjects during an ASLR has been reported (de Groot et al., 2008). That study had 13 pain free subjects who were between 12 and 40 weeks of pregnancy. This suggests the neuromuscular system may adopt a different motor control strategy for an ASLR during pregnancy.

Table 3.2 Consistency of motor patterns over two trials for the left and right active straight leg raise (ASLR), expressed via intra-class correlation coefficient (ICC) values and their 95% confidence intervals (CI). (IAP = intra-abdominal pressure, ITP = intra-thoracic pressure, RR = respiratory rate, PF = pelvic floor)

	Left ASLR: ICC (95% CI)	**Right ASLR: ICC (95% CI)**
Muscle Activation	Highest: 0.987 (0.959 – 0.996)	Highest: 0.98 (0.937 – 0.993)
	Lowest: 0.895 (0.671 – 0.966)	Lowest: 0.775 (0.299 – 0.928)
	Median: 0.948	Median: 0.889
IAP-Breath Cycle	0.869 (0.592 - 0.958)	0.899 (0.684 - 0.967)
ITP-Breath Cycle	0.924 (0.764 - 0.976)	0.985 (0.955 - 0.995)
IAP-Baseline Shift	0.405 (0 - 0.809)	0.267 (0 - 0.875)
ITP-Baseline Shift	0.710 (0.096 - 0.907)	0.896 (0.675 - 0.967)
RR	0.914(0.732 – 0.972)	0.881(0.630-0.962)
PF movement – Leg Lift	0.940 (0.813 - 0.981)	0.954 (0.856 - 0.985)
PF movement – Breath Cycle	0.976 (0.925 - 0.992)	0.945 (0.829 - 0.982)
Contralateral Leg Pressure	0.934 (0.705 - 0.985)	0.957 (0.785 - 0.991)

Biomechanical models have been generated to explain the muscular systems contribution to enhancing pelvic stability (Snijders, Vleeming, & Stoeckart, 1993a, 1993b; Vleeming, Pool-Goudzwaard, Stoeckart, van Wingerden, & Snijders, 1995). This resulted in the description of muscular slings which may contribute to pelvic stability by exerting compressive force across the pelvis (Pool-Goudzwaard, Vleeming, Stoeckart, Snijders, & Mens, 1998). Purportedly the oblique slings traverse diagonally across the pelvis giving them a mechanical advantage to provide this compression. This has been supported by in-vivo EMG studies, in particular the report of activation of gluteus maximus and latissimus dorsi on opposite sides during walking and resisted torso rotation (Mooney, Pozos, Vleeming, Gulick, & Swenski, 2001). The present study did not demonstrate co-activation of IO and EO on opposite sides as might be predicted by the model of the anterior oblique sling, but rather a motor control pattern dominated by greater activation ipsilateral to the ASLR (Figure 3.1 and 3.2). This suggests the pattern of recruitment of the abdominal muscles is based upon the nature of the task at hand as much as any predetermined neuromuscular strategy.

The results of the right CW support this idea of a change in activation pattern related to the specific demands of the task. The majority of the subjects demonstrated a shift from phasic activity relative to respiration while performing a contralateral ASLR, to tonic activation with an ipsilateral ASLR (Figure 3.3). However, not all subjects displayed this pattern (Figure 3.4), highlighting the need to consider individual variation when observing motor control patterns. The observed individual differences could have resulted from a number of factors, such as heterogeneity of cardiovascular fitness levels, which could warrant further investigation.

Gross patterns of muscle activation recorded in this study could potentially over simplify neuromuscular function during the ASLR. From a physiological perspective it must be recognised that certain muscle groups may simultaneously attend to respiratory demands and challenges to lumbopelvic stability (Hodges & Gandevia, 2000). However gross muscle patterns are of interest as they are potentially detectable by clinicians, and as such may be useful from a rehabilitation perspective.

3.5.2 Intra-abdominal pressure and intra-thoracic pressure

Subjects in this study were able to lift their leg without disturbing IAP and ITP fluctuations associated with respiration (Figure 3.5). The magnitude of the fluctuation for IAP was similar to that reported during quiet breathing (Hodges & Gandevia, 2000). Additionally there was only a slight increase in IAP associated with the ASLR (Figure 3.5). These findings support the notion that the ASLR in pain free subjects represents a low level physical load. Most subjects in this study achieved this with a pattern of tonic abdominal and chest wall muscle activation ipsilateral to the side of the ASLR. This highlights the plasticity of the system in attending to physical loading without affecting respiration. Similar findings have been observed in subjects performing an isometric lifting task (McGill, Sharratt, & Seguin, 1995), where a low increase in IAP was observed while the abdominal muscles attended to stability and the chest wall helped maintain ventilation.

There was some variability in the baseline shift of IAP lifting either leg (Table 3.1). This was despite consistent tonic patterns of motor system activation of the abdominal wall, consistent fluctuation of IAP and ITP in relation to respiration and a fairly consistent change in baseline shift of ITP. This may reflect a limitation of this study in not being able to directly monitor all the muscles which produce and control IAP, namely the PF, diaphragm and transversus abdominis. Alternatively it may reflect flexibility in the neuromuscular control system with regard to this variable under low load conditions.

3.5.3 Pelvic floor movement

Movement of the PF measured trans-abdominally may represent a combination of bladder movement and movement of the abdominal wall against the probe. This is not problematic as these two dimensions reflect adaptation of the abdominal pressure cylinder related to changes in IAP and muscle activation. Also the use of trans-abdominal ultrasound to measure PF motion is supported by a positive correlation with trans-perineal ultrasound measurement (Thompson et al., 2005).

Minimal movement of the bladder was observed during the ASLR on either side. This is similar to the findings in pain free subjects in our previous study (O'Sullivan et al., 2002), and contrasts to the bladder depression observed in a sub-group of chronic PGP subjects during an ASLR (O'Sullivan et al., 2002) and the inability of subjects from the same sub-group to elevate the PF with a conscious PF contraction (O'Sullivan & Beales, 2007a).

The level of activation of the PF musculature can not be inferred from movement observed on ultrasound. In a few of the subjects though, lifting of the PF was observed during the ASLR. This may denote a more active role of the PF in these subjects during an ASLR. Biomechanical models certainly support the role of the PF in the provision of pelvic stability (Pool-Goudzwaard et al., 2004; Snijders et al., 1993a). Further in-vivo studies directly measuring PF activation are warranted to investigate the role the PF in contributing to pelvic stability.

3.6 Conclusion

This study investigated motor control patterns during an ASLR in pain free subjects. From a motor control perspective the predominant pattern was greater ipsilateral tonic activation of the abdominal wall and chest wall on the side of the ASLR. This is achieved with apparently minimal disruption to IAP and ITP fluctuations related to respiration, and with a minimal baseline shift in IAP. These findings highlight the flexibility of the neuromuscular system in controlling load transference during an ASLR, and the plastic nature of the abdominal cylinder.

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Chapter 4: Study 2. Motor control patterns during an active straight leg raise in chronic pelvic girdle pain subjects

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4.1 Abstract

Study Design

Repeated measures.

Objective

To investigate motor control patterns in chronic pelvic girdle pain (PGP) subjects during an active straight leg raise (ASLR).

Background Data

The ASLR is a test used to assess load transference through the pelvis. Altered motor control patterns have been reported in subjects with chronic PGP during this test. These patterns may impede efficient load transfer, while having the potential to impinge upon respiratory function and/or to adversely affect the control of continence.

Method

Twelve female subjects with chronic PGP were examined. Electromyography of the anterior abdominal wall, right chest wall and the scalene, intra-abdominal pressure,

intra-thoracic pressure, respiratory rate, pelvic floor kinematics and downward leg pressure of the non-lifted leg were compared between an ASLR lifting the leg on the affected side of the body versus the non-affected side.

Results

Performing an ASLR lifting the leg on the affected side of the body resulted in a predominant motor control pattern of bracing through the abdominal wall and the chest wall. This was associated with increased baseline shift in intra-abdominal pressure and depression of the pelvic floor when compared to an ASLR lifting the leg on the non-affected side.

Conclusion

This motor control pattern, identified during an ASLR on the affected side of the body, has the potential to be a primary mechanism driving ongoing pain and disability in chronic PGP subjects.

4.2 Introduction

Pelvic girdle pain (PGP) has been adopted as an umbrella term describing disorders where symptoms arise from musculoskeletal pelvic structures (Vleeming, Albert, Ostgaard, Sturesson, & Stuge, 2008). During pregnancy 72-84% of women report pain in the lumbopelvic region (Bastiaanssen et al., 2005; Mogren & Pohjanen, 2005; To & Wong, 2003), with the point prevalence for PGP during this time being 16-20% (Albert, Godskesen, & Westergaard, 2002; Larsen et al., 1999; Ostgaard, Andersson, & Karlsson, 1991). While for most this is a self limiting occurrence, in 7-10% of cases symptoms become chronic (Albert, Godskesen, & Westergaard, 2001; Rost, Jacqueline, Kaiser, Verhagen, & Koes, 2006; Wu et al., 2004). Furthermore chronic PGP may result from other aetiologies like trauma (Chou et al., 2004; O'Sullivan et al., 2002). In some presentations of PGP a specific diagnosis can be made from imaging studies and blood work, for example ankylosing spondylitis and stress fractures (Johnson, Weiss, Stento, & Wheeler, 2001; Maksymowych et al., 2005). However, in many cases of chronic PGP subjects no specific underlying pain mechanism can be identified. The pathogenesis in these cases may include varying contributions of biomechanical, pathoanatomical, psychosocial, neurophysiological, genetic and hormonal factors potentially driving ongoing PGP (O'Sullivan & Beales, 2007b).

The active straight leg raise (ASLR) test is a clinical procedure utilised assessing PGP subjects (Figure 4.1). There is increasing evidence conferring the validity and reliability of this test to assess load transfer through the pelvis (Damen et al., 2001; Mens, Vleeming, Snijders, Koes, & Stam, 2001, 2002; Mens, Vleeming, Snijders, Stam, & Ginai, 1999; O'Sullivan et al., 2002). It is widely accepted as an integral component

Figure 4.1 (Following Page) Clinical characteristics and possible underlying mechanisms of dysfunction for the active straight leg raise test.

Figure 4.1

ACTIVE STRAIGHT LEG RAISE:

Subject lifts one leg 10-20cm off the

Underlying Biomechanics Dysfunction:

Altered patterns of loading of the pelvic joints, ligaments, muscle and fascial structures.

Subjective Response:

- Heaviness of the leg +/- pain

Clinical Observations:

- altered respiratory pattern (breath holds, upper chest breathing pattern)
- abdominal splinting
- pushing down with the other leg
- twisting of the pelvis
- depression of the pelvic floor (observable with trans-abdominal ultrasound)

Peripheral Nociceptive Drive:

Provocation of nociceptors in load sensitive structures

WITH COMPRESSION:

Positive Effect

- Reduced heaviness
- Decreased pain
- Easier breathing
- Reduced abdominal splinting
- Stable pelvic floor position

Negative Effect

- No change in heaviness
- Possible amplification of symptoms
- No improvement of motor control deficits

in physical evaluation of PGP (Vleeming et al., 2008). During testing, assessment of the primary subjective feature of heaviness of the leg (+/- pain) is complimented by observation of motor control adaptations such as respiratory disruption and abdominal bracing (O'Sullivan et al., 2002) (Figure 4.1).

Studies specifically investigating motor control patterns during an ASLR (Beales, O'Sullivan, & Briffa, 2009; Cowan et al., 2004; de Groot, Pool-Goudzwaard, Spoor, & Snijders, 2008; O'Sullivan et al., 2002) and other aspects of motor control in PGP subjects (Hungerford, Gilleard, & Hodges, 2003; O'Sullivan & Beales, 2007a; Pool-Goudzwaard et al., 2005) are summarised in Table 4.1. These studies support biomechanical models (Snijders, Vleeming, & Stoeckart, 1993) championing motor control contribution to lumbopelvic stability, and support the hypothesis of aberrant motor control patterns providing a mechanism for ongoing pain in specific PGP presentations (Mens, Hoek van Dijke, Pool-Goudzwaard, van der Hulst, & Stam, 2006; O'Sullivan & Beales, 2007b). Motor control contributes to stability in the pelvis via force closure, a complex interaction of muscles and ligaments which may, when acting in symphony, actively add compression to the pelvic ring and thereby stabilise the SIJ's (Pool-Goudzwaard, Vleeming, Stoeckart, Snijders, & Mens, 1998; Snijders et al., 1993). As there is a synergistic relationship between muscles which control lumbopelvic stability/force closure, respiration, intra-abdominal pressure (IAP) and continence, aberrant motor control may also affect respiration and continence control (O'Sullivan et al., 2002; Pool-Goudzwaard et al., 2005). This study aimed to investigate motor control patterns exhibited by chronic PGP subjects during the ASLR. Improved understanding of motor control strategies exhibited by chronic PGP subjects could assist in understanding this factor as a mechanism for the chronic pain state, and thereby aid classification and management of these subjects. It was hypothesised that PGP subjects would demonstrate; 1) altered muscle patterning lifting the affected leg, 2) altered patterning would equate to a bracing strategy, and 3) these changes would be associated with the generation of higher levels of IAP and pelvic floor (PF) depression.

Table 4.1 Findings from investigations of motor control; A: During an active straight leg raise (ASLR), and B: in pelvic girdle pain (PGP) subjects during other tasks. (SIJ = sacroiliac joint, EO = obliquus externus abdominis, IO = obliquus internus abdominis, IAP = intra-abdominal pressure, ITP = intra-thoracic pressure, PF = pelvic floor, v's = versus)

	Subjects	Motor Control Strategies
ASLR STUDIES:		
Beales et al (2009)	Pain free nulliparous females	• Increased activation of IO and EO on the side of the ASLR • Predominant pattern of increased chest wall activation on the side of the ASLR • Minimal influence on IAP and ITP
Cowan et al (2004)	Chronic groin pain v's pain free controls	• Delayed onset of transversus abdominis during ASLR in the groin pain subjects
De Groot et al (2008)	Pregnant subjects: PGP v's pain free controls	• Increased bilateral EO activity in PGP subjects • Less hip flexor force production in PGP subjects
O'Sullivan et al (2002)	Chronic SIJ pain v's pain free controls	• Decreased diaphragmatic excursion/diaphragmatic splinting in pain subjects • Altered respiratory patterns in pain subjects • Descent of the PF in pain subjects
OTHER PGP STUDIES:		
Hungerford et al (2003)	SIJ pain v's pain free controls	• Delayed onset of IO, lumbar multifidus and gluteus maximus during hip flexion in standing in the pain subjects • Early onset of biceps femoris in the pain subjects
O'Sullivan and Beales (2007a)	Chronic SIJ pain v's pain free controls	• Failure of the pain subjects to elevate the PF during a conscious attempt to do so
Pool-Goudzwaard et al (2005)	Pregnancy relate PGP v's pain free controls	• Characteristics of increased PF activation during various voluntary maneuvers in PGP subjects

4.3 Materials and Methods

4.3.1 Subjects

Twelve females with chronic unilateral PGP diagnosed according to well established criteria identifying the sacroiliac joint as a source of symptoms (Table 4.2) were recruited from the Perth metropolitan region. Exclusion criteria were: any other musculoskeletal pain disorder in the last six months; surgery in the last year; neurological or inflammatory disorders; significant respiratory disorder; pregnancy or less than six months postpartum.

The Human Research Ethics Committee of Curtin University of Technology granted ethical approval and all subjects provided written informed consent. Table 4.3 displays demographic data.

4.3.2 Equipment and set-up

Respiratory, electromyographic (EMG), pressure and kinematic data was collected simultaneously using a custom designed LabVIEW v6.1 (National Instruments, Austin, Texas) data acquisition program. The pneumotach of a Benchmark Pulmonary Exercise System (P.K. Morgan Instruments, Inc., Andover, Massachusetts) modified with an external output was utilised to record respiratory phase.

Electromyographic data were collected with two Octopus Cable Telemetric units (Bortec Electronics Inc., Calgary, Canada) from bilateral rectus abdominis (RA) (Ng, Kippers, & Richardson, 1998), obliquus externus abdominis (EO) (Ng et al., 1998), lower fibres of obliquus internus abdominis (IO)(Ng et al., 1998), anterior scalene (Sc) (Falla, Dall'Alba, Rainoldi, Merletti, & Jull, 2002), rectus femoris (for timing of the leg lift) (Perotto, 1994) and the right chest wall (CW) (Allison, Kendle et al., 1998; Gross, Grassino, Ross, & Macklem, 1979; Sharp, Hammond, Aranda, & Rocha, 1993). Exact electrode sites are described elsewhere (Beales et al., 2009). Skin was lightly abraded and cleaned so impedance was <5 kΩ (Gilmore & Meyers, 1983). Disposable Ag/AgCl electrodes (ConMed Corporation, Utica, New York) were positioned with an intra-electrode distance of 2.5cm. Earth electrodes were placed on the anterior superior iliac spine bilaterally. Input was sampled at 1000Hz at a bandwidth of 10-500Hz with a common mode rejection ratio of >115dB at 60Hz, pre-amplified and amplified at a gain of 2000.

Table 4.2 Criteria for the diagnosis of pelvic girdle pain with sacroiliac joint as a source of peripheral nociception. (SIJ = sacroiliac joint, ASLR = active straight leg raise)

<u>Symptoms:</u>

- Presenting pain primarily over the SIJ, able to refer distally, but not referring proximally to the lumbar spine (Dreyfuss, Michaelsen, Pauza, McLarty, & Bogduk, 1996; Maigne, Aivaliklis, & Pfefer, 1996; van der Wurff, Buijs, & Groen, 2006; Young, Aprill, & Laslett, 2003)
- Symptoms present for a least six months

<u>SIJ Pain Provocation Tests:</u>

- Three out of five positive SIJ pain provocation tests:-
    - Posterior shear test (Laslett, Aprill, McDonald, & Young, 2005; Laslett, Young, Aprill, & McDonald, 2003; Ostgaard, Zetherstrom, & Roos-Hansson, 1994)
    - Sacral torsion test (Laslett et al., 2005; Laslett et al., 2003)
    - Sacral thrust test (Laslett et al., 2005; Laslett et al., 2003)
    - Distraction test (Laslett et al., 2005; Laslett et al., 2003)
    - Tenderness on palpation of the long dorsal SIJ ligament (Vleeming, de Vries, Mens, & van Wingerden, 2002) and/or the inferior joint line and/or the sacrotuberous ligament

<u>ASLR Test:</u>

- Heaviness, plus or minus pain, with an ASLR which is relieved with the addition of manual pelvic compression (Mens et al., 2001; Mens et al., 1999; O'Sullivan et al., 2002)

<u>Other:</u>

- Absence of lumbar spine pain and impairment (Laslett et al., 2005; Laslett et al., 2003)
- Negative lumbar spine pain provocation tests (passive accessory tests)
- Negative neurological screening testing
- Negative neural tissue pain provocation tests

Table 4.3 Subject demographic data (mean ± standard deviation). (PGP = pelvic girdle pain, Quebec = The Quebec Back Pain Disability Scale (Kopec et al., 1996), McGill = Short Form McGill Pain Questionnaire (Melzack, 1987), VAS = Visual Analogue Scale for Usual Pain, Tampa = Tampa Scale for Kinesiophobia (Vlaeyen, Kole-Snijders, Boeren, & van Eek, 1995), UDI = Urogenital Distress Inventory: Short Form (Uebersax, Wyman, Shumaker, McClish, & Fantl, 1995), ASLR = active straight leg raise, ASLR heaviness score (Mens, Vleeming, Snijders, Koes et al., 2002), adductor strength (Mens, Vleeming, Snijders, Ronchetti, & Stam, 2002))

	PGP Subjects (n=12)
Age (years)	39.8 ± 11.2
Height (cm)	170.0 ± 3.9
Weight (cm)	67.2 ± 12.4
BMI (kg/m^2)	23.2 ± 4.6
Nulliparous	n = 5
Symptom Duration (months)	92.6 ± 78.0
Aetiology:	
- Pregnancy Related	n = 4
- Trauma	n = 6
- Insidious	n = 2
Quebec (x/100)	22.9 ± 18.7
McGill (x/45)	8.4 ± 2.7
VAS for usual pain (x/100)	43.7 ± 24.3
Tampa (x/68)	35.1 ± 9.2
Continence Dysfunction	n = 7
UDI (x/15 for n = 7)	1.8 ± 1.1
ASLR Heaviness Score (x/5)	
- Affected Side	3.1 ± 0.5
- Non-affected Side	1.2 ± 1.1
Adductor Strength (N)	92.6 ± 26.4

A custom-made silicone rubber nasogastric catheter (Dentsleeve International Ltd, Mississauga, Canada) with two small lumens was used to record IAP and ITP. Once situated in the esophagus, saline solution was passed through the lumen at high pressure. Changes in flow rate of the saline which occur in response to pressure change were monitored by a custom-built pressure transducer and output to the data collection program. One lumen was located in the abdomen and the other in the thorax by observing opposite pressure changes in both channels during respiration (Hodges & Gandevia, 2000).

Downward pressure exerted by the leg not being lifted was monitored with an inflated pad, placed under the heel, linked to another pressure transducer. Kinematics of the PF were monitored with a Capesee SSA-220A ultrasound unit (Toshiba Corporation, Tochigi, Japan) and recorded to digital video. The bladder was viewed by positioning the probe trans-abdominally, angled inferiorly. This has been established as a reliable, non-invasive method of investigating PF movement.(O'Sullivan et al., 2002; Sherburn, Murphy, Carroll, Allen, & Galea, 2005; Thompson & O'Sullivan, 2003; Walz & Bertermann, 1990)

4.3.3 Data Collection and Processing

Average root mean square (RMS) for three 3s trials of a crook lying double leg raise with cervical flexion was calculated for sub-maximal EMG normalisation (Allison, Godfrey, & Robinson, 1998; Allison, Kendle et al., 1998; Dankaerts, O'Sullivan, Burnett, Straker, & Danneels, 2004; O'Sullivan, Twomey, & Allison, 1998). Data was then collected for 60s in resting supine. An ASLR trial was then performed for each leg. A cough at the start of each trial, producing movement of the PF on ultrasound, was used to synchronise PF data with the other variables. After coughing the leg was lifted for approximately 45s. A further trial was performed on each leg for repeatability analyses.

Data were prepared for analyses with a custom LabVIEW processing program. Initially EMG was inspected for contamination by heartbeat and other artifact and manually eliminated if necessary. Data was then demeaned, band pass filtered from 4-400Hz with a 4^{th} order zero lag Butterworth filter and normalised. The RMS of the

EMG was obtained for 500ms during the middle of inspiration and expiration each of three breath cycles. This was to allow for an impression of phasic EMG changes in relation to respiration versus tonic changes in response to the ASLR.

Respiratory fluctuation of IAP and ITP were found by calculating the difference between the maximum and minimum value for each variable respectively over a breath cycle. Pressure change related to the physical load of the ASLR was assessed via a baseline shift, obtained by subtracting the minimum IAP or ITP value of relaxed supine breathing from the corresponding minimum value during the ASLR.

Respiratory rate (RR) was calculated from the respiratory traces. Pelvic floor movement was assessed by capturing two frames of video: a) slightly before and after the leg lift to ascertain bladder motion secondary to the ASLR, and b) at the maximum and minimum points of excursion over each of the three breath cycles to observe motion in response to respiration. Movement was directly measured by overlaying the two captured frames. Average downward pressure exerted by the non-lifted leg during the ASLR was calculated for each breath cycle.

4.3.4 Analyses

Values for analyses were obtained by averaging the three breath cycles. Patterns of activation (Hypothesis 1) were investigated for each muscle by comparing RMS with a two (*side:* non-affected side ASLR, affected side ASLR) by two (*respiration:* inspiration, expiration) repeated measure analysis of variance and post hoc t-tests. The affected side refers to the body side on which sacroiliac joint dysfunction was identified. The presence of a bracing strategy (Hypothesis 2) during an ASLR on the affected or non-affected side was investigated by looking at side-to-side muscle symmetry with a two (*muscle:* non-affected side, affected side) by two (*respiration:* inspiration, expiration) repeated measure analysis of variance and post hoc t-tests. Half the subjects had a symptomatic right sacroiliac joint, the other half on the left, so the EMG data was side corrected accordingly to be labeled as either the affected or non-effected side. As the CW was only collected on the right, for six subjects this represented the affected side and six the non-affected side. Due to this low sample size (n=6) and the number of factors in the statistical model this variable was not considered for statistical analyses. Intra-abdominal pressure, ITP, RR, PF movement and downward leg pressure were compared lifting each leg with paired t-tests (Hypothesis 3). Visual inspection of all data was also used to investigate the motor control patterns.

The intra-class correlation coefficient and corresponding 95% confidence intervals over two trials were calculated for all variables as an estimation of consistency. Statistical analysis was performed with SPSS 15.0 for Windows (SPSS Inc., Chicago, Illinois), with a critical p value of 0.05.

4.4 Results

4.4.1 Electromyograhy

Table 4.4 displays results from EMG analyses.

4.4.2 Internal obliquus abdominis

Patterning: The IO on the affected side showed greater activation lifting the leg on the affected side (*side* p=0.0254) (Figure 4.2). Activation of IO on the non-affected side was the same lifting either leg (*side* p=0.378) (Figure 4.2). The activation pattern for either muscle was tonic in nature and as such not overtly influenced by respiration.

Bracing: During an ASLR on the affected side there was symmetrical tonic activation of the IO's (*muscle* p=0.235) consistent with a bracing pattern, but asymmetrical tonic activation during a non-affected side ASLR (*muscle* p=0.034) (Figure 4.2). Respiration had no influence.

Visual inspection: This was consistent with greater ipsilateral activation of IO lifting the leg on the non-affected side compared to bilateral activation in a bracing pattern for IO lifting the leg on the affected side (Figure 4.3: Subject A). While this was the predominant pattern, EMG traces demonstrated some variation. Three subjects displayed bilateral activation lifting either leg (Figure 4.3: Subject B), while three tended to have greater ipsilateral activation during the affected ASLR. Interestingly two subjects appeared to have minimal IO activation during the ASLR (Figure 4.3: Subject C).

Table 4.4 Repeated analyses of variance p-values for electromyographic comparisons. (ASLR = active straight leg raise, N-A = non-affected, Aff. = affected, IO = obliquus internus abdominis, EO = obliquus externus abdominis, RA = rectus abdominis, Sc = scaleni)

1. Patterning (Affected versus Non-affected ASLR)

	side	*respiration*	*side by respiration*
IO- Aff. side	0.024*	0.854	0.728
IO- N-A side	0.378	0.559	0.625
EO- Aff. side	0.150	0.383	0.187
EO- N-A side	0.456	0.268	0.212
RA- Aff. side	0.064	0.820	0.033*
RA- N-A side	0.197	0.604	0.743
Sc- Aff. side	0.624	0.261	0.306
Sc- N-A side	0.119	0.215	0.072

2. Bracing (Muscle of Affected versus Non-affected body side)

	muscle	*respiration*	*muscle by respiration*
Aff. ASLR- IO's	0.235	0.887	0.730
Aff. ASLR- EO's	0.087	0.980	0.912
Aff. ASLR- RA's	0.111	0.143	0.195
Aff. ASLR- Sc's	0.247	0.252	0.693
N-A ASLR- IO's	0.034*	0.605	0.568
N-A ASLR- EO's	0.002*	0.180	0.710
N-A ASLR- RA's	0.235	0.762	0.145
N-A ASLR- Sc's	0.917	0.227	0.955

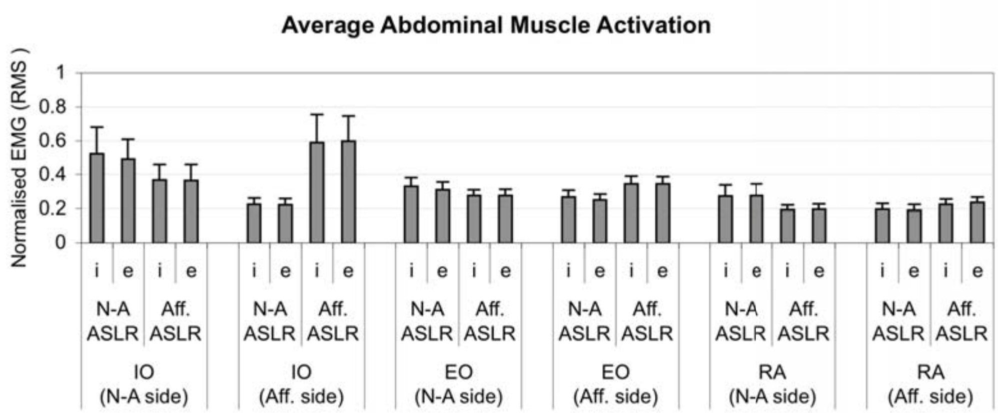
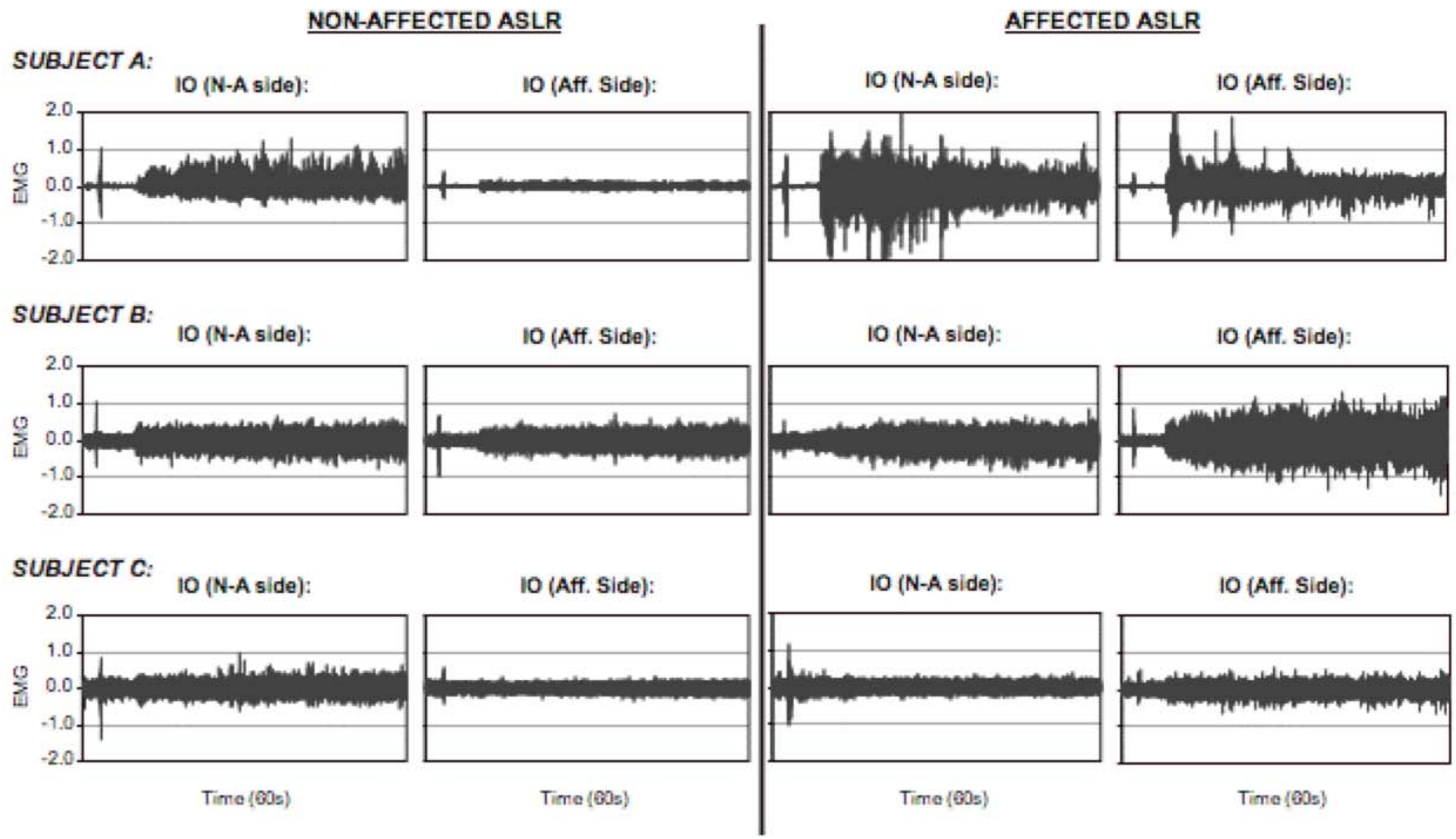


Figure 4.2 Graphical representation of the mean (standard error of the mean) root mean square (RMS) electromyography (EMG) for anterior abdominal wall. (i = inspiration, e = expiration, N-A = non-affected, Aff. = affected, ASLR = active straight leg raise, EO = obliquus externus abdominis, RA = rectus abdominis, IO = obliquus internus abdominis, RF = rectus femoris, S = side)

Figure 4.3 (following page) Demeaned and normalised electromyography (EMG) traces of obliquus internus abdominis (IO) for three subjects performing an active straight leg raise (ASLR) on both sides of the body. Subject A displays greater ipsilateral activation lifting the leg of the non-affected side, but greater bilateral activation lifting the affected side leg. Subject B displays increased greater bilateral activation lifting either leg. Subject C displays minimal activation lifting either leg. (N-A = non-affected, Aff. = affected)

Figure 4.3


NON-AFFECTED ASLR
AFFECTED ASLR
SUBJECT A:
SUBJECT B:
SUBJECT C:
IO (N-A side):
IO (Aff. Side):
EMG
2.0
1.0
0.0
-1.0
-2.0
Time (60s)

4.4.3 Externus obliquus abdominis

Patterning: There was no difference in EO activation lifting either the leg on the affected or non-affected side (affected EO: *side* p=0.150; non-affected EO: *side* p=0.456) (Figure 4.2), and no effect for respiration.

Bracing: Activation of EO was symmetrical during ASLR on the affected side (*muscle* p=0.087) but asymmetrical during ASLR on the non-affected side (*muscle* p=0.002) (Figure 4.2). There was no phasic respiratory effect.

Visual inspection: This suggested a predominant pattern of bilateral tonic EO activation lifting the affected or non-affected leg (Figure 4.2).

4.4.4 Rectus abdominis

Patterning and Bracing: No differences were found for either *side* or *muscle*. Side by respiration was significant for the affected RA (affected RA: *side by respiration* p=0.033), but there was no other effect for respiration.

Visual inspection: There was no indication of a respiratory effect with visual inspection, with all subjects displaying bilateral tonic activation.

4.4.5 Right chest wall

Visual inspection: Values for the CW are presented in Figure 4.4. The predominant pattern of CW activation was phasic when lifting the leg on the non-affected side, but increase tonic when lifting the leg on the affected side (Figure 4.5: Subject D- affected CW; Subject E- non-affect CW). There were some variants such as phasic activity lifting either leg in one case and tonic activity lifting either leg in another (Figure 4.5: Subjects B and C).

4.4.6 Anterior scaleni

Patterning and Bracing: No differences were found for either *side* or *muscle*, nor any change related to respiration (Figure 4.4).

Visual inspection: On visual inspection the Sc revealed variant patterns with a penchant for either tonic or phasic Sc activation, which within individuals tended to be consistent between lifting the affected or non-affected leg.

4.4.7 Other Variables

Data are presented as mean (standard error of the mean).

4.4.8 Intra-abdominal pressure and intra-thoracic pressure

Respiratory fluctuation of IAP and ITP did not vary lifting either leg (IAP p=0.185, ITP=0.571) (Figure 5.6). The baseline shift in IAP was greater during an ASLR on the affected side (p=0.044), but did not change for ITP (p=0.892) (Figure 5.6).

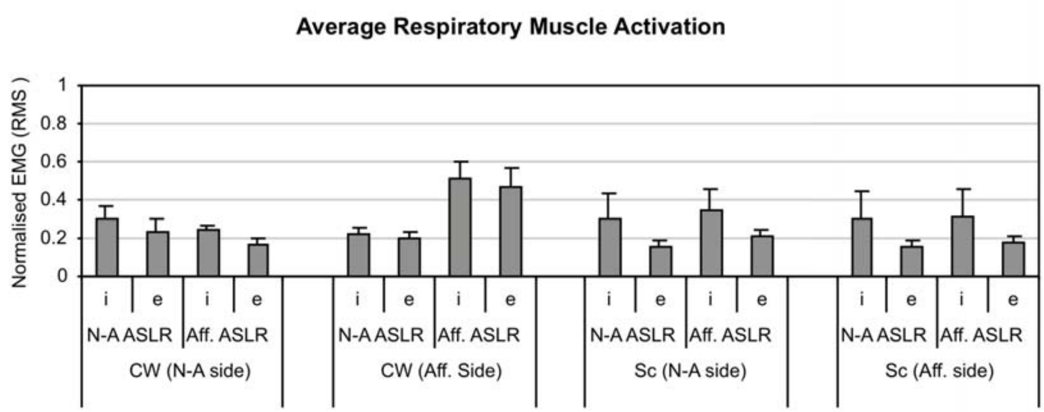


Figure 4.4 Graphical representation of the mean (standard error of the mean) root mean square (RMS) electromyography (EMG) for the chest wall (CW) and anterior scalene (Sc). (i = inspiration, e = expiration, N-A = non-affected, Aff. = affected, ASLR = active straight leg raise)

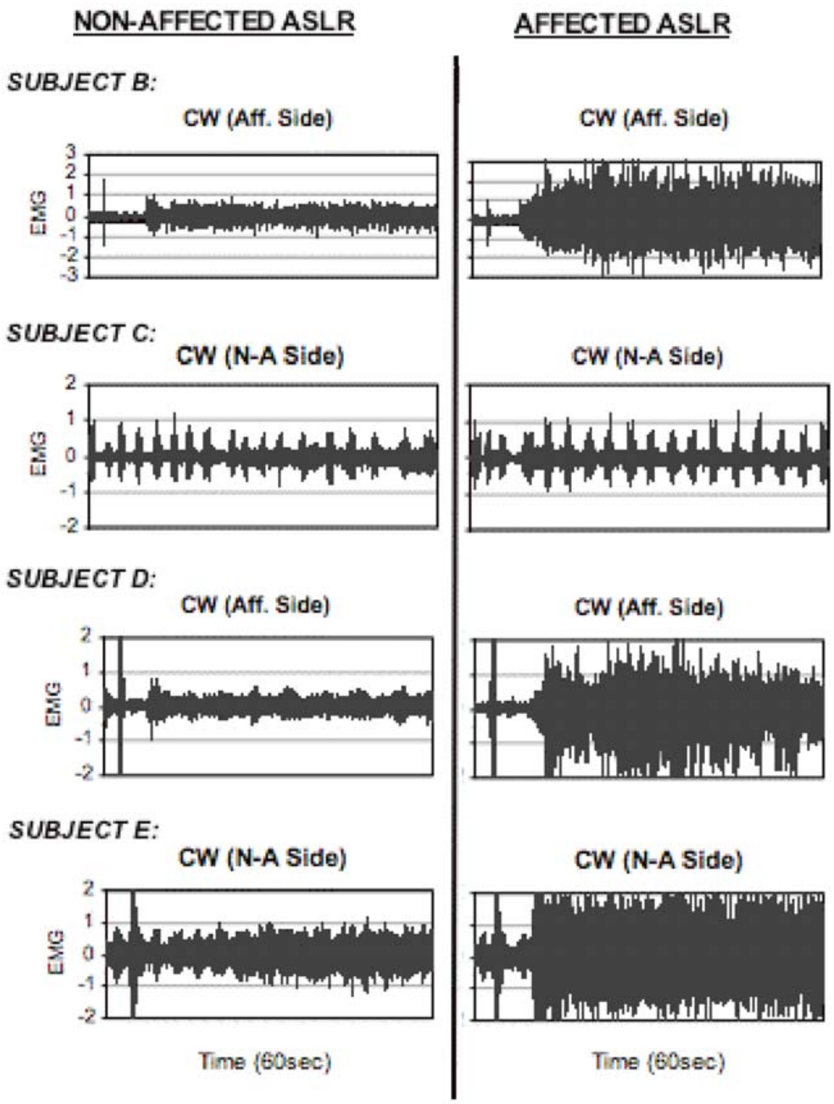
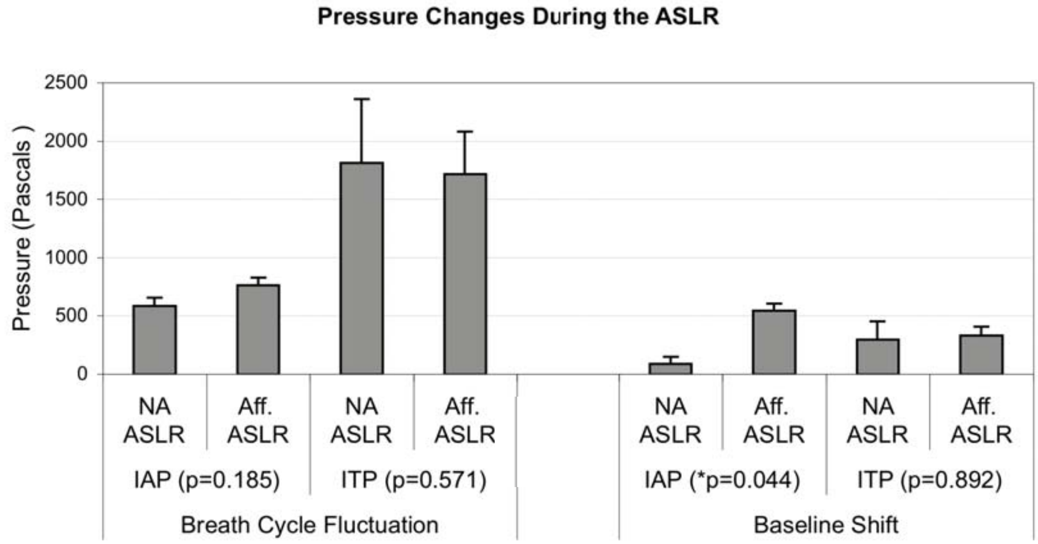


Figure 4.5 Demeaned and normalised electromyography (EMG) traces of chest wall (CW) for four subjects performing an active straight leg raise (ASLR) on both sides of the body. Subject B displays tonic activation lifting either leg, though to a greater degree lifting the leg on the affected side. Subject C displays phasic activity lifting either leg. Subjects D and E display phasic activity lifting the leg on the non-affected side, but greater tonic activation lifting the leg on the affected side. (N-A = non-affected, Aff. = affected)



Pressure Traces (Subject F):

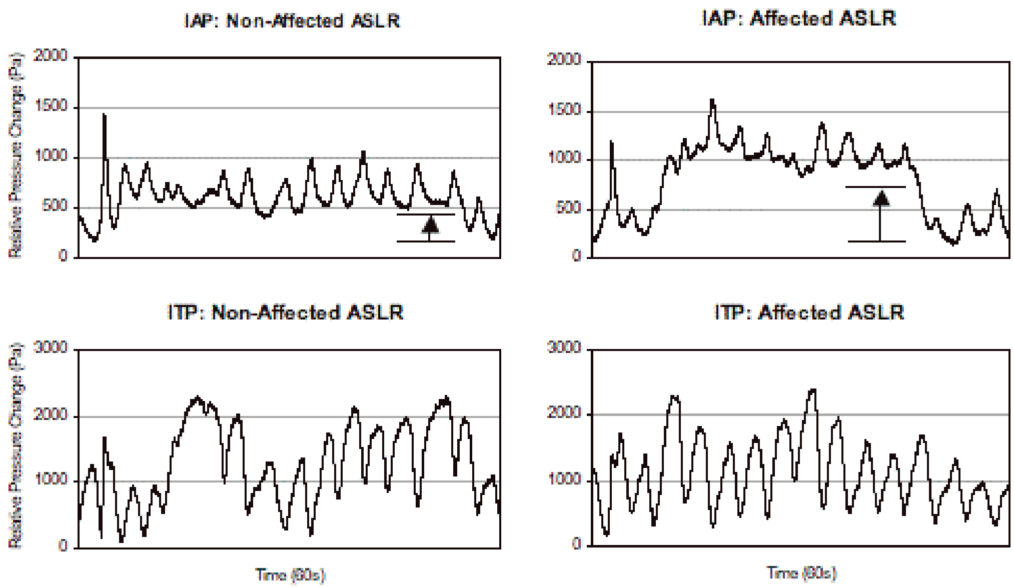


Figure 4.6 Pressure changes (mean, standard error of the mean) for intra-abdominal pressure (IAP) and intra-thoracic pressure (ITP). Subject F displays a larger baseline shift of IAP performing an active straight leg raise (ASLR) on the affected side. (N-A = non-affected, Aff. = affected)

4.4.9 Respiratory rate

The RR did not differ lifting either leg (affected ASLR: 16.8(1.4) breaths/min; non-affected ASLR: 16.5(1.5) breaths/min; p=0.748).

4.4.10 Pelvic floor movement

There was greater PF downward movement in response to an ASLR on the affected side (affected ASLR: 9.0(1.8)mm; non-affected ASLR: 4.0(0.6)mm; p=0.012). There was no difference for PF motion with respiration (affected ASLR: 3.1(0.6)mm; non-affected ASLR: 3.0(0.5)mm; p=0.887).

4.4.11 Contralateral leg downward pressure

Downward leg pressure with the non-lifted leg did not differ during either ASLR (affected ASLR: 58.85(6.75)N; non-affected ASLR: 65.04(7.79)N; p=0.326).

4.4.12 Consistency of patterns

Repeated trials were not available for two subjects as urgent need to void urine resulted in early cessation of data collection. Repeatability was good to very good, except for the baseline shift of IAP during a non-affected ASLR and PF movement lifting either leg, which displayed more variability (Table 4.5).

4.5 Discussion

As hypothesised, subjects with unilateral chronic PGP of mild to moderate severity adopt bracing motor control strategies performing an affected side ASLR, with associated generation of higher levels of IAP and greater PF depression.

4.5.1 Muscle activation

During an ASLR on the affected side a bracing strategy highlighted by bilateral tonic activation of IO and EO was observed. These findings contrast to the strategy of greater ipsilateral activation of these muscle groups, particularly IO, observed in

Table 4.5 Consistency of motor patterns over two trials for the non-affected and affected active straight leg raise (ASLR), expressed via intra-class correlation coefficient (ICC) (95% confidence interval (CI)) values. (IAP = intra-abdominal pressure, ITP = intra-thoracic pressure, RR = respiratory rate, PF = pelvic floor

	Non-affected ASLR: ICC (95% CI)	**Affected ASLR: ICC (95% CI)**
Muscle Activation	Highest: 0.995 (0.980 – 0.999) Lowest: 0.858 (0.427 – 0.965) Median: 0.944	Highest: 0.987 (0.948 – 0.997) Lowest: 0.742 (0 – 0.936) Median: 0.912
IAP-Breath Cycle	0.910 (0.636 - 0.978)	0.943 (0.778 - 0.985)
ITP-Breath Cycle	0.854 (0.495 - 0.958)	0.815 (0.358 - 0.947)
IAP-Baseline Shift	0.498 (0 - 0.875)	0.911 (0.644 - 0.978)
ITP-Baseline Shift	0.926 (0.704 - 0.982)	0.979 (0.916 - 0.995)
RR	0.970 (0.879 - 0.993)	0.953 (0.810 – 0.988)
PF movement – Leg Lift	0.383 (0 - 0.847)	0.538 (0 - 0.885)
PF movement – Breath Cycle	0.698 (0 - 0.925)	0.813 (0.247 - 0.954)
Contralateral Leg Pressure	0.887 (0.341 - 0.981)	0.910 (0.473 - 0.984)

nulliparous pain free females (Beales et al., 2009). This bracing strategy concurs with the finding of greater EO activation during an ASLR in pregnant subjects with PGP compared to pain free pregnant subjects (de Groot et al., 2008).

Activation of the right chest wall during an ASLR in pain free subjects has been reported as variable. In that study there was a tendency in eight of 14 subjects for tonic activation lifting the ipsilateral leg, but phasic activation lifting the contralateral leg, suggesting a change in motor control pattern dependant on the side of the leg lift. In this study CW activation in PGP subjects was not overtly influenced by lifting the contralateral or ipsilateral leg, but was influenced more by if the ASLR was on the affected or non-affected side. Specifically, performing an ASLR on the affected side predominantly resulted in tonic CW activation (ie. bracing strategy) whether this was ipsilateral or contralateral to the CW. This concurs with ultrasound observation of diaphragmatic splinting during an affected ASLR in a similar group of subjects (O'Sullivan et al., 2002) suggesting a shift in function of the CW from respiration to additional control of IAP. These observations on chest wall activation must be considered cautiously due to the small sample size in this study, but would be an interesting area for further research.

Over half the subjects demonstrated tonic activation of the Sc, whereas Sc activity was phasic in pain free subjects (Beales et al., 2009). This might reflect a general increase in muscle tone, or tonic activation of accessory breathing muscles as a component of the bracing strategy in some subjects. This could provide a mechanism for the development of concurrent cervicothoracic symptoms, which clinical observations denote as a common co-morbidity in subjects with chronic lumbopelvic pain.

It should be noted that even though a commonality in muscle activation patterns has been identified between subjects, examination of raw EMG traces demonstrates some individual variability (Figure 4.3 and 4.5). This is an important consideration in the physical examination of PGP subjects. Not all chronic PGP subjects present in the same manner, nor respond to the same intervention (Stuge, Morkved, Haug Dahl, & Vollestad, 2006). Clinical identification of individual variants in motor control patterns may facilitate targeted intervention (O'Sullivan & Beales, 2007b, 2007c).

4.5.2 Intra-abdominal pressure and intra-thoracic pressure

To the author's knowledge this is the first study to measure IAP in chronic PGP subjects. The major finding was an increased baseline shift in IAP when performing an affected ASLR, while preserving respiratory IAP fluctuation. This is consistent with the finding of a bracing activation pattern through the abdominal wall and CW.

Variability between tests with IAP baseline shift performing a non-affected ASLR despite good repeatability of the EMG activation was noted, which is similar to what has been observed in pain free individuals during an ASLR (Beales et al., 2009). It was suggested that this may be due to the fact that not all muscles (ie transversus abdominis, pelvic floor) which produce IAP were monitored, a limitation shared by this study, or that it might reflect flexibility in the control of IAP under low load conditions. In contrast the repeatability for IAP baseline shift during an affected ASLR was very good. This suggests that PGP subjects have reduced flexibility in their motor control strategy with regard to the generation of IAP during an affected ASLR.

4.5.3 Pelvic floor movement

Greater depression of the PF was noted during the affected ASLR, as previously reported in SIJ pain subjects (O'Sullivan et al., 2002). This contrast to observations in pain free subjects (Beales et al., 2009; O'Sullivan et al., 2002). It may result from an inability of PF musculature to resist downward force created by increased baseline IAP. However, these findings do not inform regarding the level of PF muscle activation. Further research into PF activation during the ASLR would be useful in enlightening the role of the PF in the production of force closure.

Recent research has demonstrated a strong positive correlation between lumbopelvic pain and continence dysfunction (Eliasson, Elfving, Nordgren, & Mattsson, 2008; Smith, Russell, & Hodges, 2006, 2008). Caution must be taken in implying 'cause and effect' between the two disorders from these cross-sectional studies. However, depression of the PF during an ASLR, or with an attempt to voluntarily elevate the PF, has been linked to continence dysfunctions (O'Sullivan & Beales, 2007a; O'Sullivan et al., 2002; Thompson & O'Sullivan, 2003) and there is growing evidence of other forms of motor control dysfunction linking these two disorders (Pool-Goudzwaard et al., 2005; Smith, Coppieters, & Hodges, 2007a, 2007b, 2008). It is important to recognise though that the presence of PF depression does not automatically mean that continence will be compromised as five subjects did not report continence issues despite demonstrating PF depression during an affected ASLR.

4.5.4 Implications

All subjects in this study had reduced heaviness of the leg with the addition of compression during the affected ASLR (Table 4.2), consistent with inefficient load transfer through the pelvis. This could result from impairments in passive pelvic stability (form closure), insufficient dynamic pelvic stability (reduced force closure), or a combination of these factors (O'Sullivan et al., 2002). The addition of manual pelvic compression to the ASLR has been shown to have a positive effect on motor control in a similar group of subjects to those in this study. Altered breathing patterns, decreased diaphragmatic motion and PF descent have been improved with compression during an ASLR (O'Sullivan et al., 2002). Presumably compression improves load transference by enhancing both passive stability of the SIJ's and motor control patterns/force closure. As such compression might well have a positive effect on the bracing strategy observed in the present study, and may facilitate a reduction in baseline IAP. This is the topic of an ongoing study by our research group.

Psychosocial factors such as fear avoidance can also effect load transfer through the pelvis, though this is unlikely to be a factor in the subjects in this study as the average score for the Tampa Scale for Kinesiophobia was within normal limits (Table 4.3). Further screening of other psychosocial factors, such as anxiety and depression, would be advantageous in future studies investigating motor control strategies in chronic PGP.

The bracing strategies observed in this study could be a reaction of the neuromuscular system to impaired load transference and pain, consistent with a *protective* response. There is growing evidence though that bracing patterns may be *provocative* in nature, providing a mechanism for ongoing pain. In-vivo examination has determined that bracing contraction of the abdominal wall is less effective at creating pelvic stiffness/force closure than local muscle activation (Richardson et al., 2002). As such, the bracing patterns observed in this study may result in sub-optimal force closure, compromising effective load transference through the pelvis. This potentially creates ongoing stimulation of sensitised peripheral nociceptors during loading, and consequently a mechanism for ongoing pain. Supporting this is the finding that exercise intervention re-enforcing bracing patterns tends to worsen symptoms in PGP (Mens, Snijders, & Stam, 2000). Conversely interventions initially promoting local muscle control are effective at alleviating some presentations of chronic PGP (O'Sullivan & Beales, 2007a; Stuge, Veierod, Laerum, & Vollestad, 2004).

Furthermore it has been postulated from a theoretical model that high levels of IAP could be sufficient to mechanically provoke painful pelvic structures (Mens et al., 2006), providing a peripheral nociceptive drive for ongoing PGP. The magnitude of IAP elicited by the ASLR in our study was below the pressure thresholds calculated for this biomechanical model. Never the less, the increased baseline IAP observed during the affected ASLR could potentially result in ongoing mechanically mediated peripheral pain generation in the manner described by this model. Further research investigating IAP production in chronic PGP subjects during functional activities and high load tasks is warranted.

4.6 References: Chapter 4

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Chapter 5: Study 3. The effect of increased physical load during an active straight leg raise in pain free subjects

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5.1 Abstract

Purpose

It has been proposed that pelvic girdle pain (PGP) subjects adopt a high load motor control strategy during the low load task of the active straight leg raise (ASLR). This study investigated this premise by observing the motor control patterns adopted by pain free subjects during a loaded ASLR (ASLR+PL).

Method

Trunk muscle activation, intra-abdominal pressure, intra-thoracic pressure, pelvic floor motion, downward pressure of the non-lifted leg and respiratory rate were compared between resting supine, ASLR and ASLR+PL. Additionally, side-to-side comparisons were performed for ASLR+PL.

Results

Incremental increases in muscle activation were observed from resting supine to ASLR to ASLR +PL. During the ASLR+PL there was a simultaneous increase in intra-abdominal pressure with a decrease in intra-thoracic pressure, while respiratory fluctuation of these variables were maintained. The ASLR+PL also resulted in increased pelvic floor descent and greater downward pressure of the non-lifted leg.

Trunk muscle activation was comparable between sides during ASLR+PL in all muscles except lower obliquus internus abdominis, which was more active on the leg lift side.

Conclusion

This study documents motor control patterns when physical load is added to the ASLR in pain free subjects. Despite a general increase in anterior trunk muscle activation during an ASLR+PL, the pattern of greater activation on the side of the leg lift observed during an unloaded ASLR is preserved.

5.2 Introduction

The active straight leg raise (ASLR) test is a valid and reliable physical evaluation procedure utilised in the assessment of load transfer through the pelvis (Mens, Vleeming, Snijders, Koes, & Stam, 2001; Mens, Vleeming, Snijders, Stam, & Ginai, 1999; O'Sullivan et al., 2002). It is an integral part of the assessment of patients with pelvic girdle pain (PGP) (Vleeming, Albert, Ostgaard, Sturesson, & Stuge, 2008), and may also be useful in the examination of hip and groin pain (Cowan et al., 2004; Mens, Inklaar, Koes, & Stam, 2006) and lumbar spine pain disorders (Roussel, Nijs, Truijen, Smeuninx, & Stassijns, 2007). The test requires subjects to lie supine and lift their leg 10-20cm. In the presence of impairment, there is a report of heaviness of the leg ± pain. This is repeated with the addition of pelvic compression through the anterior superior iliac spines, applied manually or with a pelvic belt. A positive test is associated with a reduction of the feeling of heaviness and relief of pain, (Mens et al., 1999; O'Sullivan et al., 2002).

Various studies have investigated motor control strategies during the ASLR in an effort to improve the understanding of the motor control mechanisms associated with load transference through the pelvis. Pain free subjects demonstrate a pattern of greater abdominal and chest wall (CW) activation ipsilateral to the ASLR with minimal change to intra-abdominal pressure (IAP) and respiration, and minimal alteration in position of the pelvic floor (PF) (Beales, O'Sullivan, & Briffa, 2009b; O'Sullivan et al., 2002). This is consistent with the ASLR representing a low level physical load upon the neuromuscular control system. In contrast, chronic PGP subjects demonstrate increased muscle activation in the anterior abdominal wall bilaterally and right CW, increased IAP, PF depression, diaphragmatic splinting and/or altered respiratory patterns during an ASLR on the symptomatic side of the body (Beales, O'Sullivan, & Briffa, 2009a; de Groot, Pool-Goudzwaard, Spoor, & Snijders, 2008; O'Sullivan et al., 2002). It has been proposed that these patients with impaired load transference through the pelvic girdle adopt bracing strategies under low load that under normal circumstances would only be expected during high level physical loading activities (O'Sullivan et al., 2002).

Therefore, the purpose of this study was to investigate the trunk motor control response in pain free subjects during a low as compared to a high lower limb load task, utilising the ASLR maneuver. The hypotheses were: 1. Trunk muscle activation, IAP and PF descent would increase during an ASLR with additional physical load on the leg (ASLR+PL), and 2. Trunk muscle activation during the ASLR+PL would be symmetrical, corresponding to the bracing strategy observed during ASLR in PGP subjects with a positive ASLR test.

5.3 Materials and Methods

5.3.1 Subjects

Ten pain free, nulliparous females (average age 30.0±6.5 years, average BMI 23.6±2.3kg/m^2) were recruited from the Perth metropolitan region. Subjects were excluded if there was a history of a musculoskeletal pain disorder in the last six months, surgery in the last year, current neurological or inflammatory disorders or a history of a significant respiratory disorder. All subjects provided written informed consent. The Human Research Ethics Committee of Curtin University of Technology granted ethical approval.

5.3.2 Tasks

Data were collected for approximately 60s during three test conditions; resting supine (RS), left ASLR, and left ASLR with a weight equal to 6% of the subjects body weight around the left ankle as a physical load (ie. ASLR+PL). The value of 6% was determined during pilot testing as providing a challenge that shifted the ASLR from a low load activity to a high load activity. All subjects were right side dominant.

5.3.3 Respiration

Respiratory phase was recorded with the pneumotach of a Benchmark Pulmonary Exercise System (P.K. Morgan Instruments, Inc., Andover, Massachusetts) that was modified with an external output. Data were recorded with a custom designed LabVIEW v6.1 (National Instruments, Austin, Texas) data collection program. Respiratory rate (RR) was calculated directly from the respiratory traces that were generated by graphing this data.

5.3.4 Electromyography

Electrode sites were prepared by light abrasion and cleaning with alcohol so that impedance was <5kΩ (Gilmore & Meyers, 1983). Round self-adhesive disposable Ag/AgCl electrodes with a sensor diameter of 1cm (ConMed Corporation, Utica, New York) were placed parallel to the muscle fibre direction with an inter-electrode distance of 2.5cm (all muscles were collected bilaterally except where noted):

- rectus abdominis (RA) 1cm above and 2cm lateral to the umbilicus (Ng, Kippers, & Richardson, 1998)
- obliquus externus abdominis (EO) just under the rib cage on a line connecting the inferior costal margin with the contralateral pubic tubercle (Ng et al., 1998)
- lower fibres of obliquus internus abdominis (IO) just medially and inferior to the anterior superior iliac spine (Ng et al., 1998)
- right CW in the sixth and seventh intercostal spaces, 2cm lateral to the mid clavicular line (Allison, Kendle et al., 1998; Gross, Grassino, Ross, & Macklem, 1979; Sharp, Hammond, Aranda, & Rocha, 1993)
- anterior scalene (Sc) adjacent to the lower third point of a line between the mastoid and the sternal notch (Falla, Dall'Alba, Rainoldi, Merletti, & Jull, 2002)
- rectus femoris (RF) half way between the anterior superior iliac spine and the superior border of the patella (Perotto, 1994)

Data were collected with two Octopus Cable Telemetric units (Bortec Electronics Inc., Calgary, Canada) earthed to the anterior superior iliac spine, one for each side of the body. Data were sampled at 1000Hz, at a bandwidth of 10 to 500Hz, with a common mode rejection ratio of >115dB at 60Hz, and pre-amplified and amplified at an overall gain of 2000, then input into the data collection program.

A separate custom-designed LabVIEW program was used to process data. Initially the electromyography (EMG) was inspected for contamination by electrocardiography or other artifact that was manually eliminated if necessary. Data were then demeaned and band pass filtered from 4 to 400Hz with a 4^{th} order zero lag Butterworth filter. Average root mean square (RMS) for three 3s trials of a crook lying double leg raise with cervical flexion was used for sub-maximal EMG normalisation (Allison, Godfrey, & Robinson, 1998; Dankaerts, O'Sullivan, Burnett, Straker, & Danneels, 2004; Falla et al., 2002; O'Sullivan, Twomey, & Allison, 1998). Finally the RMS was calculated for 500ms during the middle of both the inspiratory and expiratory phases of three breath cycles. This was to enable the investigation of tonic EMG changes in response to the physical load of the ASLR, while simultaneously investigating phasic EMG changes in relation to respiration.

5.3.5 Intra-abdominal pressure and intra-thoracic pressure

Pressure data were collected simultaneously with a custom-made silicone rubber nasogastric catheter (Dentsleeve International Ltd, Mississauga, Canada). Saline solution was passed through two small lumen in the catheter at high pressure. Changes in flow rate of the saline that occur in response to pressure change within the thorax and abdomen were collected via a custom-built pressure transducer that output to the data collection program. Real time monitoring of the movement of IAP and ITP in opposite directions during respiration allowed for accurate placement of one lumen in the thorax and the other in the abdomen (Hodges & Gandevia, 2000b).

Calculations were performed to assess two aspects of both IAP and ITP. The respiratory fluctuation of these variables was ascertained from the difference between the maximum and minimum values for each variable respectively over a breath cycle. Pressure change related to the physical load of lifting the leg was calculated by subtracting the minimum IAP or ITP value during relaxed supine breathing from the minimum value during each of the ASLR tasks. This was termed a baseline shift.

5.3.6 Pelvic floor

A Capesee SSA-220A ultrasound unit (Toshiba Corporation, Tochigi, Japan) was used to monitor PF motion during testing. The bladder was visualised with the probe positioned trans-abdominally and angled inferiorly, a reliable non-invasive method of investigating PF kinematics (O'Sullivan et al., 2002; Sherburn, Murphy, Carroll, Allen, & Galea, 2005; Thompson & O'Sullivan, 2003; Walz & Bertermann, 1990). Ultrasound scans were recorded to digital video. A cough at the start of each trial produced movement of the PF that was used to synchronise this PF movement with the other variables collected in the LabView acquisition program.

Pelvic floor movement was firstly assessed in relation to lifting the leg. Two frames of video were captured slightly before and after the leg lift, and superimposed so the magnitude of movement could be directly measured. To assess movement in relation to respiration the same process was followed, capturing two frames at the maximum and minimum points of excursion over each of the three breath cycles.

5.3.7 Downward pressure of the non-lifted leg

An inflated pad was placed under the heel of the non-lifted leg. This was linked to another pressure transducer that recorded downward leg pressure of the right leg while the left leg was being lifted.

5.3.8 Analyses

Values for analyses were obtained by averaging the three breath cycles. The EMG data for Hypothesis 1 was investigated with a three (*task:* RS, ASLR, ASLR+PL) by two (*respiration:* inspiration, expiration) repeated measures analysis of variance and post hoc least square difference tests for each muscle. Intra-abdominal pressure and ITP respiratory fluctuations, RR and PF movement in response to respiration were analysed across the three tasks with one-way analysis of variance and post hoc least square difference tests. Intra-abdominal pressure and ITP baseline shift, PF movement in response to the leg lift and downward pressure of the non-lifted leg were analysed with paired t-tests (ASLR versus ASLR+PL). Hypothesis 2 was investigated with a two (*side:* left side muscle, right side muscle) by two (*respiration:* inspiration, expiration) repeated measures analysis of variance and post hoc least square difference tests. All statistical evaluation was complimented with visual inspection of the data. Additionally, repeatability of the ASLR+PL over two consecutive trials was assessed with intra-class correlation coefficients and corresponding 95% confidence intervals. Repeatability for the ASLR has been reported elsewhere (Beales et al., 2009b). Statistical analysis was performed with SPSS 15.0 for Windows (SPSS Inc., Chicago, Illinois), with a critical p value of 0.05.

5.4 Results

Table 5.1 and Table 5.2 show the value of all variables.

Table 5.1 (following page) Mean (standard error of the mean) for root mean square electromyographic activity of all muscles during resting supine (RS), left active straight leg raise (ASLR) and left active straight leg raise with 6% of body weight around the ankle as an additional physical load (ASLR+PL). Results (p values) from repeated measures analysis of variance are also presented (Hypothesis 1). (IO = obliquus internus abdominis, EO = obliquus externus abdominis, RA = rectus abdominis, CW = chest wall, Sc = scaleni, RF = rectus femoris)

Table 5.1

Muscle	RS	ASLR	ASLR+PL	*task*	*respiration*	*task by respiration*
Left IO - inspiration	0.1634 (0.05)	0.3994 (0.09)	0.8834 (0.17)	0.004*	0.571	0.835
- expiration	0.1644 (0.05)	0.3983 (0.08)	0.9034 (0.16)			
Right IO - inspiration	0.1521 (0.04)	0.3115 (0.09)	0.5126 (0.13)	0.003*	0.100	0.317
- expiration	0.1534 (0.04)	0.3148 (0.09)	0.5379 (0.14)			
Left EO - inspiration	0.1332 (0.02)	0.2692 (0.04)	0.6743 (0.09)	0.001*	0.441	0.234
- expiration	0.1271 (0.02)	0.2741 (0.03)	0.6988 (0.09)			
Right EO - inspiration	0.1244 (0.02)	0.2291 (0.02)	0.5459 (0.08)	0.001*	0.041*	0.154
- expiration	0.1257 (0.02)	0.2332 (0.02)	0.5781 (0.08)			
Left RA - inspiration	0.1100 (0.02)	0.2494 (0.05)	0.4564 (0.11)	0.011*	0.217	0.196
- expiration	0.1084 (0.02)	0.2581 (0.06)	0.4898 (0.10)			
Right RA - inspiration	0.1182 (0.02)	0.1846 (0.03)	0.4021 (0.07)	0.004*	0.015*	0.007*
- expiration	0.1175 (0.02)	0.1921 (0.03)	0.4512 (0.07)			
Right CW - inspiration	0.1551 (0.04)	0.2734 (0.05)	0.6164 (0.13)	0.008*	0.154	0.571
- expiration	0.1183 (0.03)	0.2248 (0.04)	0.5734 (0.12)			
Left Sc - inspiration	0.1148 (0.02)	0.1028 (0.01)	0.2035 (0.04)	0.022*	0.129	0.152
- expiration	0.1030 (0.02)	0.0934 (0.01)	0.1542 (0.03)			
Right Sc - inspiration	0.1146 (0.02)	0.1377 (0.03)	0.2370 (0.06)	0.066	0.272	0.758
- expiration	0.1022 (0.01)	0.1270 (0.03)	0.1887 (0.05)			
Left RF - inspiration	0.0976 (0.01)	2.1395 (0.20)	4.1476 (0.54)	< 0.001*	0.324	0.294
- expiration	0.0970 (0.01)	2.0827 (0.20)	4.3929 (0.55)			
Right RF - inspiration	0.0917 (0.01)	0.1381 (0.02)	0.3322 (0.09)	0.019*	0.219	0.202
- expiration	0.0915 (0.01)	0.1401 (0.02)	0.3124 (0.08)			

Table 5.2 Mean (standard error of the mean) for intra-abdominal pressure (IAP), intra-thoracic pressure (ITP), respiratory rate (RR), pelvic floor (PF) movement and downward pressure of the non-lifted leg. Results (p values) for the statistical comparisons between resting supine (RS), left active straight leg raise (ASLR) and left active straight leg raise with 6% of body weight around the ankle as an additional physical load (ASLR+PL) are also presented (Hypothesis 1).

	RS	**ASLR**	**ASLR+PL**	**p value**
IAP (Pa)				
Respiratory Fluctuation	618.5 (121.7)	478.9 (66.2)	1118.4 (306.5)	0.107
Baseline Shift	-	50.6 (64.3)	382.4 (138.5)	0.022*
ITP (Pa)				
Respiratory Fluctuation	987.0 (378.1)	842.8 (272.2)	1452.1 (656.3)	0.154
Baseline Shift	-	-152.5 (73.8)	-616.9 (112.7)	< 0.001*
RR (breaths/minute)	11.4 (0.8)	14.8 (1.5)	15.4 (1.6)	0.014*
PF Movement (mm)				
Related to respiration	3.7 (0.5)	3.0 (0.6)	5.0 (0.8)	0.014*
Related to leg lift	-	3.9 (1.2)	13.4 (2.9)	0.004*
Downward Leg Pressure (N)	-	48.2 (6.5)	86.0 (12.8)	0.003*

5.4.1 Hypothesis 1: Comparisons between resting supine, active straight leg raise and active straight leg raise with physical load

There was a difference in muscle activation with regard to task for all muscles except the right Sc (Table 5.1). Post hoc analyses (Table 5.3) confirmed the pattern of muscle activation for the abdominals, chest wall and RF muscles that increased from RS to ASLR, and increased again from ASLR to ASLR+PL. This pattern was consistent with Hypothesis 1. Left Sc activation was similar for RS and ASLR, but the level of activation increased during the ASLR+PL. The right Sc was not statistically significant but shows a trend for this same pattern (Table 5.1). Increased muscle activation from ASLR to ALST+PL can be observed in the EMG profiles of one subject for these two tasks, displayed in Figure 5.1.

There was respiratory fluctuation in activation of the right EO and right RA. Both muscles demonstrated phasic activity during an ASLR+PL (post hoc right EO $p=0.047$, right RA $p=0.025$) in sync with greater activation during expiration. Right RA was also phasic during the ASLR (post hoc $p=0.021$). There was no respiratory effect for right IO, right CW, right Sc or any of the muscles on the left side during the ASLR+PL.

There was no change in IAP or ITP with regard to respiratory fluctuation. However, concurrent with the increased muscle activation there was an increased upward baseline shift of IAP from ASLR to ALSR+PL (Table 5.2, Figure 5.2), while in contrast there was an increased downward baseline shift in ITP (Table 5.2). These changes were accompanied by greater downward pressure of the non-lifted leg and downward PF movement in response to the leg lift during an ASLR+PL (Table 5.2). Movement of the PF in relation to respiration was found to be greater during ASLR+PL compared to ASLR (post hoc $p<0.001$). The RR increased from RS to ASLR (post hoc $p=0.038$) and was also increased from RS to ASLR+PF (post hoc $p=0.015$), but didn't change from ASLR to ASLR+PL (post hoc $p=0.616$).

Table 5.3 Results for the post hoc analyses via the least square difference tests for comparisons of muscle activation levels between resting supine (RS), active straight leg raise (ASLR) and ASLR with additional physical load (ASLR+PL) (Hypothesis 1). There was no post hoc analysis for the right Sc as there was not a statistically significant main effect for this muscle. (IO = obliquus internus abdominis, EO = obliquus externus abdominis, RA = rectus abdominis, CW = chest wall, Sc = scaleni, RF = rectus femoris)

Muscle	**RS v ASLR**	**ASLR v ASLR+PL**	**RS v ASLR+PL**
Left IO	0.020*	0.001*	0.002*
Right IO	0.057	0.001*	0.01*
Left EO	0.001*	<0.001*	<0.001*
Right EO	<0.001*	0.001*	<0.001*
Left RA	0.019*	0.044*	0.004*
Right RA	0.028*	0.001*	0.001*
Right CW	0.009*	0.006*	0.002*
Left Sc	0.454	0.008*	0.047*
Right Sc	-	-	-
Left RF	<0.001*	0.001*	<0.001*
Right RF	0.004*	0.022*	0.015*

Figure 5.1a:

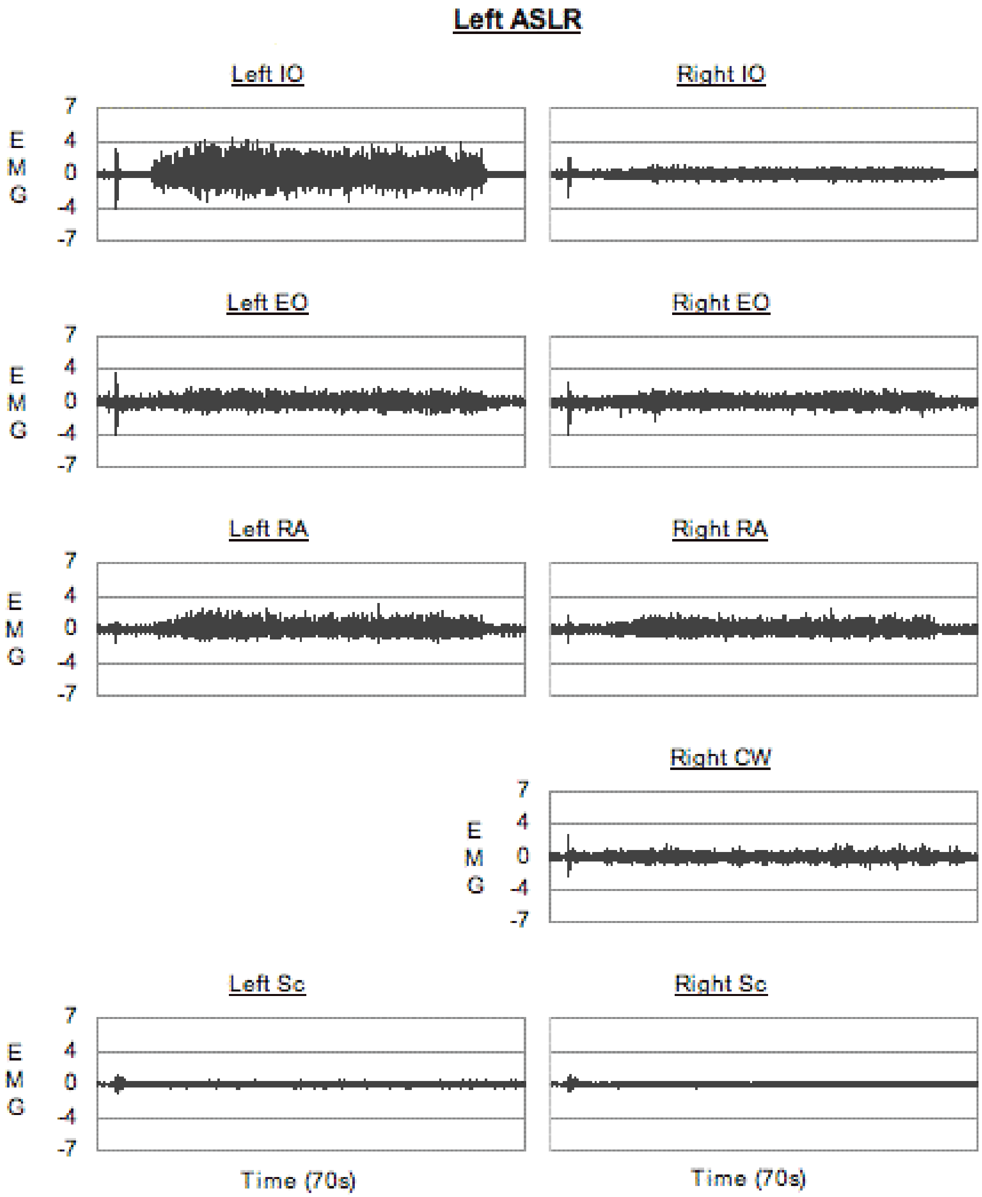
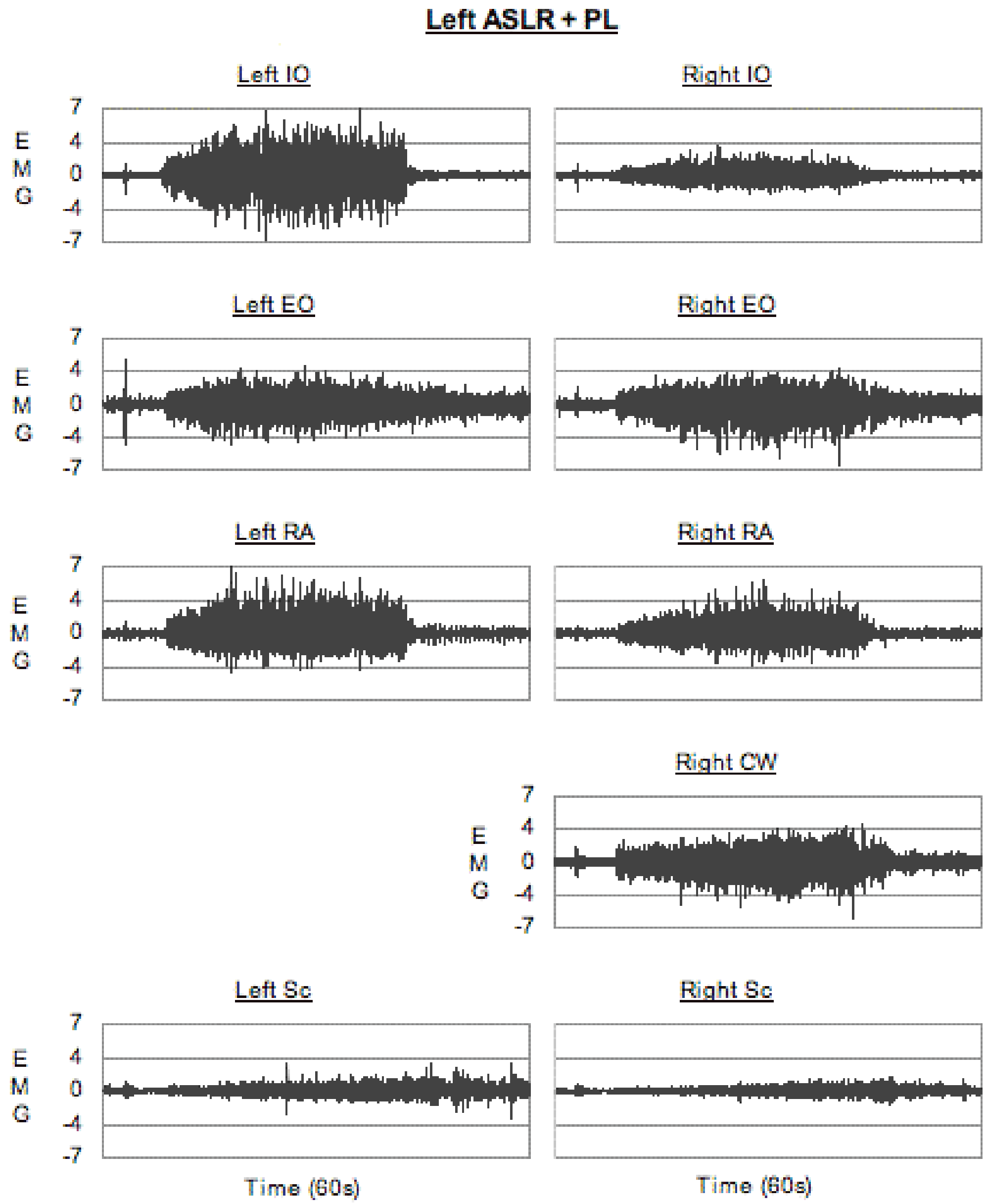


Figure 5.1 Demeaned and normalised electromyography (EMG) profiles for one subject during; a) a left active straight leg raise (ASLR), and b) (following page) a left ASLR with additional physical load (ASLR+PL). The dominant feature for the ASLR is greater obliquus internus abdominis (IO) activation on the side of the leg lift. During the ASLR+PL there is notable increased activation of all muscle, but still greater IO activation on the side of the leg lift. (EO = obliquus externus abdominis, RA = rectus abdominis, CW = chest wall, Sc = scaleni, RF = rectus femoris)

Figure 5.1b:



Left ASLR + PL
Left IO
Right IO
Left EO
Right EO
Left RA
Right RA
Right CW
Left Sc
Right Sc
EMG
7
4
0
-4
-7
Time (60s)
Time (60s)

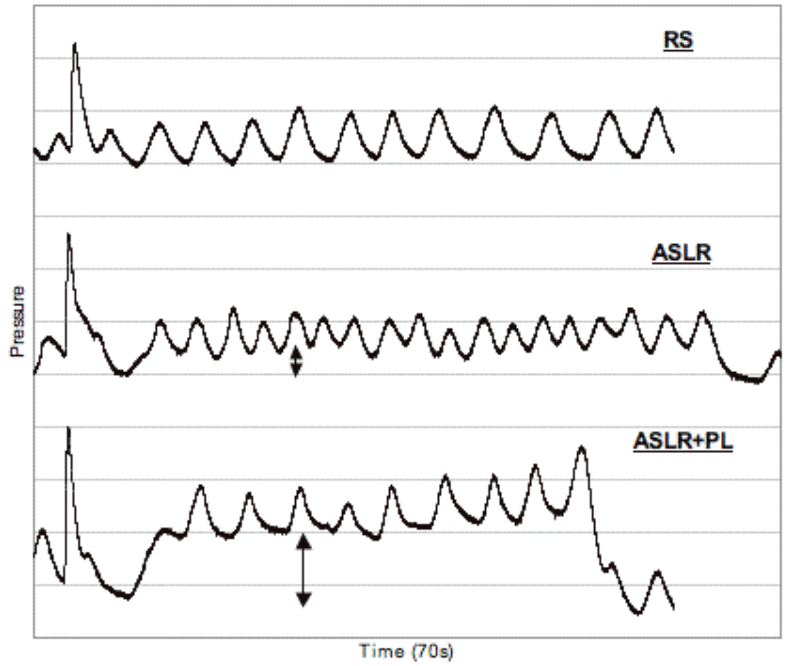


Figure 5.2 Raw traces of intra-abdominal pressure for one subject during the three tasks. Note there is no baseline shift during resting supine (RS), some baseline shift in response to lifting the leg during an active straight leg raise (ASLR), and still greater baseline shift during an ASLR with additional load around the ankle (ASLR+PL).

5.4.2 Hypothesis 2: Left versus right muscle activation during the active straight leg raise with physical load

Activation of EO, RA and Sc was symmetrical during ASLR+PL (Table 5.4). However, activation of IO was greater ipsilateral to the leg being lifted (ie left side) (Table 5.4, Figure 5.1b). Likewise there was greater RF activation on the side of the leg lift (Table 5.4).

5.4.3 Consistency of patterns during the active straight leg raise with physical load

Repeatability over two trials for all variables was very good, except for the respiratory fluctuation of IAP which was more variable (Table 5.5).

Table 5.4 Results of the repeated measures analyses of variance for the left to right comparison of muscle activation during the active straight leg raise with additional physical load (ASLR+PL) (Hypothesis 2). (IO = obliquus internus abdominis, EO = obliquus externus abdominis, RA = rectus abdominis, CW = chest wall, Sc = scaleni, RF = rectus femoris)

Side to side comparisons for each muscle during the ASLR+PL:			
	side	*respiration*	*side by respiration*
IO	0.002*	0.289	0.850
EO	0.109	0.177	0.738
RA	0.343	0.099	0.430
Sc	0.352	0.285	0.963
RF	< 0.001*	0.229	0.161

Table 5.5 Results for the intra-class correlation coefficients (ICC) and corresponding 95% confidence intervals (CI) repeatability analyses of the active straight leg raise with additional physical load (ASLR+PL). (IAP = intra-abdominal pressure, ITP = intra-thoracic pressure, RR = respiratory rate, PF = pelvic floor)

	ASLR+PL: ICC (95% CI)
Muscle Activation	Highest: 0.995 (0.974– 0.999)
	Lowest: 0.817 (0.086– 0.963)
	Median: 0.9355
IAP - Respiratory Fluctuation	0.407 (0 - 0.853)
IAP - Baseline Shift	0.928 (0.642 - 0.986)
ITP - Respiratory Fluctuation	0.985 (0.938 - 0.996)
ITP - Baseline Shift	0.959 (0.793 - 0.992)
RR	0.905 (0.526 - 0.981)
PF movement - Respiration	0.978 (0.891 - 0.996)
PF movement - Leg Lift	0.953 (0.764 - 0.991)
Downward Leg Pressure	0.993 (0.964 - 0.999)

5.5 Discussion

Motor control patterns may be affected by a number of factors (Figure 5.3). For instance a motor control strategy could be expected to differ dependant upon the load of the task (Cresswell & Thorstensson, 1994; Harman, Frykman, Clagett, & Kraemer, 1988; McGill, Sharratt, & Seguin, 1995). The response of the neuromuscular system in pain free subjects to the ASLR has been documented in detail elsewhere (Beales et al., 2009b). A strategy of tonic muscle activation ipsilateral to the side of the ASLR, particularly in the IO, with minimal change in IAP was described. This appeared to be consistent with the representation of a

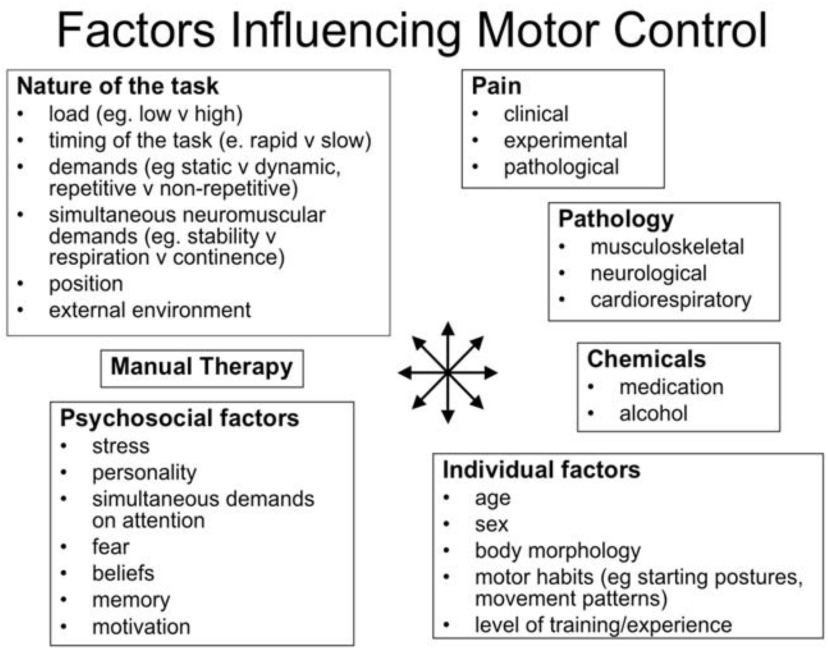


Figure 5.3 Factors potentially influencing lumbopelvic motor control strategies.

unilateral motor response of the trunk muscles during the low level physical load of an ASLR (Beales et al., 2009b). To our knowledge this is the first study to investigate muscle activation, IAP and ITP during a loaded ASLR, to shift the nature of the task from being a low load challenge to a high load challenge. The major finding of this study was that the neuromuscular system responds to the increased load with an increase in muscle activation and a simultaneous increase in IAP during an ASLR+PL compared to an ASLR in pain free subjects.

Consistent with the findings, a concomitant increase in muscle activation and IAP with the addition of load is known to also occur during a variety of tasks such as isometric and through range lifting (Cholewicki, Ivancic, & Radebold, 2002; Cresswell & Thorstensson, 1994; Hagins, Pietrek, Sheikhzadeh, Nordin, & Axen, 2004; Hemborg & Moritz, 1985; Hemborg, Moritz, Hamberg et al., 1985; Hemborg, Moritz, Hamberg, Lowing, & Akesson, 1983). Increased muscle activation during an ASLR+PL appears to represent the adoption of a bracing strategy, and is consistent with this task presenting a high load challenge to the neuromuscular system. Presumably the neuromuscular system responds to the higher demand of the ASLR+PL by utilising this motor control strategy to provide a higher level of lumbopelvic stability, whilst controlling respiration, in order to complete the task.

5.5.1 Intra-abdominal pressure

The level of increase in base line IAP for this study, at an average 382.4Pa, is relatively low compared to many reports of the level of IAP during loaded lifting tasks (Cresswell & Thorstensson, 1994; Hagins, Pietrek, Sheikhzadeh, & Nordin, 2006; Harman et al., 1988). In part this may be due to the methodological difference in assigning the baseline shift to the change of IAP in relation to physical loading in this study versus the use of peak IAP in the other studies. Also the participants being positioned in supine rather than upright may have contributed to this difference. However, this observation is consistent with the finding of lower increases in IAP during isometric lifting tasks when the glottis remained open to allow continual respiration (McGill et al., 1995). Those authors suggested that keeping the glottis open precluded the development of higher levels of IAP, which has also been reported previously (Hemborg, Moritz, & Lowing, 1985). More recently it has been shown that a breath hold at the end of inspiration is conducive to the generation of greater levels of IAP (Hagins et al., 2006; Hagins et al., 2004; Harman et al., 1988).

All the subjects in the current study continued to breath during the tasks, as is evident by the continual respiratory fluctuation of IAP and ITP. There was also no evidence of prolonged breath holds during inspection of the raw respiratory traces. Thus it would seem that the maintenance of relatively normal respiration by the subjects in this study could have negated the generation of higher levels of IAP. Given that all the subjects completed the task successfully, this motor strategy could be considered adequate for this task.

The generation of IAP occurs secondary to activation of the muscles around the abdomino-pelvic cavity. It is likely that the mechanical action of these muscles on the spine, and resultant IAP itself, both have a role in enhancing trunk stiffness and stability (Essendrop, Andersen, & Schibye, 2002). Little is known of how IAP itself might influence pelvic stability. It has been proposed that the generation of abnormally high levels of IAP during functional tasks may overload and/or provoke symptoms from sensitised pelvic ligaments (Mens, Hoek van Dijke, Pool-Goudzwaard, van der Hulst, & Stam, 2006). This could act as a possible underlying mechanism in the development and maintenance of chronic PGP. Further research is needed on the role of IAP in providing pelvic stability and its relationship to chronic PGP.

5.5.2 Intra-thoracic pressure

This study demonstrated a very consistent pattern of decreased baseline ITP, which was greater during ASLR+PL compared to ASLR, while baseline IAP increased. This is consistent with an earlier study that found ITP generally decreased during through range lifting tasks when expiring, though there was some individual variation (Hemborg, Moritz, & Lowing, 1985). In contrast to these studies, it has been reported that during isometric lifting of a heavy object there is a concurrent increase in IAP and ITP with an associated increase in trunk muscle activation (Cholewicki et al., 2002). Lifting in that study was completed with either a breath hold or whilst exhaling. Under these conditions the authors suggested that increases in these variables could not be decoupled. However they reported one subject disassociated ITP from IAP. Similarly, another study has reported simultaneous increases in peak ITP and IAP during a variety of tasks (Harman et al., 1988), though phase of respiration was not considered. The differences in these studies compared to the present study may result from task specific motor responses, which might also be modulated by the concurrent status of respiration. It could also reflect the difference in starting positions between the ASLR and the different tasks utilised in the other studies, or methodological differences in the way ITP and IAP were analysed. In this study baseline shift and respiratory fluctuation variables were used, whereas other studies have used peak pressure measurements.

An important consideration here is the role of the diaphragm in the control of IAP and ITP. Trans-diaphragmatic pressure (P(di)) is used to estimate the tension in/work of the diaphragm (Aliverti et al., 1997; Harman et al., 1988; Hemborg, Moritz, & Lowing, 1985). It is calculated by: P(di) = IAP – ITP. The downward baseline shift in ITP with the simultaneous upward baseline shift of IAP results in increased P(di). We were not able to record EMG directly from the diaphragm in this study, however, this increase in P(di), plus increased activation of the right CW, a likely synergist of the diaphragm, suggests that the diagram was activated to assist in completion of the ASLR+PL task. Furthermore, the maintenance of respiratory fluctuations of both ITP and IAP in opposite directions suggests a concurrent respiratory role for the diaphragm. Such a concurrent respiratory and postural role for the diaphragm has been previously reported (Hodges & Gandevia, 2000a).

5.5.3 Comparison to pelvic girdle pain subjects

During an ASLR on the affected side, chronic PGP subjects exhibit a bracing strategy through the abdominal wall with a concomitant increase in IAP (Beales et al., 2009a), an apparently high load motor strategy for an arguably relatively low load task. The findings of this study during an ASLR+PL support this hypothesis, however there are some interesting comparisons to be made in the patterns adopted by the two groups:

1. During the ASLR+PL the pain free subjects in this study exhibited increased activation of both IO muscles, though they maintained relatively greater activation on the side ipsilateral to the leg lift. This pattern is consistent with what pain free subjects do during an ASLR without additional load (Beales et al., 2009b). In contrast chronic PGP subjects (Beales et al., 2009a), and pregnant subjects with PGP (de Groot et al., 2008), exhibit symmetrical activation of IO.
2. In pain free subjects EO and RA on the side contralateral to the leg lift exhibited some expiratory modulation during ASLR+PL. In contrast, activation of EO and RA tended to be tonic in chronic PGP subjects during an affected side ASLR (Beales et al., 2009a). Activation of the CW was predominantly tonic in both groups during the respective tasks.
3. Pain free subjects had an increased base line shift of IAP during an ASLR+PL similar to that demonstrated in chronic PGP subjects during an ASLR on the symptomatic side (Beales et al., 2009a). Conversely, increased downward baseline shift of ITP in pain free subjects from an ASLR to an ASLR+PL contrasts to the upward baseline shift found in PGP subjects during a symptomatic side ASLR (Beales et al., 2009a).

4. Downward pressure of the leg not being lifted was significantly greater during the ASLR+PL in pain free subjects. This in conjunction with a simultaneous increase in activation of RF in the non-lifted leg may represent a splinting strategy of the non-lifted leg during the ASLR+PL. Chronic PGP pain subjects did not use the non-lifted leg in the same manner, as downward leg pressure did not change from a non-affected to an affected ASLR (Beales et al., 2009a).
5. Both groups exhibit downward PF movement in response to the leg lift during their respective tasks (Beales et al., 2009a). Pain free subjects also had greater respiratory related movement of the PF during the ASLR+PL, a pattern not observed in chronic PGP subjects during an affected ASLR (Beales et al., 2009a).

Thus, while both groups adopted a motor control strategy consistent with a high load task, in spite of the PGP patients only lifting their affected leg, there were inherent differences. These differences may reflect inherent changes in the way the neuromuscular system attends to the ASLR task in the presence of pain and impairment.

5.6 Limitations

The small number of subjects used in this study could be considered a limitation of this study. Despite this, significant findings have been identified that support both the clinical and scientific validity of this study. Further studies including larger numbers of subjects would be useful. In further studies it could be advantageous to directly monitor the activation of other muscles involved in the production of IAP, namely the PF, diaphragm and transversus abdominis.

5.7 Conclusion

This study documents motor control strategies in pain free subjects with the addition of a physical load to an ASLR. During the ASLR+PL subjects demonstrated increased muscle activation through the trunk, which was symmetrical in all the trunk muscles apart from IO that was found to have greater activation on the side of the leg lift. Concurrently there was an increased baseline shift of IAP and decreased baseline shift of ITP, but respiratory fluctuation of these variables was unaffected. There was also descent of the PF in response to lifting the leg and greater downward pressure of the non-lifted leg. This motor control pattern is consistent with what would be expected for a high load task, reflecting a bracing activation strategy, and shows some similarities with the pattern used by PGP subjects during a symptomatic ASLR. Conspicuously though, PGP subjects have equal bilateral muscle activation during an ASLR on the symptomatic side of the body compared to greater ipsilateral activation in pain free subjects during ASLR+PL. This supports that the motor control patterns in PGP subjects during an ASLR are aberrant in nature.

5.7 References: Chapter 5

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Chapter 6: Study 4. The effect of resisted inspiration during an active straight leg raise in pain free subjects

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6.1 Abstract

Purpose

Alterations of respiratory patterns have been observed in pelvic girdle pain subjects during the active straight leg raise (ASLR). This study investigated how pain free subjects coordinate motor control during an ASLR when this task is complicated by the addition of a respiratory challenge.

Method

Trunk muscle activation, intra-abdominal pressure, intra-thoracic pressure, pelvic floor motion, downward pressure of the non-lifted leg and respiratory rate were compared between resting supine, ASLR, breathing with inspiratory resistance (IR) and ASLR+IR.

Results

Subjects responded to ASLR+IR with an increase in the motor activation in the abdominal wall and chest wall compared to when ASLR and IR were performed in isolation. This incremental increase of motor activity correlate with greater IAP baseline shift when lifting the leg during ASLR+IR compared to ASLR. Individual

variation was apparent in the form of the motor control patterns, mostly reflected in variable respiratory activation of the abdominal wall.

Conclusion

The findings highlight the flexibility of the neuromuscular system in adapting to simultaneous respiratory and stability demands.

6.2 Introduction

The active straight leg raise (ASLR) test is used in the diagnosis and classification of chronic pelvic girdle pain (PGP) (Mens, Vleeming, Snijders, Koes, & Stam, 2001; Mens, Vleeming, Snijders, Stam, & Ginai, 1999; O'Sullivan & Beales, 2007b; O'Sullivan et al., 2002). The ASLR challenges load transference through the lumbopelvic region by imposing a low level physical load on the neuromuscular system (Beales, O'Sullivan, & Briffa, 2009b). Aberrant motor control patterns have been observed in subjects with chronic PGP during the ASLR and are proposed to have a negative impact on load transference and lumbopelvic stability (Beales, O'Sullivan, & Briffa, 2009a; O'Sullivan & Beales, 2007a; O'Sullivan et al., 2002). Interestingly the aberrant motor control patterns observed in PGP subjects not only affect load transference through the pelvis but also impact on respiration (O'Sullivan et al., 2002) and control of the pelvic floor (PF) and continence (O'Sullivan & Beales, 2007a; O'Sullivan et al., 2002; Pool-Goudzwaard et al., 2005).

It is the role of the neuromuscular system to coordinate simultaneous demands upon various body systems such as the provision of spinal stability while maintaining respiration and ensuring continence. Some muscle groups are able to balance these seemingly conflicting roles by attending to differing tasks at the same time. For example it has been shown that the diaphragm and transversus abdominis respond simultaneously to respiration and repetitive postural adjustments required during rapid arm movements (Hodges & Gandevia, 2000a, 2000b). This type of synchronised attention to multiple body systems is highlighted in the finding of different motor neuron pools for both stability and respiratory tasks in both transversus abdominis and obliquus internus abdominis (IO) (Puckree, Cerny, & Bishop, 1998). At other times though attention to one task may alter the response to the demands of another. An example of this is respiratory inhibition of internal intercostal activation seen with sustained trunk rotation (Rimmer, Ford, & Whitelaw, 1995).

Further investigation of respiratory and lumbopelvic motor control has examined the effect of challenging either the respiratory system or spinal stability (or both). One finding in pain free subjects has been preferential recruitment of the abdominal muscles to the maintenance of stability during lifting with a respiratory challenge (McGill, Sharratt, & Seguin, 1995; Wang & McGill, 2008). In other cases though changes in and challenges to respiration in pain free subjects appears to disrupt the contribution of the abdominal wall and diaphragm to stability (Hodges, Gandevia, & Richardson, 1997; Hodges, Heijnen, & Gandevia, 2001; Kang & Lee, 2002). Differences in the findings from these types of studies are for the most part indicative of the task specificity of motor control. Individual differences in the motor control of singular tasks have also been described, and it has been suggested some of these differences could expose some individuals to a higher risk of injury in specific situations (McGill et al., 1995; Wang & McGill, 2008). For example abdominal muscle contribution to spinal stability during lifting can be inhibited by recruitment of the abdominals to a respiratory demand (McGill et al., 1995).

The purpose of this study was to investigate the effect of a respiratory load during an ASLR in pain free subjects. A better understanding of how pain free subjects co-ordinate these tasks would improve understanding of aberrant motor control patterns that affect respiration in PGP subjects. It was hypothesised that pain free subjects would coordinate the task of an ASLR with a challenge to inspiration by an incremental increase of motor activity in comparison to performing these tasks in isolation. A secondary hypothesis was that the addition of a respiratory challenge would not compromise the pattern of greater IO activation on the side of the leg lift previously reported during an ASLR at either low or high load (Beales et al., 2009b; Beales, O'Sullivan, & Briffa, 2009c).

6.3 Materials and methods

6.3.1 Subjects

Fourteen pain free, nulliparous females participated in this study (average age 28.9±5.9 years, average BMI 23.0±2.1kg/m^2). They were recruited from the Perth metropolitan region. Subjects were excluded if there was a history of a musculoskeletal pain disorder in the last six months, surgery in the last year, current neurological or inflammatory disorders or a history of a significant respiratory disorder. Ethical approval was granted from The Human Research Ethics Committee of Curtin University of Technology. Written informed consent was obtained prior to testing.

6.3.2 Tasks

Motor control patterns were compared over four tasks, the first being resting supine (RS). Next was a right ASLR, the results for which have been analysed as a singular task previously (Beales et al., 2009b). The next task was lying supine while breathing through a threshold loading device for inspiratory muscle training (IR). This device adds resistance to inspiration but allows non-resisted expiration. The device was set at a resistance of 30 cm H_2O that was determined from pilot testing as presenting a significant inspiratory challenge. The final task was performing a right ASLR whilst breathing with inspiratory resistance (ASLR+IR).

6.3.3 Testing and processing procedures

The methodology for this study has been described previously (Beales et al., 2009b). A custom designed LabVIEW v6.1 (National Instruments, Austin, Texas) data collection program was used to simultaneously record data for all variables except where noted. Data processing was performed with a second custom-designed LabVIEW program unless otherwise noted.

6.3.4 Respiration

The pneumotach of a Benchmark Pulmonary Exercise System (P.K. Morgan Instruments, Inc., Andover, Massachusetts), modified with an external output, was used to monitor the phase of respiration. Graphs of the respiratory data were used to calculate respiratory rate (RR).

6.3.5 Muscle activation

Round self-adhesive disposable Ag/AgCl electrodes with a sensor diameter of 1cm (ConMed Corporation, Utica, New York) were used for electromyography (EMG). The skin was prepared by light abrasion and cleaning with alcohol so that impedance was <5kΩ (Gilmore & Meyers, 1983). Electrodes were placed at the following sites with an inter-electrode distance of 2.5cm, parallel to the muscle fibre direction (all muscles were collected bilaterally except where noted):

- rectus abdominis (RA) 1cm above and 2cm lateral to the umbilicus (Ng, Kippers, & Richardson, 1998)
- obliquus externus abdominis (EO) just below the rib cage on a line connecting the inferior costal margin with the contralateral pubic tubercle (Ng et al., 1998)
- lower fibres of IO just medially and inferior to the anterior superior iliac spine (Ng et al., 1998)
- right chest wall (CW) in the sixth and seventh intercostal spaces, 2cm lateral to the mid clavicular line (Allison, Kendle et al., 1998; Gross, Grassino, Ross, & Macklem, 1979; Sharp, Hammond, Aranda, & Rocha, 1993)
- anterior scalene (Sc) adjacent to the lower third point of a line between the mastoid and the sternal notch (Falla, Dall'Alba, Rainoldi, Merletti, & Jull, 2002)
- earth electrodes were place on the anterior superior iliac spines

Two Octopus Cable Telemetric units (Bortec Electronics Inc., Calgary, Canada) were used for collection of EMG activity, one for each side of the body. Data were sampled at 1000Hz, at a bandwidth of 10 to 500Hz, with a common mode rejection ratio of >115dB at 60Hz, and pre-amplified and amplified at an overall gain of 2000 prior to being recorded in the data collection program.

The EMG was inspected for contamination by heartbeat and other artifact, and eliminated manually if necessary. Data were then demeaned and band pass filtered from 4 to 400Hz with a 4th order zero lag Butterworth filter. Sub-maximal normalisation was performed with the average root mean square (RMS) for three 3s trials of a crook lying double leg raise with cervical flexion (Allison, Godfrey, &

Robinson, 1998; Dankaerts, O'Sullivan, Burnett, Straker, & Danneels, 2004; Falla et al., 2002; O'Sullivan, Twomey, & Allison, 1998). Then the RMS was calculated for 500ms during the middle of both the inspiratory and expiratory phases of three breath cycles. This allowed investigation of tonic EMG changes in response to the physical load of the ASLR and phasic EMG changes in relation to respiration.

6.3.6 Intra-abdominal and intra-thoracic pressures

A custom-made silicone rubber nasogastric catheter (Dentsleeve International Ltd, Mississauga, Canada) with two small lumen, one for the abdominal cavity and one for the thorax, was placed in situ. Pressurised saline solution was passed through the lumen. A custom-built pressure transducer converted changes in flow rate of the saline that occur in response to pressure changes to pressure values. Accurate placement of the lumen in the thoracic and abdominal cavities was afforded by real time monitoring of the fluctuation of intra-abdominal pressure (IAP) and intra-thoracic pressure (ITP) in opposite directions during respiration (Hodges & Gandevia, 2000b).

Two aspects of both IAP and ITP were investigated. Respiratory fluctuation was ascertained by subtracting the minimum from the maximum value for each variable over a breath cycle. Pressure change related to the physical load of an ASLR was calculated by subtracting the minimum IAP or ITP value of RS from the minimum value during each of the ASLR tasks. This was termed a baseline shift. For ASLR+IR, the baseline shift was calculated in the same manner but by substituting IR for RS.

6.3.7 Pelvic Floor

Motion of the PF was recorded to digital video via the external output of a Capesee SSA-220A ultrasound unit (Toshiba Corporation, Tochigi, Japan). The probe was positioned trans-abdominally and angled inferiorly to view the bladder, a reliable non-invasive method of investigating PF kinematics (O'Sullivan et al., 2002; Sherburn, Murphy, Carroll, Allen, & Galea, 2005; Thompson & O'Sullivan, 2003; Walz & Bertermann, 1990). Subjects were instructed to cough at the start of each trial, producing movement of the PF and a marker on the EMG traces that was used to synchronize PF data with the other variables.

Movement of the PF was assessed to determine its relationship to respiration and at the instant of lifting the leg. For respiration two frames of video were captured at the maximum and minimum points of excursion over each of the three breath cycles. These two frames were then superimposed and the magnitude of movement was measure directly from this composite picture. The same process was used for PF motion in relation to the ASLR, using frames of video slightly before and after the leg lift.

6.3.8 Downward pressure of the non-lifted leg

An inflated pad, linked to a pressure transducer, was placed under the heel of the left leg to record any downward leg pressure that occurred in response to lifting the right leg. The average value over one breath cycle was used for analyses.

6.3.9 Analyses

The average of three breath cycles was used for analyses where appropriate. Statistical analysis was performed with SPSS 16.0 for Mac (SPSS Inc., Chicago, Illinois) using a critical p value of 0.05. Statistical evaluation was complimented with visual inspection of the data.

Hypothesis 1: Incremental increase of motor activity during ASLR+IR

The EMG data was compared with a four (*task:* RS, ASLR, IR, ASLR+IR) by two (*respiration:* inspiration, expiration) repeated measures analysis of variance and post hoc least square difference (LSD) tests for each muscle. Respiratory fluctuation of IAP and ITP, RR and PF movement in response to respiration were analysed across the four tasks with one-way analysis of variance and post hoc LSD tests. The baseline shift of IAP and ITP, PF movement in response to the leg lift and downward pressure of the non-lifted leg were analysed with paired t-tests (ASLR versus ASLR+IR).

Hypothesis 2: Symmetry of muscle activation

A two (*side:* left side muscle, right side muscle) by two (*respiration:* inspiration, expiration) repeated measures analysis of variance and post hoc LSD tests were used to assess the symmetry of response for each individual muscle during the right ASLT+IR.

Repeatability of IR and ASLR+IR

Repeatability of the ASLR has been previously reported (Beales et al., 2009b). The consistency of the response to IR and ASLR+IR was assessed over two consecutive trials with intra-class correlation coefficients (ICC) and corresponding 95% confidence intervals (CI).

6.4 Results

The values for the all variables during the four tasks are presented in Table 6.1 and Table 6.2.

Table 6.1 (following page) Mean (standard error of the mean) of root mean square electromyographic activity of all muscles during resting supine (RS), right active straight leg raise (ASLR), breathing against inspiratory resistance in supine (IR) and right active straight leg raise with inspiratory resistance (ASLR+IR). Results (p values) from repeated measures analysis of variance are also presented (Hypothesis 1) (insp = inspiration, exp = expiration, IO = obliquus internus abdominis, EO = obliquus externus abdominis, RA = rectus abdominis, CW = chest wall, Sc = anterior scaleni)

Table 6.1

Muscle	RS	ASLR	IR	ASLR+IR	p values		
					task	*respiration*	*task by respiration*
Right IO - insp	0.1339 (0.03)	0.4062 (0.07)	0.4152 (0.14)	0.6653 (0.14)	0.002*	0.361	0.714
- exp	0.1352 (0.03)	0.4159 (0.08)	0.3801 (0.13)	0.6266 (0.15)			
Left IO - insp	0.1421 (0.04)	0.1617 (0.02)	0.2689 (0.07)	0.3531 (0.07)	0.01*	0.783	0.782
- exp	0.1421 (0.04)	0.1676 (0.03)	0.2650 (0.08)	0.3646 (0.09)			
Right EO - insp	0.0991 (0.02)	0.2563 (0.04)	0.1725 (0.02)	0.3395 (0.05)	<0.001*	0.103	0.304
- exp	0.1002 (0.02)	0.2470 (0.04)	0.1452 (0.02)	0.3096 (0.05)			
Left EO - insp	0.1131 (0.02)	0.1859 (0.03)	0.1957 (0.03)	0.3286 (0.05)	0.002*	0.254	0.053
- exp	0.1086 (0.02)	0.1892 (0.02)	0.1660 (0.02)	0.3021 (0.05)			
Right RA - insp	0.1090 (0.02)	0.1924 (0.03)	0.1321 (0.02)	0.2536 (0.05)	0.003*	0.830	0.061
- exp	0.1087 (0.02)	0.1989 (0.03)	0.1191 (0.02)	0.2643 (0.05)			
Left RA - insp	0.1099 (0.02)	0.1569 (0.02)	0.1345 (0.02)	0.1825 (0.03)	0.027*	0.417	0.067
- exp	0.1092 (0.02)	0.1630 (0.02)	0.1225 (0.01)	0.1807 (0.02)			
Right CW - insp	0.1291 (0.03)	0.2596 (0.05)	0.3458 (0.06)	0.5038 (0.08)	0.001*	0.113	0.316
- exp	0.0993 (0.02)	0.2235 (0.04)	0.2080 (0.06)	0.3865 (0.10)			
Right Sc - insp	0.1204 (0.01)	0.1788 (0.03)	0.8187 (0.13)	0.8913 (0.12)	<0.001*	<0.001*	0.003*
- exp	0.1019 (0.01)	0.1414 (0.03)	0.2330 (0.04)	0.3047 (0.04)			
Left Sc - insp	0.1285 (0.02)	0.1539 (0.03)	0.8325 (0.14)	0.8457 (0.13)	0.001*	<0.001*	0.003*
- exp	0.1122 (0.02)	0.1325 (0.02)	0.2090 (0.04)	0.2526 (0.04)			

Table 6.2 Mean (standard error of the mean) for intra-abdominal pressure (IAP), intra-thoracic pressure (ITP), respiratory rate (RR), pelvic floor (PF) movement and downward pressure of the non-lifted leg (DLP) during resting supine (RS), right active straight leg raise (ASLR), inspiratory resistance (IR) and right active straight leg raise combined with inspiratory resistance (ASLR+IR). Results (p values) for the statistical comparisons are also presented (Hypothesis 1). (IO = obliquus internus abdominis, EO = obliquus externus abdominis, RA = rectus abdominis, CW = chest wall, Sc = anterior scaleni)

	RS	**ASLR**	**IR**	**ASLR+IR**	**p value**
IAP (Pa)					
Respiratory Fluctuation	638.8 (95.6)	589.5 (73.4)	1383.6 (429.7)	1840.6 (597.7)	0.056
Baseline Shift	-	127.6 (60.9)	-	351.6 (87.1)	0.037*
ITP (Pa)					
Respiratory Fluctuation	1389.0 (531.5)	1474.3 (545.6)	3468.7 (270.4)	3564.7 (241.9)	<0.001*
Baseline Shift	-	-15.1 (154.9)	-	-271.7 (255.1)	0.398
RR (breaths/min)	12.3 (0.9)	15.0 (1.3)	17.6 (1.9)	18.0 (2.0)	0.045
PF Motion (mm)					
For respiration	3.1 (0.5)	3.4 (0.6)	6.4 (2.0)	7.1 (1.9)	0.108
For leg lift	-	4.0 (1.0)	-	3.6 (1.2)	0.822
DLP (N)	-	54.5 (6.4)	-	56.6 (6.6)	0.565

6.4.1 *Hypothesis 1: Incremental increase of motor activity during active straight leg raise with inspiratory resistance*

An effect for task was found for all muscle groups, plus an effect for respiration and task*respiration for the Sc (Table 6.1). In the results for muscle activation post hoc LSD results are reported subsequently for meaningful comparisons.

6.4.2 *Obliquus internus abdominis*

For both IO there was no difference between the activation level for the ASLR and IR tasks when considered independently (LSD: right IO p=0.891, left IO p=0.112). However there was greater IO activation during the ASLR+IR when compared with the ASLR (LSD: right IO p=0.018*, left IO p=0.006*) and the IR (LSD: right IO p<0.001*, left IO p=0.002*) tasks in isolation. This indicates an incremental increase of IO activity when the ASLR and IR are performed simultaneously. A representation of this effect is visible in the EMG trace of the left IO in Figure 6.1. There was no statistically significant change in IO activation with respiratory fluctuation, but with visual inspection of the EMG traces four subjects displayed obvious phasic respiratory activation of IO. This effect was apparent almost exclusively during the IR and ASLR+IR tasks. Respiratory activation was synchronous with expiration in two subjects, but inspiration in two other (Figure 6.2).

6.4.3 *Obliquus externus abdominis*

Activation of left EO was similar for the ASLR and IR tasks (LSD: left EO p=0.753). However the right EO was activated more by the ASLR than IR (LSD: right EO p=0.005*). Activation of EO on both sides during ASLR+IR was greater than the ASLR (LSD: right EO p=0.015*, left EO p=0.003*), and the IR tasks (LSD: right EO p<0.001*, left EO p=0.003*). Similar to IO, there was an incremental increase of muscle activity for EO bilaterally with the combined ASLR and IR tasks. In the four subjects who displayed obvious respiratory activation of IO, visual inspection demonstrated synergistic phasic activation of EO with the respiratory activation observed for IO.

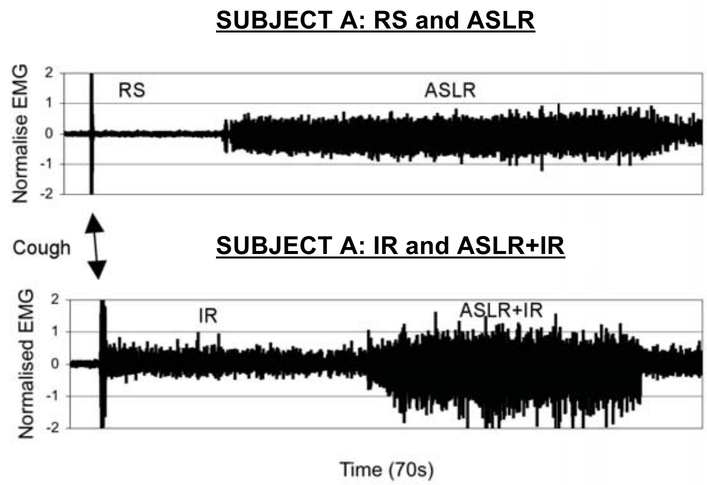

Figure 6.1 Normalised and equally scaled electromyography (EMG) profiles of obliquus internus abdominis (IO) for Subject A during resting supine (RS), the active straight leg raise (ASLR), breathing with inspiratory resistance (IR) and ASLR+IR. The IO activation level is larger during ASLR+IR than during either of the two tasks performed independently, consistent with an incremental increase of muscle recruitment when the tasks are performed together.

6.6.4 Rectus abdominis

The right RA demonstrated greater activation during the ASLR task when compared to IR (LSD: right RA p=0.001*). A similar trend observed for the left RA did not quite reach statistic significance (LSD: left RA p=0.053). There was greater activation during ASLR+IR task compared to IR (LSD: right RA p=0.008*, left RA p=0.012*). However there was no difference between ASLR+IR and the ASLR (LSD: right RA p=0.194, left RA p=0.059). While there was no statistical effect for respiratory activation of RA, on visual inspection the four subjects who demonstrated IO and EO respiratory activation demonstrated similar phasic respiratory RA activation.

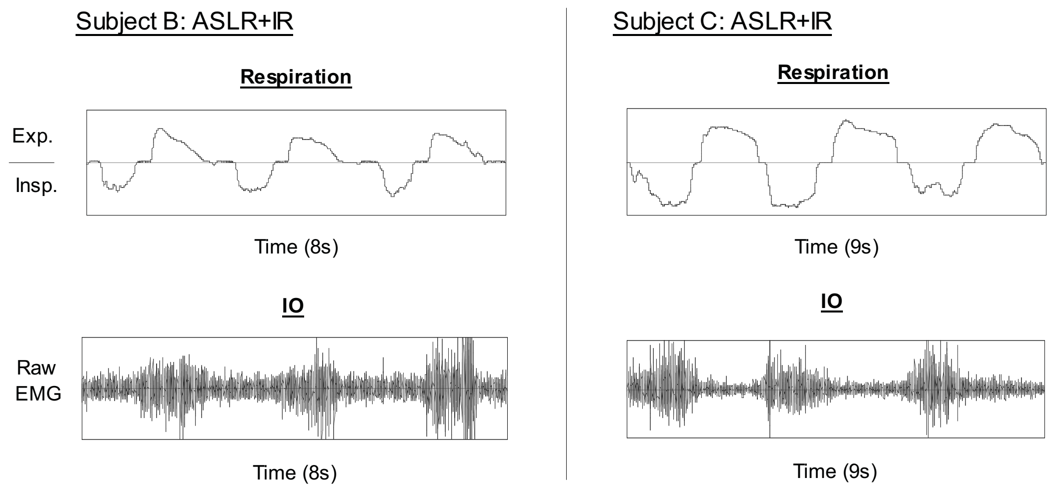

Figure 6.2 Respiratory and raw electromyography (EMG) traces denoting respiratory activation of the left obliquus internus abdominis (IO) during the active straight leg raise performed with inspiratory resistance (ASLR+IR). Subject B demonstrates phasic IO activation timed with expiration. Conversely Subject C demonstrated phasic activity timed to inspiration. (Exp. = expiration, Insp. = inspiration)

6.6.5 Right chest wall

Activation of the right CW was the same for ASLR and IR (LSD: right CW p=0.333). There was greater CW activation during the ASLR+IR when compared to the ASLR (LSD: right CW p=0.003*), and IR alone (LSD: right CW p=0.007*), consistent with an incremental increase in CW activation when the ASLR and IR were combined. An example of this is shown in Figure 6.3. On visual inspection 13 subjects exhibited phasic inspiratory activation of the right CW during IR and ASLR+IR (Figure 6.4). The remaining subject displayed phasic activation synchronised to expiration (Figure 6.4).

SUBJECT D:

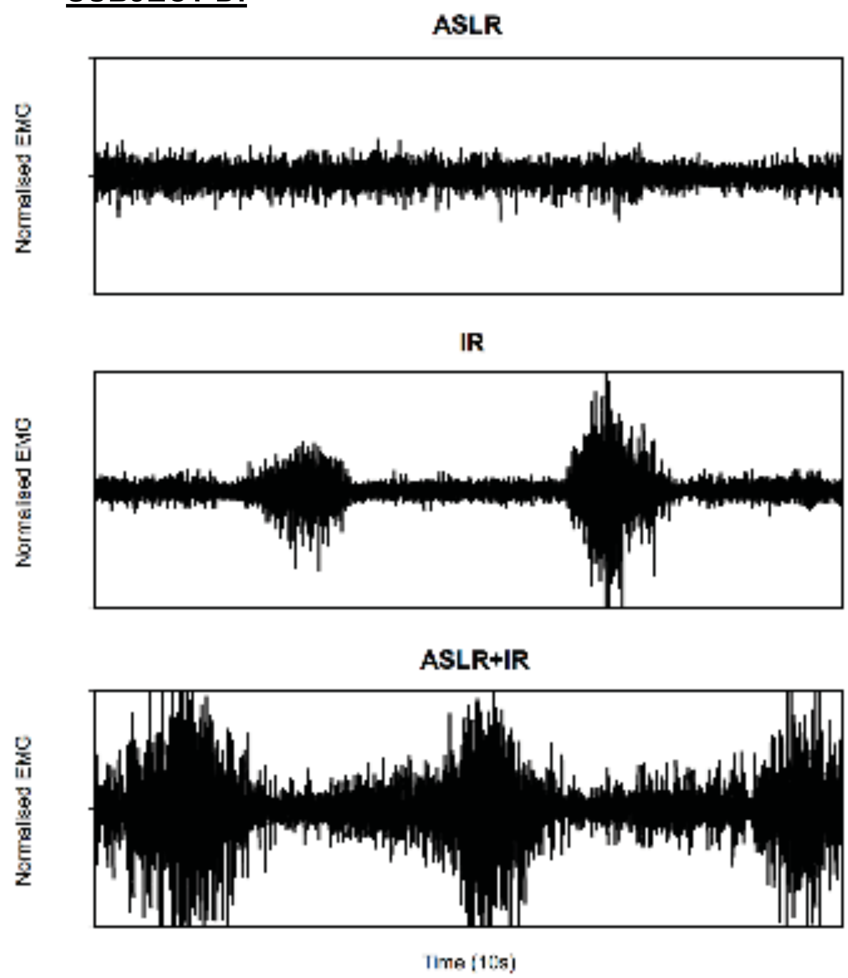

Figure 6.3 Random 10s samples of normalised and equally scaled electromyography (EMG) profiles of the right chest wall (CW) for Subject D during the active straight leg raise (ASLR), breathing with inspiratory resistance (IR) and ASLR+IR. The CW activation is tonic during ASLR, but phasic during IR. During the ASLR+IR activation is still phasic, but there is an apparent incremental increase of EMG compared to performing either ASLR or IR in isolation. (Note: traces are not phased for respiration)

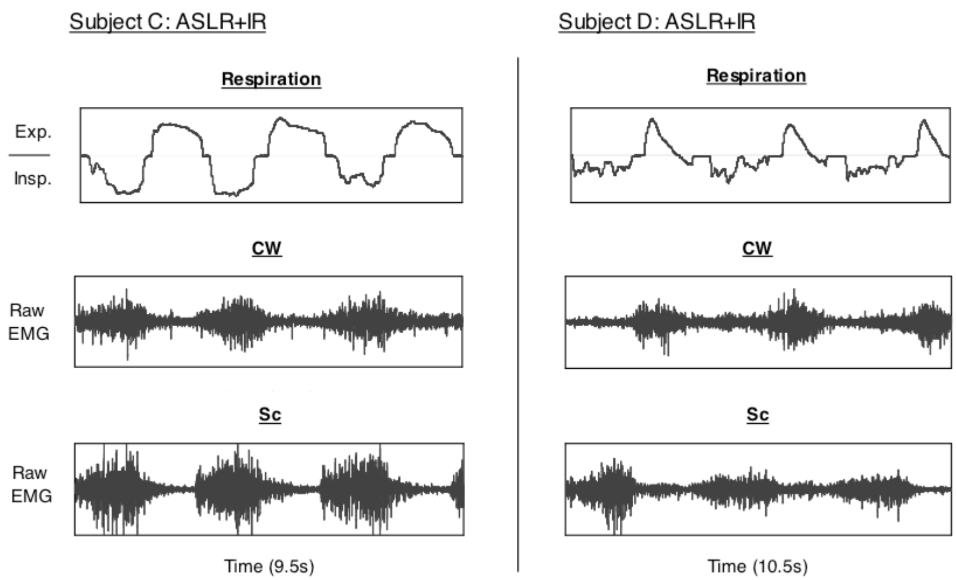

Figure 6.4 Respiratory and raw electromyography (EMG) traces denoting respiratory activation of the right chest wall (CW) and right anterior scaleni (Sc) during the active straight leg raise performed with inspiratory resistance (ASLR+IR). Thirteen subjects, like Subject C, demonstrated phasic CW activation timed with inspiration during this task. One subject though, Subject D, demonstrated phasic activity timed to expiration. All subjects had phasic Sc activation timed with inspiration during ASLR+IR. (Exp. = expiration, Insp. = inspiration)

6.6.6 Anterior scaleni

There was an increased respiratory activation of Sc during the IR inclusive tasks. There was greater Sc activation during IR compared to ASLR (LSD: right Sc $p<0.001$*, left Sc $p=0.012$*) and RS (LSD: right Sc $p<0.001$*, left Sc $p<0.001$*). Similarly there was increased Sc activation during ASLR+IR compared to both ASLR (LSD: right Sc $p<0.001$*, left Sc $p<0.001$*) and RS (LSD: right Sc $p<0.001$*, left Sc $p<0.001$*). Figure 6.4 shows EMG traces denoting the inspiratory activation of Sc during ASLR+IR.

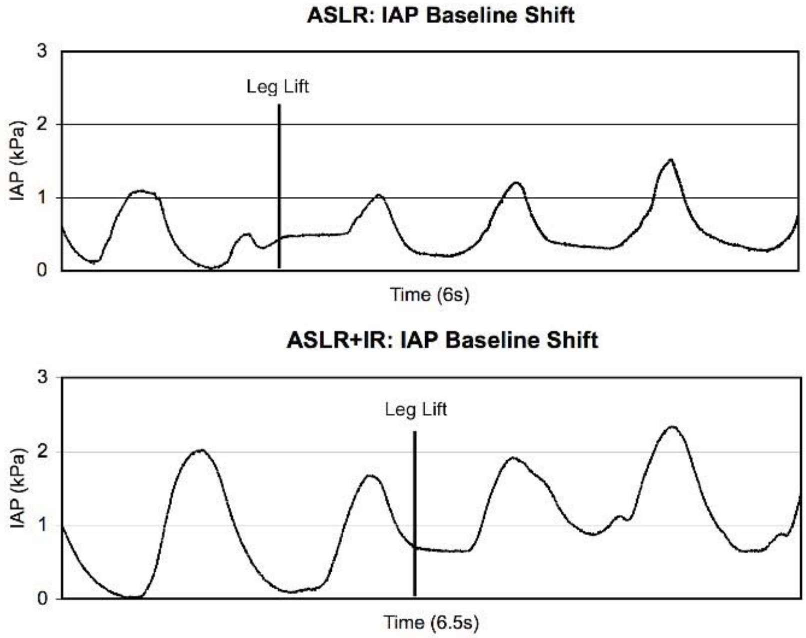

Figure 6.5 Intra-abdominal pressure (IAP) baseline shift in response to lifting the leg during an active straight leg raise (ASLR) and during an ASLR performed while breathing with inspiratory resistance (ASLR+IR) for Subject D. The baseline shift is greater when performing the ASLR+IR compared to an ASLR without an imposed respiratory load. Greater respiratory fluctuation of IAP can be observed in the IR related tasks in the bottom graph compared to the non-IR tasks in the top graph.

6.6.7 Intra-abdominal pressure

Increased IAP respiratory fluctuation during the tasks with IR, observable in Figure 6.5, did not reach statistical significance (Table 6.2, p=0.056). However there was greater IAP baseline shift performing ASLR+IR compared to performing the ASLR (Table 6.2, p=0.037*) (Figure 6.5).

6.6.8 Intra-thoracic pressure

The respiratory fluctuation of ITP varied across tasks (Table 6.2, p<0.001*). Changes in ITP were greater in tasks including IR (Figure 6.6). Resting supine and

ASLR were not different from one another (LSD: p=0.826), and this was the same for IR and ASLR+IR (LSD: p=0.566). However ITP was greater during IR than RS (LSD: p=0.001*) or ASLR (LSD: p<0.001*). Also ITP was greater during ASLR+IR when compared to RS (LSD: p=0.001*) or ASLR (LSD: p=0.001*). There was no significant difference in ITP baseline shift from ASLR to ASLR+IR (Table 6.2, p=0.398).

6.6.9 Respiratory rate

A change in RR was noted between the four conditions (Table 6.2, p=0.045). It was lower in RS compared to the ASLR (LSD: p=0.005*), IR (LSD: p=0.016*) and ASLR+IR (LSD: p=0.016*). No differences were found between ASLR, IR or ASLR+IR.

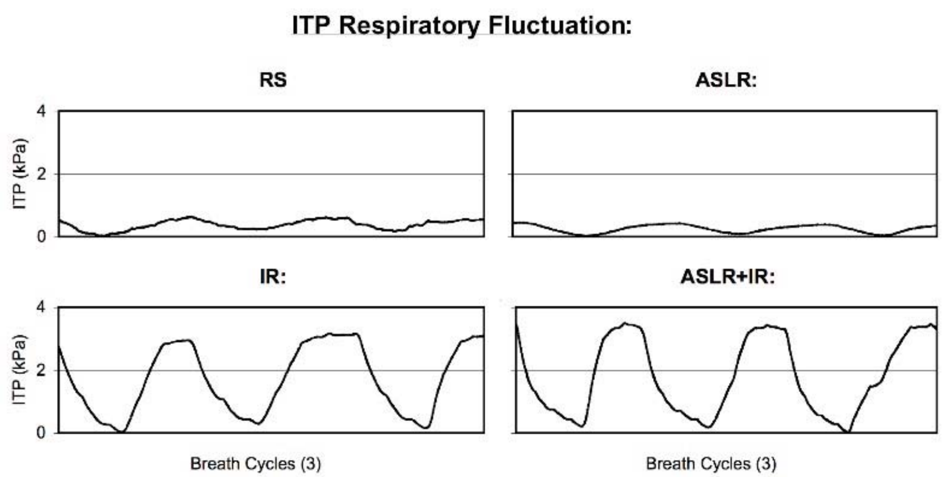

Figure 6.6 Intra-thoracic pressure (ITP) respiratory fluctuation for Subject A during resting supine (RS), active straight leg raise (ASLR), inspiratory resistance (IR) and performing an ASLR with IR (ASLR+IR). Greater ITP fluctuation is noted with the tasks that include IR.

6.6.10 Pelvic floor

No significant difference was found between the four tasks for respiratory motion of the PF (Table 6.2, p=0.108), nor was there a difference during the leg lift from ASLR to ASLR+IR (Table 2, p=0.822).

6.6.11 Downward leg pressure of the non-lifted leg

There was no difference in downward leg pressure during ASLR compared to downward leg pressure during ASLR+IR (Table 6.2, p=0.565).

6.6.12 Hypothesis 2: Symmetry of muscle activation

The results for this analysis are presented in Table 6.3. The IO muscle demonstrated greater activation on the right compared to the left during a right side ASLR+IR, but symmetrical activation during IR. All other muscles displayed symmetrical activation for both IR and ASLR+IR tasks. As previously noted, there was phasic respiratory activation of the Sc. There was an effect in RA for respiration during IR, but this was not supported by post hoc analyses.

6.6.13 Repeatability of inspiratory resistance and the active straight leg raise with inspiratory resistance

Two trials for repeatability were available for seven of the 14 subjects. Duplicate trials for repeatability analyses were added to the protocol after the first four subjects had been recruited and tested. Three of the remaining 10 subjects could not complete second trials due to urgent need to void urine. The ICC and 95% CI for all variables are displayed in Table 6.4. Consistency was very good for all variables except baseline shift of IAP and ITP that were poor and fair respectively.

Table 6.3 Results of the repeated measures analyses of variance for the left and right comparison of muscle activation during inspiratory resistance in supine (IR) and while performing an right side active straight leg raise with simultaneous IR (ASLR+IR) (Hypothesis 2). (IO = obliquus internus abdominis, EO = obliquus externus abdominis, RA = rectus abdominis, Sc = anterior scaleni)

Muscle	**IR** (p)	**ASLR+IR** (p)
IO		
-side	0.059	0.004*
-respiration	0.480	0.698
-side by respiration	0.295	0.086
EO		
-side	0.242	0.852
-respiration	0.146	0.279
-side by respiration	0.820	0.840
RA		
-side	0.836	0.078
-respiration	0.026*	0.725
-side by respiration	0.820	0.167
Sc		
-side	0.918	0.341
-respiration	0.001*	<0.001*
-side by respiration	0.651	0.925

Table 6.4 Results for the intra-class correlation coefficients (ICC) and corresponding 95% confidence intervals (CI) repeatability analyses for the tasks of inspiratory resistance (IR) and an active straight leg raise with inspiratory resistance (ASLR+IR). (IAP = intra-abdominal pressure, ITP = intra-thoracic pressure, RF = respiratory fluctuation, BS = baseline shift, RR = respiratory rate, PF = pelvic floor, DLP = downward leg pressure)

	IR: ICC (95% CI)	**ASLR+IR: ICC (95% CI)**
Muscle Activation	Highest: 0.993 (0.960– 0.999) Lowest: 0.337 (0 – 0.886) Median: 0.949	Highest: 0.997 (0.867– 0.996) Lowest: 0.576 (0 – 0.927) Median: 0.907
IAP		
- RF	0.940 (0.758 - 0.985)	0.789 (0.150 - 0.948)
- BS	-	0.227 (0 - 0.867)
ITP		
- RF	0.965 (0.794 - 0.994)	0.969 (0.822 - 0.995)
- BS	-	0.393 (0 - 0.896)
RR	0.993 (0.967 - 0.999)	0.993 (0.966 - 0.999)
PF motion		
- for respiration	0.983 (0.899 - 0.997)	0.950 (0.707 - 0.991)
- for leg lift	-	0.728 (0 - 0.953)
DLP	-	0.994 (0.946 - 0.999)

6.7 Discussion

6.7.1 Hypothesis 1: Incremental increase of motor activity during the active straight leg raise with inspiratory resistance

In pain free subjects the physical load of an ASLR elicits a motor response in the abdominal wall that is primarily tonic in nature, presumably contributing to lumbopelvic stability and effective load transference through the pelvis (Beales et al., 2009b, 2009c). The purpose of using IR was to bias the motor system to a respiratory task in order to investigate the capacity of the central nervous system to adapt to a combined physical and respiratory loading task. This response was achieved with increased respiratory activation of the accessory inspiratory muscles (Sc and right CW), which would presumably occur with a concurrent increase in synergistic activation of the diaphragm. Results from performing ASLR and IR simultaneously supported the first hypothesis that pain free subjects would attend to this dual task with an incremental increase of motor activity compared to performing these tasks in isolation. Evidence for this was found with increased EMG activity of IO, EO and CW during an ASLR+IR compared to performing either ASLR or IR alone. The increase in the activation of these muscle groups was associated with a simultaneous increase in IAP baseline shift in response to ASLR+IR compared to ASLR alone (Figure 6.5).

In addition to this general effect, individual differences were observed in the motor pattern adopted by individuals during the dual task of an ASLR+IR. This is consistent with numerous descriptions of individual variations in motor control studies examining the ability of the neuromuscular system to balance respiratory and stability demands (Abraham et al., 2002; Grenier & McGill, 2008; Hodges & Gandevia, 2000b; McGill et al., 1995; Wang & McGill, 2008). It fits the concept of subjects having an individual neurosignature (Melzack, 2005) for these tasks. From the individual variation observed, it appears that subjects adopt different strategies with the abdominal muscles in response to ASLR+IR. Some displayed motor patterns that were tonic in nature, which would appear to be a strategy primarily related to the task of lifting the leg. This type of recruitment pattern, where the abdominal wall appears to attend to lumbopelvic stability over respiration, has been previously reported (McGill et al., 1995; Wang & McGill, 2008). On the other hand some subjects demonstrated clear patterns of phasic activation, which would appear to be a primary response to breathing with inspiratory resistance. Respiratory activation of the abdominal wall has been well documented during normal breathing and with respiratory challenges (Abe, Kusuhara, Yoshimura, Tomita, & Easton, 1996; Abraham et al., 2002; Aliverti et al., 1997; Aliverti et al., 2002; Hodges & Gandevia, 2000b; McGill et al., 1995; Wang & McGill, 2008). It has been proposed that individuals who demonstrate respiratory activation of the abdominal wall when there is a concurrent requirement for lumbopelvic stability (eg lifting) could put themselves at greater risk of tissue strain (McGill et al., 1995; Wang & McGill, 2008). However, pain free subjects may have adequate lumbopelvic stability from non-muscular sources (ie passive stability), providing sufficient resilience in the system so as to not increase the risk of tissue strain if there is a conflict in activation of the motor system (Grenier & McGill, 2008). The long-term effects of such a conflict are not known though, but could potentially contribute to repetitive micro-trauma and pain.

For some subjects respiratory activation of the abdominal wall was synchronised with expiration (Figure 6.2). Expiratory activation of the abdominal muscles is well known (Abe et al., 1996). Expiratory activation of the abdominal wall observed in this study is a likely result of subjects recruiting these muscles for active expulsion of gas from the lungs. Other subjects demonstrated respiratory activation of the abdominal wall synchronised to inspiration (Figure 6.2). Normally the control of respiration, especially during ventilatory challenges, is facilitated by abdominal activation that extends into the inspiratory cycle (Abe et al., 1996; Aliverti et al., 2002). This is facilitated by gradual active relaxation (rather than a rapid switching off) of the abdominals during early inspiration, which imposes an expiratory load that the respiratory muscles must overcome to initiate inspiration. The observation of inspiratory abdominal activation in this study goes beyond active relaxation though, to one of primary initiation and recruitment during inspiration. This action of the abdominal wall has been noted previously as a variant motor pattern during simultaneous lifting and ventilatory challenges (McGill et al., 1995). In this study it is possible that these subjects activated the abdominal wall during inspiration as a means of controlling IAP during tasks with IR. Though activation of the diaphragm was not directly recorded in this study, it is fair to assume IR would increase diaphragm activity in a manner similar to the Sc and CW, which are generally accepted as accessory inspiratory muscles and synergists of the diaphragm (Rodarte & Shardonofsky, 2000). The finding of greater ITP respiratory fluctuations during the IR tasks (Figure 6.6), and a trend for greater IAP respiratory fluctuations during these tasks (Table 6.1), may attest to increased diaphragm activation during IR and ASLR+IR.

One subject who demonstrated inspiratory activation of the right CW during RS on visual inspection, changed to expiratory activation of the right CW during IR (Figure 6.4). This contrasts to all of the other subjects who exhibited inspiratory activation of the chest wall during IR. This difference in motor response for this subject in response to IR might have been linked to the strong expiratory abdominal wall activation they also demonstrated. This strategy for expiratory CW activation, using surface EMG, has been noted as a variant motor control pattern previously (McGill et al., 1995). Surface EMG of the CW is a likely composite of the intercostal muscles and the costal diaphragm. Fine wire EMG investigation of the CW has found that respiratory activation of the intercostals varies regionally (De Troyer, Gorman, & Gandevia, 2003; Saboisky, Gorman, De Troyer, Gandevia, & Butler, 2007) and between the muscular layers, with the external intercostals primarily an inspiratory muscle and the internal intercostal an expiratory muscle (Hodges & Gandevia, 2000c; Rodarte & Shardonofsky, 2000; Taylor, 1960). Our CW measure could not differentiate these functions.

This interpretation of motor strategies via surface EMG is useful, as they may represent patterns that can be detected by clinicians and thereby help inform decision making processes in the management of subjects with motor control deficits. However, this type of analyses can oversimplify the motor control processes that are occurring. Individual muscles have motor units which may allow one muscle to attend to respiratory and stability demands simultaneously (Hodges & Gandevia, 2000a; Puckree et al., 1998). Regional variations in the activation of muscles also occurs (De Troyer et al., 2003; Saboisky et al., 2007; Urquhart, Hodges, Allen, &

Story, 2005; Urquhart, Hodges, & Story, 2005). Equally though recordings from a small sample of motor units may not fully reflect that muscles primary task. For example muscle activation in response to lifting can completely attenuate respiratory related activation of that same muscle (McGill et al., 1995; Wang & McGill, 2008).

Ultrasound of the PF was utilized as a non-invasive procedure to monitor the bottom of the abdominal cylinder during the tasks in this study. While no difference was found for PF motion between tasks, there does appear a trend for increased respiratory motion of the PF during the IR tasks (Table 6.1). Respiratory activation of the PF muscles has been previously reported (Hodges, Sapsford, & Pengel, 2007). While motion on US of the PF does not imply activation, the trend of greater respiratory PF motion on US may be reflective of increased PF respiratory activation during the IR inclusive tasks in response to changes in IAP. It is most likely related to the similar trend for greater IAP respiratory fluctuation during the IR tasks. This premise is worthy of further investigation.

6.7.2 Hypothesis 2: Symmetry of muscle activation

During an ASLR, pain free subjects show higher activation of the IO on the side of the leg lift compared to the non-lifted side (Beales et al., 2009b). This recruitment pattern is maintained when the ASLR is changed from a low load activity to a high load activity with the addition of weight around the ankle (Beales et al., 2009c). The findings of this study show that the addition of IR to an ASLR does not disrupt this pattern. This is consistent with the asymmetry of the ASLR task, and the ability of the neuromuscular system to respond to the ASLR+IR with an incremental increase in trunk muscle activity while maintaining the pattern. In contrast, subjects with chronic PGP respond to the ASLR with a bilateral pattern of activation of IO in a bracing strategy (Beales et al., 2009a). The effect of IR during an ASLR in PGP pain subjects is the topic of ongoing research.

6.7.3 Repeatability

The consistency of the motor patterns adopted by these subjects during IR and ASLR+IR was very good. Similar findings have been reported in pain free subjects during ASLR and ASLR with additional physical resistance (Beales et al., 2009b, 2009c). Despite this consistency of motor activation between trials, the baseline shift of IAP and ITP when lifting the leg during ASLR+IR was more variable. This is possibly a consequence of not monitoring activation of all the muscles involved in the production and control of IAP, such as the PF, diaphragm and transversus abdominis in particular (Beales et al., 2009b).

6.7.4 Limitations

A limitation of this study was that the inspiratory load was set at a fixed value (30 cm H_2O), and not adjusted to the respiratory capacity of individual subjects. Thus factors such as physical fitness levels and inspiratory muscle strength could have confounded the results. Also the power of this study may have not been sufficient to fully inform the intricacies of the motor control patterns displayed by these subjects. An example of this is the visual evidence of respiratory activation of the abdominal wall that wasn't apparent from the statistical analyses. Despite these limitations though, the results still provide insight into the way pain free subjects attend to the tasks in this study.

6.8 Conclusion

This study has documented motor control strategies where pain free subjects attend to a low level stability challenge of an ASLR combined with the respiratory challenge of IR with an incremental increase of the motor activation observed when the subjects perform these tasks in isolation. Variation was apparent in the form of the motor control patterns adopted by individuals, consistent with previous research investigating simultaneous stability and respiratory challenges. This highlights the individuality of the neuromuscular system in pain free subjects to perform the same task. The findings will assist clinicians in understanding the implications of motor control strategies in pain subjects. Further research is required to investigate these patterns in the presence of chronic lumbopelvic pain. Furthermore, studies investigating the control of simultaneous physical and respiratory challenges during functional and weight bearing tasks are required to assess whether the findings of this study translate to other activities.

6.9 References: Chapter 6

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Chapter 7: Study 5. Non-uniform motor control changes with manually applied pelvic compression during an active straight leg raise in chronic pelvic girdle pain subjects

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7.1 Abstract

A sub-group of pelvic girdle pain patients with a positive active straight leg raise responds positively to the application of external pelvic compression during the test. This study investigated the effect of this phenomenon on electromyographic activity of the trunk muscles and intra-abdominal and intra-thoracic pressures in subjects with a unilateral sacroiliac joint pain disorder ($n = 12$). All subjects reported reduced difficulty ratings during an active straight leg raise with pelvic compression (paired t-test: $p < 0.001$), yet no statistically significant changes in the muscle activation or IAP pressure variables were found. However, visual inspection of the data revealed two divergent motor control strategies with the addition of compression. Seven subjects displayed characteristics of decreased motor activation, while in the other five subjects motor activation appeared to increase. As such this study provides preliminary evidence of disparate patterns of motor control in response to the addition of pelvic compression to an active straight leg raise. The findings may reflect different mechanisms, not only in the response to pelvic compression, but also of the underlying pelvic girdle pain disorder.

7.2 Introduction

Compression of the pelvis via a pelvic belt is commonly used in the management of subjects with pelvic girdle pain (PGP) (Haugland, Rasmussen, & Daltveit, 2006; Mens, Snijders, & Stam, 2000; Nilsson-Wikmar, Holm, Oijerstedt, & Harms-Ringdahl, 2005; Ostgaard, Zetherstrom, Roos-Hansson, & Svanberg, 1994). The major benefit of compression from a treatment perspective appears to be the provision of symptomatic relief (Mens, Damen, Snijders, & Stam, 2006; Mens, Vleeming, Snijders, Stam, & Ginai, 1999; Ostgaard, Zetherstrom, Roos-Hansson et al., 1994). In some subjects though compression may negatively influence symptoms (Mens et al., 1999; Ostgaard, Zetherstrom, Roos-Hansson et al., 1994). An interesting aspect of this dichotomy is reflected in the situation where on one hand compression with a belt can provide symptomatic relief, while on the other hand manual compression is used as a provocation test for sacroiliac joint (SIJ) pain (Laslett, Aprill, McDonald, & Young, 2005). Additionally, it has been proposed that these contrasting responses to compression can be helpful in the identification of sub-groups of patients with PGP (O'Sullivan & Beales, 2007b, 2007c).

A number of studies have investigated mechanisms by which pelvic compression may alleviate PGP symptoms. Compression across the ilium with a belt has been shown to increase SIJ stiffness, as measured by Doppler imaging of vibration, in both pain free (Damen, Spoor, Snijders, & Stam, 2002) and PGP subjects (Mens, Damen et al., 2006). Similarly pelvic compression using a belt results in decreased sagittal SIJ rotation in cadaver specimens of the pelvis (Vleeming, Buyruk, Stoeckart, Karamursel, & Snijders, 1992). These findings suggest that pelvic compression can increase intra-articular compression in the sacroiliac joints (SIJs), augmenting the passive stability of the pelvis (increased form closure) and subsequently relieve symptoms by decreasing the load on pain sensitive structures, particularly the ligaments supporting the SIJs.

Altered motor patterns could also potentially create a mechanism for PGP by abnormally loading pain sensitive pelvic structures. Altered motor control patterns have been detailed in chronic PGP subjects during the active straight leg raise

(ASLR) test (Beales, O'Sullivan, & Briffa, 2009a; O'Sullivan et al., 2002). The ASLR is a valid and reliable tool used to assess load transfer through the pelvis (Damen et al., 2001; Mens, Vleeming, Snijders, Koes, & Stam, 2001, 2002; Mens et al., 1999; O'Sullivan et al., 2002), and is well suited to investigation of both motor control and the effects of pelvic compression. Pelvic floor (PF) descent, diaphragmatic splinting and aberrant respiratory patterns during the ASLR can all be positively influenced with the addition of manual pelvic compression through the ilia during the ASLR (O'Sullivan et al., 2002). These findings suggest that the mechanisms for symptom reduction with pelvic compression may result from augmentation of the active components of pelvic stability (force closure).

We have recently documented motor control patterns in subjects with chronic PGP during an ASLR (Beales et al., 2009a). Subjects in that study demonstrated a predominant motor control pattern of bracing through the abdominal wall and the chest wall (CW), that was associated with increased intra-abdominal pressure (IAP) and depression of the PF when lifting the leg on the affected side of the body. The purpose of this study was to investigate the effect of manual pelvic compression during the ASLR on the patterns observed in those subjects. It was hypothesised that compression would result in a reduction in global muscle activation and a reduction in IAP associated with maintaining the ASLR.

7.3 Methods

7.3.1 Subjects

Twelve females with chronic PGP were recruited from the Perth metropolitan region. Group characteristics are displayed in Table 7.1. The subjects were identified as having a unilateral SIJ (and/or surrounding ligaments) as the source of their symptoms according to specific diagnostic criteria (Table 7.2). Ethical approval was granted by the Human Research Ethics Committee of Curtin University of Technology. All subjects provided written informed consent.

Table 7.1 Demographic data (mean ± standard deviation). (Adductor Strength (Mens, Vleeming, Snijders, Ronchetti, & Stam, 2002), BMI = body mass index, Quebec = The Quebec Back Pain Disability Scale (Kopec et al., 1996), McGill = Short Form McGill Pain Questionnaire (Melzack, 1987), VAS = Visual Analogue Scale for Usual Pain, Tampa = Tampa Scale for Kinesiophobia (Vlaeyen, Kole-Snijders, Boeren, & van Eek, 1995), UDI = Urogenital Distress Inventory: Short Form (Uebersax, Wyman, Shumaker, McClish, & Fantl, 1995), ASLR = active straight leg raise, ASLR Heaviness Score (Mens, Vleeming, Snijders, Koes et al., 2002))

Subject Characteristics:	
Age (years)	39.8 ± 11.2
BMI (kg/m^2)	23.2 ± 4.6
Nulliparous	n = 5
Symptom Duration (months)	92.6 ± 78.0
Adductor Strength (N)	92.6 ± 26.4
Aetiology of the Disorder:	
Pregnancy Related	n = 4
Trauma	n = 6
Insidious	n = 2
Pain and Disability Scales:	
Quebec (x/100)	22.9 ± 18.7
McGill (x/45)	8.4 ± 2.7
VAS for usual pain (x/100)	43.7 ± 24.3
Tampa (x/68)	35.1 ± 9.2
Continence Dysfunction	n = 7
UDI (x/15 for n = 7)	1.8 ± 1.1
ASLR Heaviness Score (x/5)	
Affected Side	3.1 ± 0.5
Affected Side with Compression	0.9 ± 0.8

Table 7.2 Inclusion and exclusion criteria. The inclusion criteria have good validity for identifying pelvic girdle pain subjects where the sacroiliac joint (SIJ) and/or surrounding ligamentous are the primary source of peripheral nociception.

Inclusion Criteria
Presenting pain: • Pain primarily over the SIJ which may refer distally, but not referring proximally to the lumbar spine (Dreyfuss, Michaelsen, Pauza, McLarty, & Bogduk, 1996; Maigne, Aivaliklis, & Pfefer, 1996; van der Wurff, Buijs, & Groen, 2006; Young, Aprill, & Laslett, 2003) SIJ Pain Provocation Tests: • Minimum three out of five positive SIJ pain provocation tests:- o Posterior shear test (Laslett et al., 2005; Laslett, Young, Aprill, & McDonald, 2003; Ostgaard, Zetherstrom, & Roos-Hansson, 1994) o Sacral torsion test (Laslett et al., 2005; Laslett et al., 2003) o Sacral thrust test (Laslett et al., 2005; Laslett et al., 2003) o Distraction test (Laslett et al., 2005; Laslett et al., 2003) o Tenderness on palpation of the long dorsal SIJ ligament (Vleeming, de Vries, Mens, & van Wingerden, 2002) and/or the inferior joint line and/or the sacrotuberous ligament Active Straight Leg Raise Test: • Heaviness +/- pain, which is relieved when performed with manual pelvic compression (Mens et al., 2001; Mens et al., 1999; O'Sullivan et al., 2002) Other Tests: • Absence of lumbar spine pain and impairment (Laslett et al., 2005; Laslett et al., 2003) • Lumbar spine pain provocation tests (passive accessory tests) are normal • Normal neurological screening testing • No neural tissue mechanosensitivity
Exclusion Criteria
• Any other musculoskeletal pain disorder in the last six months • Surgery in the last year • Neurological disorder • Inflammatory disorder • Respiratory disorder • Pregnancy or less than six months postpartum

7.3.2 Procedure

Subjects were tested performing an ASLR on the affected side of the body, and then during an ASLR with additional manual pelvic compression through the ilia (ASLR+Comp). The methodology used in this study has been fully documented previously (Beales et al., 2009a; Beales, O'Sullivan, & Briffa, 2009b). A custom-built LabVIEW v6.1 (National Instruments, Austin, Texas) acquisition program was used for synchronised data collection, and a separate LabVIEW program was used for data processing.

7.3.3 Respiratory phase

A pneumotach from a Benchmark Pulmonary Exercise System (P.K. Morgan Instruments, Inc., Andover, Massachusetts) was modified with an external output to record respiratory phase. Respiratory rate (RR) was directly calculated from this.

7.3.4 Muscle activation

Two Octopus Cable Telemetric units (Bortec Electronics Inc., Calgary, Canada), one for each body side, were used to record muscle activity bilaterally from the lower fibres of obliquus internus abdominis (IO) (Ng, Kippers, & Richardson, 1998), obliquus externus abdominis (EO) (Ng et al., 1998), rectus abdominis (RA) (Ng et al., 1998), anterior scalene (Sc) (Falla, Dall'Alba, Rainoldi, Merletti, & Jull, 2002), and the right CW (Allison, Kendle et al., 1998; Gross, Grassino, Ross, & Macklem, 1979; Sharp, Hammond, Aranda, & Rocha, 1993). The anterior superior iliac spines were used for earth electrodes. Following light abrasion and cleaning of the skin to an impedance level below 5 kΩ (Gilmore & Meyers, 1983), dual disposable Ag/AgCl electrodes (ConMed Corporation, Utica, New York) were placed in situ with an inter-electrode distance of 2.5cm. Collection occurred at sample rate of 1000Hz at a bandwidth of 10-500Hz with a common mode rejection ratio of >115dB at 60Hz, pre-amplified and amplified to a gain of 2000.

The electromyography (EMG) was inspected for contamination from heartbeat and other artifact. Where necessary, artifact was and manually eliminated. Data were then demeaned, band pass filtered from 4-400Hz with a 4^{th} order zero lag

Butterworth filter and normalised. Normalisation was performed with the average root mean square (RMS) from three 3s trials of a crook lying double leg raise with cervical flexion (Allison, Godfrey, & Robinson, 1998; Allison, Kendle et al., 1998; Dankaerts, O'Sullivan, Burnett, Straker, & Danneels, 2004; Falla et al., 2002; O'Sullivan, Twomey, & Allison, 1998). Then the root mean square was calculated for 500ms during the middle of the inspiratory and expiratory phases of three breath cycles. This allowed for investigation of phasic EMG changes in relation to respiration and tonic changes in response to the physical load of lifting the leg.

7.3.5 Intra-abdominal and intra-thoracic pressures

A custom-made silicone rubber nasogastric catheter (Dentsleeve International Ltd, Mississauga, Canada) was used to record IAP and intra-thoracic pressure (ITP). The catheter contained two small lumens, through which saline solution was passed at a constant high pressure. A custom-built pressure transducer detected changes in flow rate of this saline that occurred in response to pressure changes within the abdominal and thoracic cavities.

Two aspects of IAP and ITP were calculated:

1. Respiratory Fluctuation: the difference between the maximum and minimum values for each variable respectively over a breath cycle.
2. Baseline Shift: the minimum IAP or ITP value for each of three relaxed supine breath cycles was subtracted from and the corresponding minimum value during the ASLR/ASLR+Comp. This was to assess pressure change in response to lifting the leg rather than respiratory related change.

7.3.6 Pelvic floor motion

A Capesee SSA-220A ultrasound unit (Toshiba Corporation, Tochigi, Japan) was used to monitor PF motion, which was recorded to digital video. The probe was positioned trans-abdominally and angled inferiorly to view the bladder, a non-invasive method to reliably monitor PF movement (O'Sullivan et al., 2002; Sherburn, Murphy, Carroll, Allen, & Galea, 2005; Thompson & O'Sullivan, 2003; Walz & Bertermann, 1990).

Subjects were asked to cough prior to performing a leg lift. This provided a marker for the PF video footage to be synchronised with the rest of the data collected with the acquisition program. A frame of video was captured either side of the leg lift, then overlaid so that movement of the PF could be directly measured to ascertain bladder motion secondary to the ASLR. Video frames were also captured at the maximum and minimum points of excursion over each of the three breath cycles and measurement taken in the same manner to ascertain PF motion in relation to respiration.

7.3.7 Downward pressure of the non-lifted leg

A pressure transducer connected to an inflated pad placed under the heel monitored this variable. Average downward pressure exerted by the non-lifted leg was calculated for each breath cycle.

7.3.8 Analyses

Subjective scores for difficulty of the ASLR and ASLR+Comp (Mens, Vleeming, Snijders, Koes et al., 2002) collected during subject screening were compared with a paired t test. Where appropriate, variables over the three processed breath cycles were averaged for analyses. Muscle activation was compared with a two (*task:* ASLR, ASLR+Comp) by two (*respiration:* inspiration, expiration) repeated measures analysis of variance and post hoc t tests. Six subjects were symptomatic on the left, six on the right. Hence side will be referred to as affected or non-affected side corresponding to the side of the body the SIJ disorder was identified on. Statistical analysis was not performed on the right CW as the sample size of six on the affected side and six on the non-affected was deemed to small. Intra-abdominal pressure, ITP, RR, PF movement and downward leg pressure were compared between the ASLR and ASLR+Comp with paired t-tests. Statistical analysis was performed with SPSS 16.0 for Mac (SPSS Inc., Chicago, Illinois), with a critical p value of 0.05, and complimented with visual inspection of all data.

7.4 Results

In line with the inclusion criteria, all subjects reported it was easier to lift their leg when manual pelvic compression was applied during the ASLR. Consistent with this, the mean subjective ASLR heaviness score (Table 7.1) was lower during the ASLR+Comp compared to the ASLR ($p<0.001$).

Muscle activation during ASLR did not change with the addition of manual pelvic compression (Table 7.3). There was a respiration main effect for the affected IO and the affected RA, but there was no respiratory effect for either muscle when tasks were examined independently (post hoc t tests: affected IO- ASLR $p=0.798$ and ASLR+Comp $p=0.12$; affected RA- ASLR $p=0.086$ and ASLR+Comp $p=0.098$). The effect was not apparent on visual inspection of the EMG traces. A task by respiration effect was found for the non-affected IO, equating to an apparent respiratory modulation of EMG during ASLR+Comp (post hoc t tests: non-affected IO- ASLR $p=0.796$ and ASLR+Comp $p=0.023$), however this respiratory effect was not evident in IO with visual inspection of any subjects.

There were no differences in IAP, ITP, RR, PF motion or downward leg pressure of the non-lifted leg between tasks (Table 7.4).

Visual inspection of the motor patterns revealed a tendency for subjects to respond to compression by either decreasing motor activity (n=7), or conversely increasing motor activity (n=5). Figure 7.1 (*decrease* in motor activity with ASLR+Comp) and Figure 7.2 (*increase* in motor activity with ASLR+Comp) demonstrate pronounced examples of these divergent motor responses. Data were further examined following the categorisation of subjects into either an increased or decreased motor activation group. The magnitude of the changes and the ratios of muscle involvement varied between subjects but overall were consistent with the presence of these divergent responses to ASLR+Comp (see Section 7.8 Electronic Supplementary Material).

Table 4.3 Mean (standard error of the mean) root mean square (RMS) electromyographic (EMG) values for all muscles during the active straight leg raise (ASLR) on the affected body side, and the ASLR completed with additional manual pelvic compression (ASLR+Comp). Results of the repeated measures analyses of variance are also presented. (N-A = non-affected, Aff. = affected, IO = obliquus internus abdominis, EO = obliquus externus abdominis, CW = chest wall' RA = rectus abdominis, Sc = scaleni, *t* = task, *r* = respiration)

	ASLR	ASLR+Comp	p
EMG (RMS)			
Aff IO - inspiration	0.5888 (0.16)	0.5537 (0.14)	*t*: 0.89
- expiration	0.5949 (0.15)	0.6164 (0.18)	*r*: 0.005
			*t***r*: 0.356
N-A IO - inspiration	0.3674 (0.09)	0.3884 (0.17)	*t*: 0.748
- expiration	0.3651 (0.09)	0.4171 (0.18)	*r*: 0.09
			*t***r*: 0.044
Aff EO - inspiration	0.3429 (0.05)	0.3677 (0.06)	*t*: 0.654
- expiration	0.3433 (0.04)	0.3889 (0.06)	*r*: 0.119
			*t***r*: 0.166
N-A EO - inspiration	0.2749 (0.03)	0.3441 (0.07)	*t*: 0.401
- expiration	0.2742 (0.04)	0.3475 (0.07)	*r*: 0.858
			*t***r*: 0.767
Aff RA - inspiration	0.2246 (0.03)	0.2487 (0.04)	*t*: 0.468
- expiration	0.2338 (0.03)	0.2811 (0.06)	*r*: 0.038
			*t***r*: 0.257
N-A RA - inspiration	0.1907 (0.03)	0.2619 (0.05)	*t*: 0.154
- expiration	0.1955 (0.03)	0.2927 (0.07)	*r*: 0.071
			*t***r*: 0.186
Aff CW - inspiration	0.5066 (0.10)	0.2763 (0.06)	
- expiration	0.4703 (0.09)	0.2710 (0.06)	
N-A CW - inspiration	0.2419 (0.02)	0.3686 (0.10)	
- expiration	0.1694 (0.03)	0.3558 (0.11)	
Aff Sc - inspiration	0.3122 (0.14)	0.3993 (0.14)	*t*: 0.064
- expiration	0.1768 (0.03)	0.2544 (0.06)	*r*: 0.236
			*t***r*: 0.482
N-A Sc - inspiration	0.3437 (0.12)	0.4246 (0.13)	*t*: 0.245
- expiration	0.2152 (0.03)	0.2752 (0.06)	*r*: 0.188
			*t***r*: 0.402

Table 7.4 Mean (standard error of the mean) values for intra-abdominal pressure (IAP), intra-thoracic pressure (ITP), respiratory rate (RR), pelvic floor (PF) descent and downward leg pressure of the non-lifted leg during the active straight leg raise (ASLR) on the affected body side, and the ASLR with manual pelvic compression (ASLR+Comp). The results of paired sample t tests are also presented.

	ASLR	**ASLR+Comp**	**p**
IAP (Pa)			
Respiratory Fluctuation	758.2 (143.9)	782.8 (163.4)	0.885
Baseline Shift	543.6 (204.7)	360.2 (323.8)	0.560
ITP (Pa)			
Respiratory Fluctuation	1715.7 (361.4)	1717.9 (378.6)	0.987
Baseline Shift	328.0 (526.9)	-359.5 (403.9)	0.129
RR (breaths/minute)	16.8 (1.5)	18.2 (1.6)	0.220
PF Movement (mm)			
Related to respiration	3.1 (0.6)	2.5 (0.4)	0.215
Related to leg lift	9.0 (1.8)	5.6 (2.3)	0.246
Downward Leg Pressure (N)	58.9 (6.8)	57.7 (8.1)	0.871

Visual inspection of IAP profiles was also consistent with the observed motor strategies (Figure 7.3). Increased motor activation in response to ASLR+Comp was coupled with a simultaneous increase in IAP, and vice versa. This was also supported by secondary investigation (see Section 7.8 Electronic Supplementary Material).

Figure 7.1a

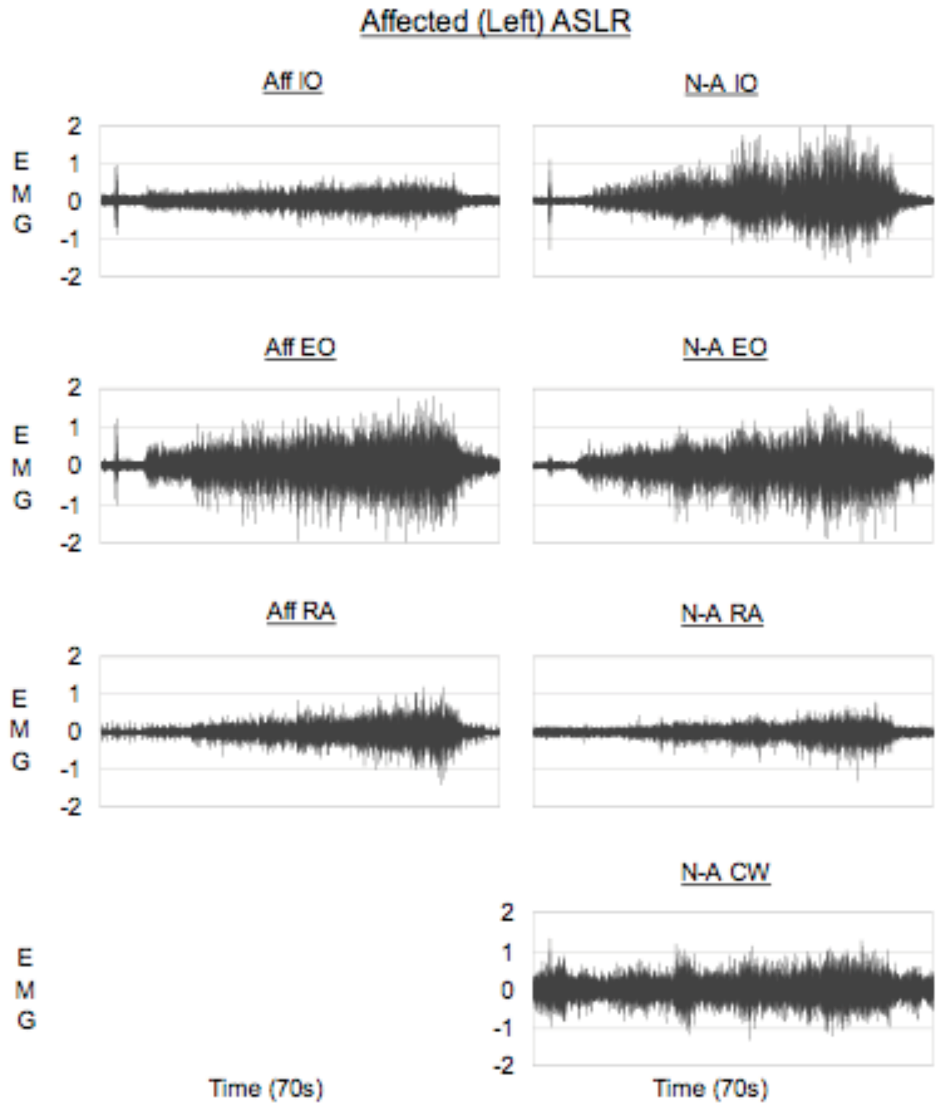
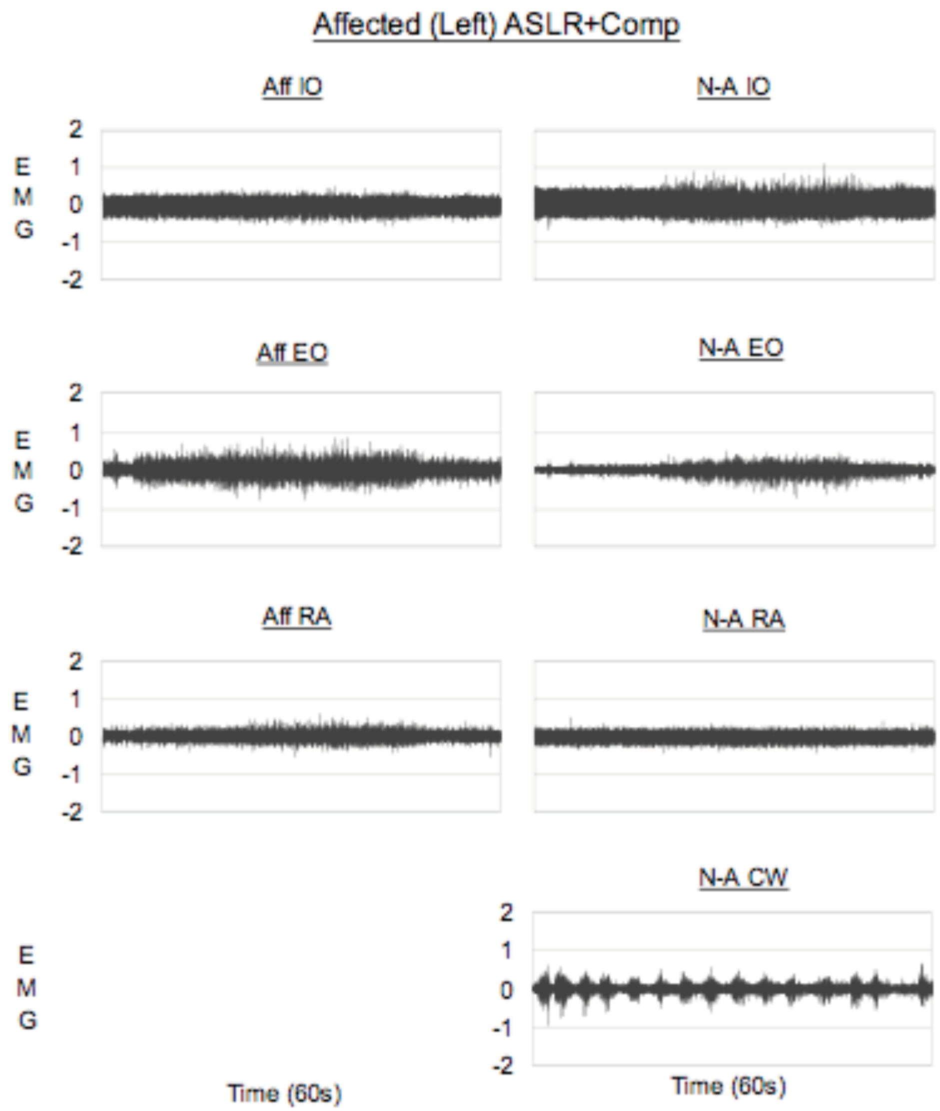


Figure 7.1 Demeaned and normalised electromyography (EMG) profile for a subject during the active straight leg raise (ASLR) (1a) that displays *decreased* motor activation of the trunk muscles with the addition of compression to the ASLR (ASLR+Comp) (1b) (following page). The chest wall (CW) changes from an overriding tonic pattern to a phasic respiratory pattern. (Aff = Affected, N-A = Non-Affected, IO = obliquus internus abdominis, EO = obliquus externus abdominis, RA = rectus abdominis)

Figure 7.1b



Affected (Left) ASLR+Comp
Aff IO
N-A IO
Aff EO
N-A EO
Aff RA
N-A RA
N-A CW
EMG
2
1
0
-1
-2
Time (60s)
Time (60s)

Figure 7.2a:

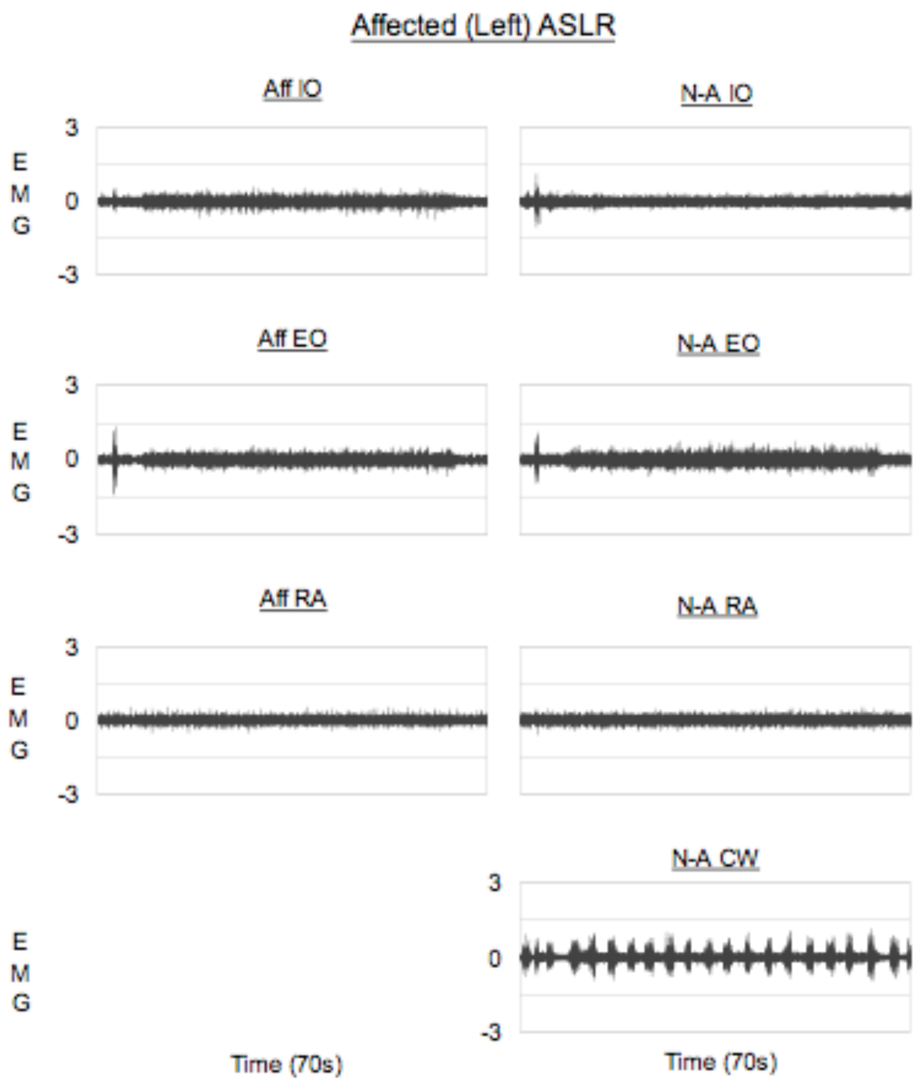
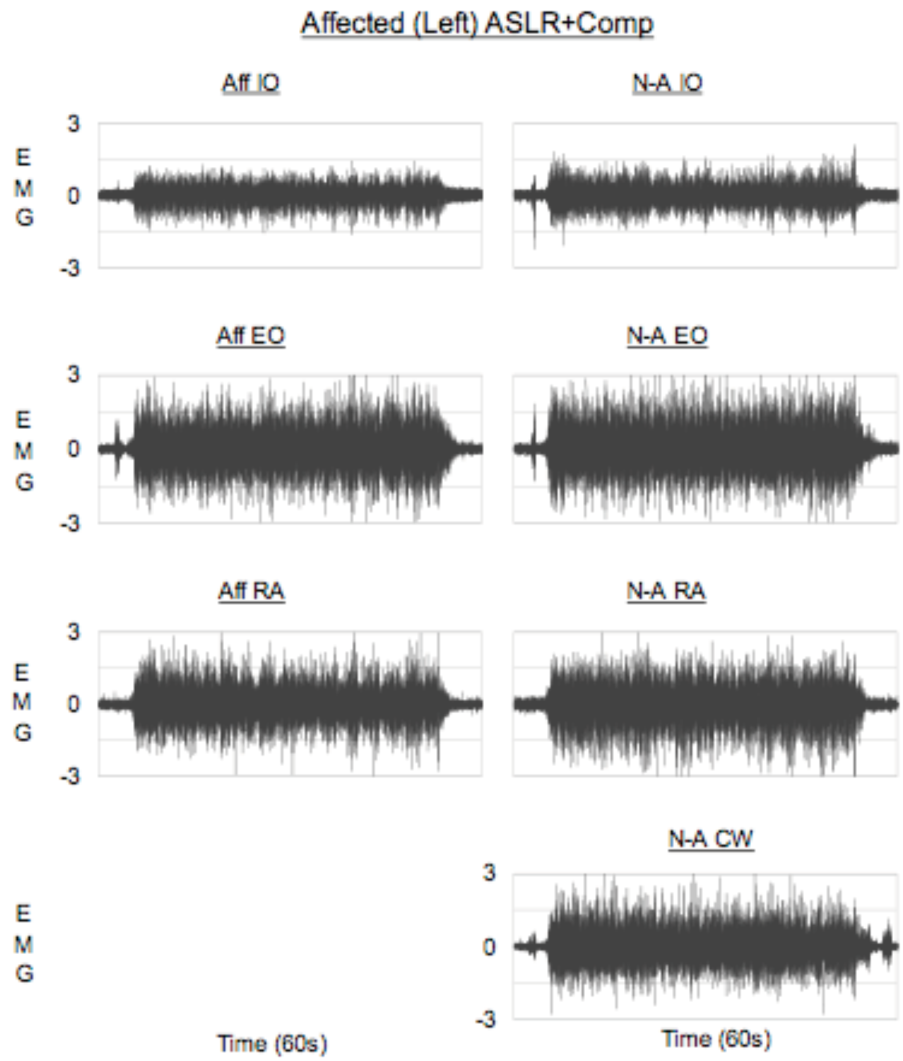


Figure 7.2 Demeaned and normalised electromyography (EMG) profile for a subject during the active straight leg raise (ASLR) (a) that displays *increased* motor activation of the trunk muscles with the addition of compression to the ASLR (ASLR+Comp) (b) (following page). There is obvious bracing of the trunk muscles including dominant tonic pattern of the chest wall (CW) during the ASLR+Comp. (Aff = Affected, N-A = Non-Affected, IO = obliquus internus abdominis, EO = obliquus externus abdominis, RA = rectus abdominis)

Figure 7.2b:



Affected (Left) ASLR+Comp
Aff IO
N-A IO
Aff EO
N-A EO
Aff RA
N-A RA
N-A CW
EMG
3
0
-3
Time (60s)
Time (60s)

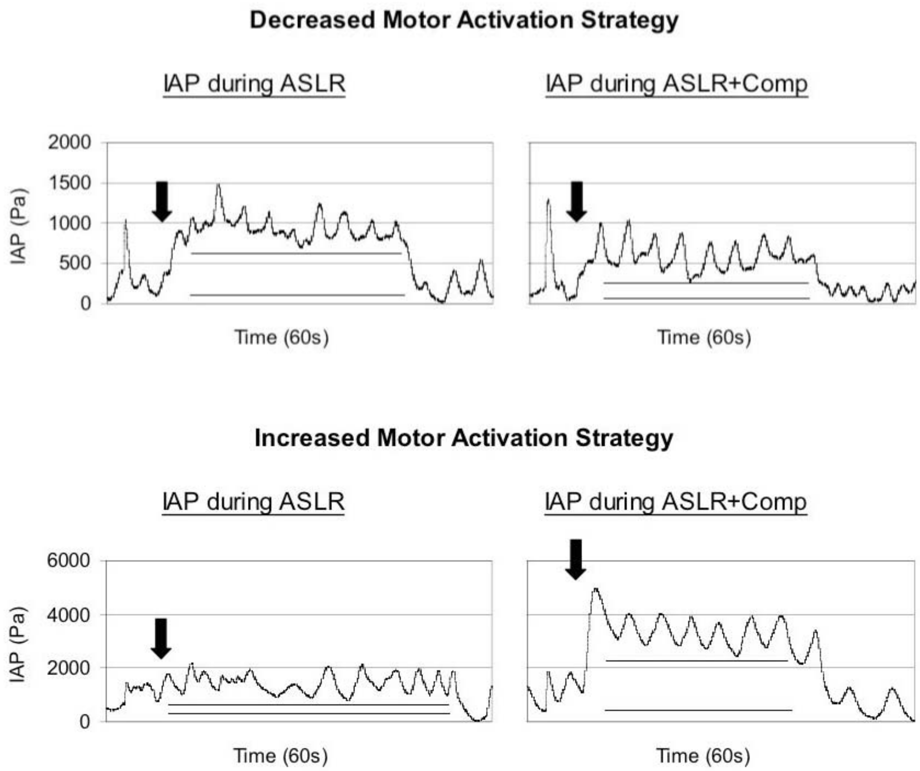


Figure 7.3 Profiles of intra-abdominal pressure (IAP) during an active straight leg raise (ASLR) on the affected side, followed by ASLR with pelvic compression (ASLR+Comp). Bold arrow depicts the timing of lifting the leg. Horizontal lines highlight the baseline shift in IAP in response to lifting the leg. The first subject who responded to the ASLR+Comp with decreased trunk muscle activation displayed a simultaneous decrease in IAP baseline shift. Conversely the second subject displays increased IAP baseline shift during ASLR+Comp consistent with an increased motor activation strategy during this task.

7.5 Discussion

The hypothesis that subjects in this study would demonstrate a reduction in global muscle activation and a reduction in IAP when performing an ASLR+Comp compared to an unaided ASLR was not supported in this study. Visual inspection of the motor control patterns during these two tasks suggests that subjects may actually respond to compression during an ASLR by either increasing or decreasing motor activity.

To our knowledge no other study has investigated the affect of compression during an ASLR on trunk muscle activation or IAP in chronic PGP subjects. Recently a complex static three-dimensional biomechanical model of the pelvis predicted that the addition of compression at the level of the anterior superior iliac spines in standing would result in changes in muscle activation that would include increased activation of the abdominal wall (ventral IO, upper EO), and would also result in increased SIJ stiffness and reduced vertical shear forces on the SIJ (Pel, Spoor, Goossens, & Pool-Goudzwaard, 2008). In contrast, an in vivo study of pain free subjects has found that pelvic compression via a pelvic belt in erect standing reduced activation of IO and RA, while having no effect on OE (Snijders, Ribbers, de Bakker, Stoeckart, & Stam, 1998). Neither study made mention of individual variation in the muscle activation patterns they described. While the present study utilised the ASLR rather than standing, and was in chronic PGP subjects rather than pain free subjects, it appears the two contrasting standing studies separately describe patterns similar to the increased and decreased motor activity patterns observed in this study.

Variation in the response to compression just above the greater trochanter has been previously reported on pelvic rotation in cadaver specimens (Vleeming et al., 1992). Seven specimens demonstrated reduced sagital rotation with the addition of compression, three showed no change, while one specimen demonstrated increased sagital rotation. It was theorised that this response may have resulted from unidentified pathology of the SIJ (Vleeming et al., 1992), but could represent normal individual variants.

Previously we reported reduced descent of the PF during an ASLR+Comp (O'Sullivan et al., 2002). While this effect was not statistically significant in the present study, there was a trend for such an effect. The trend of reduced PF descent with compression during the ASLR appears to hold true for both the increased and reduced motor activation strategies (see Section 7.8 Electronic Supplementary Material), which is suggestive of altered PF function independent of the motor strategy adopted in the abdominal wall. Further investigation of this, including direct measurement of PF activation levels, is warranted.

7.5.1 Symptom reduction and compression

Ilium compression has the potential to improve symptoms (heaviness +/- pain) in subjects with PGP, during an ASLR and other aggravating movements, postures and functional tasks, via a number of possible mechanisms (Damen et al., 2002; Mens, Damen et al., 2006; Mens et al., 1999; O'Sullivan et al., 2002; Pel et al., 2008; Snijders et al., 1998; Vleeming et al., 1992). Dependent upon an individual subject presentation, compression may influence factors including levels of form closure, force closure/motor control, and/or potentially even psychosocial factors such as fear reduction with the addition of manual support. Clinically this phenomenon is useful as it may assist in the classification of subjects with chronic PGP disorders (O'Sullivan & Beales, 2007b, 2007c; Stuge, Morkved, Haug Dahl, & Vollestad, 2006) and can provide symptom control during rehabilitation.

Even though all the subjects in this study felt it was easier to lift the leg during ASLR+Comp, diversity in the motor control pattern adopted with compression was observed. Although speculative, in subjects where compression resulted in inhibition of the motor system, it may be that compression augmented form closure, thereby reducing the need for muscular system contribution to pelvic stability. In contrast, subjects for whom compression resulted in facilitation of the motor system may represent a sub-group with an underlying deficit of the force closure/motor control system. In both cases, compression appears to have an effect on the motor system as well as a local mechanical effect via increased joint stiffness. Moreover, in chronic PGP subjects, the mode by which compression improves load transfer through the pelvis may depend on other factors not clearly identified in this study.

In either case, simply applying pelvic compression for management of PGP disorders may in fact reinforce aberrant motor responses as the motor patterns exhibited during ASLR+Comp in Figure 7.1b and 7.2b differ from motor patterns observed in pain free subjects during an ASLR (Beales et al., 2009b), despite the subjective improvement in heaviness. Aberrant motor control patterns have been suggested as a possible mechanism for ongoing pain and disability in chronic PGP subjects (Beales et al., 2009a; Mens, Hoek van Dijke, Pool-Goudzwaard, van der Hulst, & Stam, 2006; O'Sullivan et al., 2002) and intervention that appears to reinforce aberrant motor control patterns has a detrimental effect on symptoms (Mens et al., 2000). As such the application of pelvic compression, although beneficial in the short term, could have the potential to be problematic in the long term by reinforcing abnormal motor processing. This might explain the clinical observation that some subjects who gain initial temporary relief from a pelvic belt, commonly report that the belt becomes less effective with more prolonged use. It may also have implications for other pressure garments that are sometimes used in the management of PGP (Kalus, Kornman, & Quinlivan, 2008).

The European Guidelines for the Diagnosis and Treatment of Pelvic Girdle Pain recommends that pelvic belts be trialed for symptomatic relief, and if successful only be used for short periods of time (Vleeming, Albert, Ostgaard, Sturesson, & Stuge, 2008). The results of this study support this recommendation, as the belt may provide relief but could reinforce abnormal motor patterns with longer periods of use. These findings lend support for the need for active management strategies that promote normalisation of aberrant motor control strategies adopted by chronic PGP subjects (O'Sullivan & Beales, 2007a; Stuge, Veierod, Laerum, & Vollestad, 2004). Further investigation is required to clarify the effect of external pelvic compression, such as the application of SIJ belts, on motor control in aggravating postures and during functional tasks. It would also be useful to look at changes in motor control with more prolonged use of ilium compression, as opposed to the immediate effects investigated in this study.

A reduction of fear avoidance is unlikely to be the primary mechanism resulting in the motor control changes observed in the subjects in this study during ASLR+Comp as the Tampa Scale for Kinesiophobia scores for the group were within normal limits (Table 7.1). Other psychosocial factors, such as beliefs regarding the mechanisms underlying the disorder (O'Sullivan & Beales, 2007b, 2007c), could also potentially affect motor pattern changes with compression. Greater screening of psychosocial factors may be beneficial in future studies investigating the phenomena observed here.

7.5.2 Abdominal belts and muscle activation

One systematic review of the mechanisms of lumbar belts identified equal number of studies that demonstrate either decreased motor activation, no effect on motor activation, or inconsistent effects of the belt on motor activation (van Poppel, de Looze, Koes, Smid, & Bouter, 2000). Subsequent studies continue to demonstrate inconsistent effects of a lumbar belt on motor activity (Ivancic, Cholewicki, & Radebold, 2002; Warren, Appling, Oladehin, & Griffin, 2001). These inconsistencies could be due to methodological differences in the studies investigating the effect of lumbar belts, particularly differences in the tasks used during the investigations. They may also reflect individual variations in response as elicited in this study with pelvic compression. Evidence for the use of lumbar belts in prevention and treatment of low back disorders is low (van Duijvenbode, Jellema, van Poppel, & van Tulder, 2008) , and may be detrimental if their use is ceased after a period of time (Reddell, Congleton, Dale Huchingson, & Montgomery, 1992).

7.6 Conclusion

Contrary to a hypothesised uniform motor control response to the addition of pelvic compression to an affected ASLR, divergent motor control strategies were observed. Unfortunately after categorisation into increased or decreased motor activation categories, sample size was insufficient to perform meaningful statistical analyses to fully validate these groups. Nevertheless, the documented observations are sufficient to warrant further investigation.

Despite all the subjects reporting subjective improvement during ASLR+Comp according to the inclusion criteria, differences in motor control patterns were observed concurrent with these subjective reports. This might reflect differences in the underlying mechanisms driving the chronic PGP state in these subjects. This premise requires further investigation and raises questions regarding the application of pelvic compression for the management of PGP.

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7.8 Electronic Supplementary Material

Visual inspection of the EMG traces of the individual subjects demonstrated a tendency to respond to ASLR+Comp in one of two general ways. Seven subjects had an apparent decrease in motor activity, while five displayed increased motor activity. To check this general categorisation the EMG of all muscle for each individual subject were added separately for both ASLR and ASLR+Comp as a general indication of total motor activity for each task (Table A). The results for categorisation from comparisons of the total EMG values for each subjects support the findings from the visual inspection of the EMG profiles.

Table A:

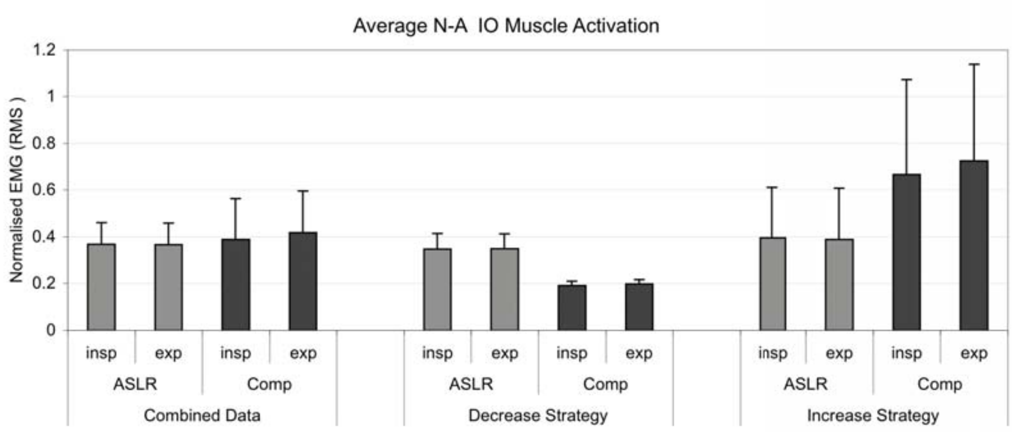
Subject	**Visual Inspection Strategy**		**Total EMG Values**		**EMG Value Strategy**	
	Increase	Decrease	ASLR	ASLR+Comp	Increase	Decrease
1		✓	6.37	4.75		✓
2		✓	4.36	3.64		✓
3	✓		6.64	8.60	✓	
4	✓		5.04	5.28	✓	
5	✓		8.18	11.72	✓	
6	✓		3.23	11.61	✓	
7		✓	8.71	8.66		✓
8		✓	5.17	4.07		✓
9		✓	5.98	3.75		✓
10	✓		6.77	9.65	✓	
11		✓	3.61	2.80		✓
12		✓	4.80	3.44		✓

The change in EMG for two of the subjects (Table A: Subjects 4 and 7), while increased and decreased respectively, are only slightly changed. As such it could be argued that there has been no overall change with the addition of compression in these two subjects. Thus there may be three categories of response to compression, increased motor response, decreased motor response, or no change in motor response.

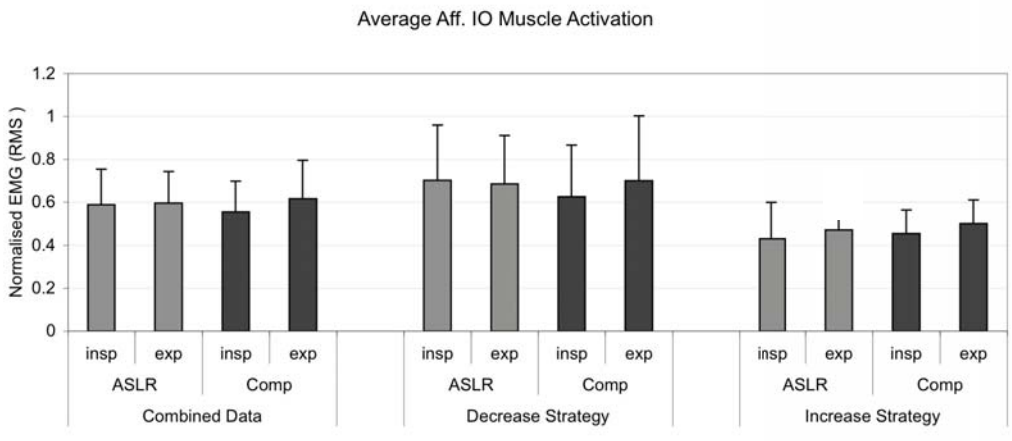
Sub-Analysis of the decreased/increased motor strategies:

Following are graphs for all variables with three categories; combined data, decreased motor strategy and increased motor strategy. The low number of subjects makes statistical analysis impractical, but these graphs do demonstrate some trends in the data which support sub-categorisation of these subjects and support the need further research in this area.

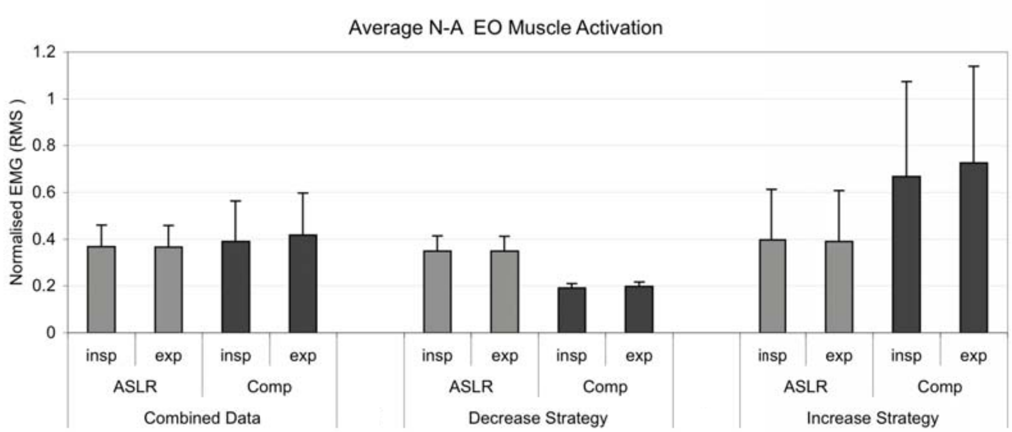
Graph A: Non-affected IO- while the overall data displays no change, there is a downwards trend and upwards trend in this muscle during ASLR+Comp in the decrease and increase groups respectively.



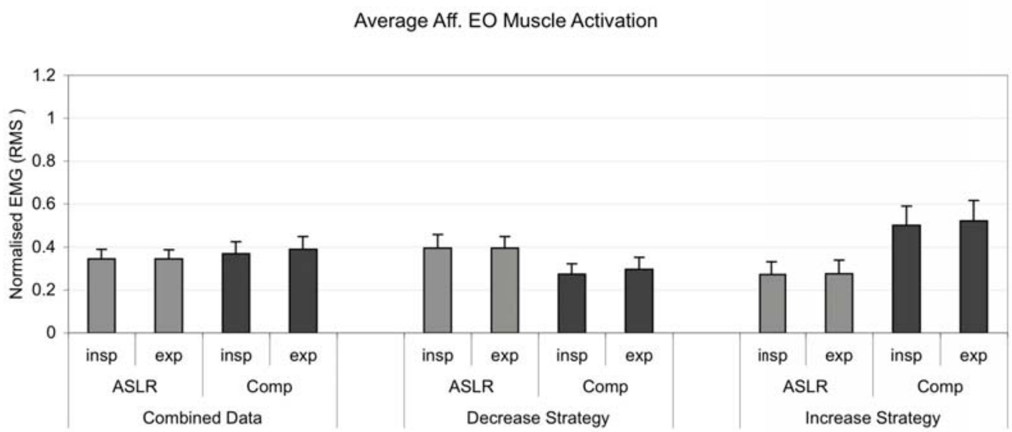
Graph B: Affected IO- Interestingly the affected side IO doesn't display the same trends as IO on the non-affected side. This is likely due to the fact that IO is known to activate more on the side of a leg lift during an ASLR anyway (Beales et al., 2009b).



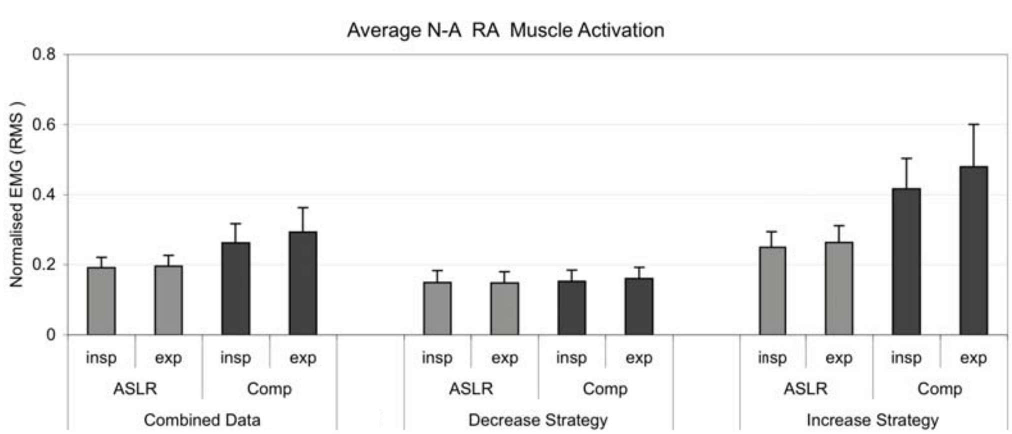
Graph C: Non-affected EO- trend visible for less activation in the decrease category during the ASLR+Comp, and more in the increase group.



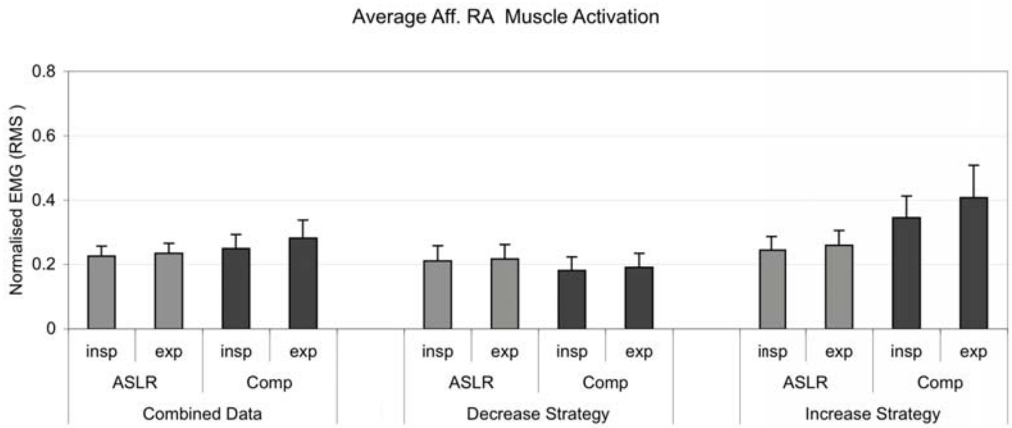
Graph D: Affected EO- The same trend as the non-affected IO and EO is observable.



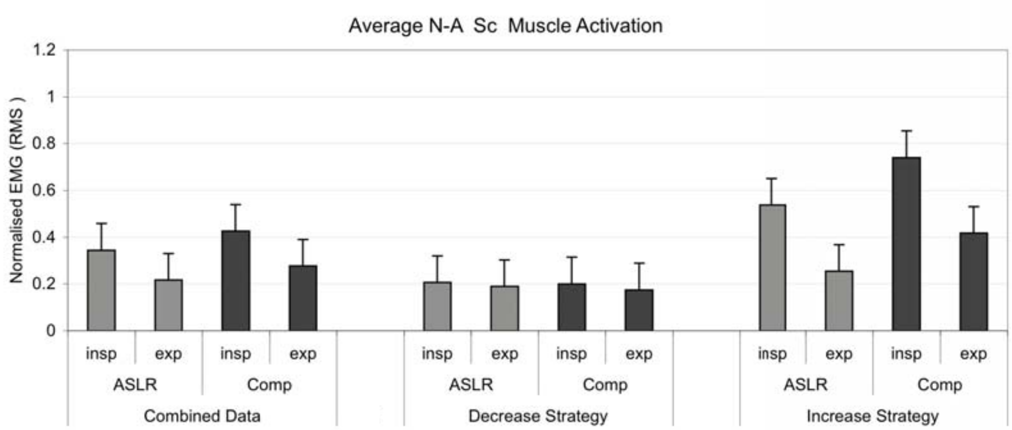
Graph E: Non-Affected RA- little effect is noticeable in the decrease group, but there is greater activation in the increase group.



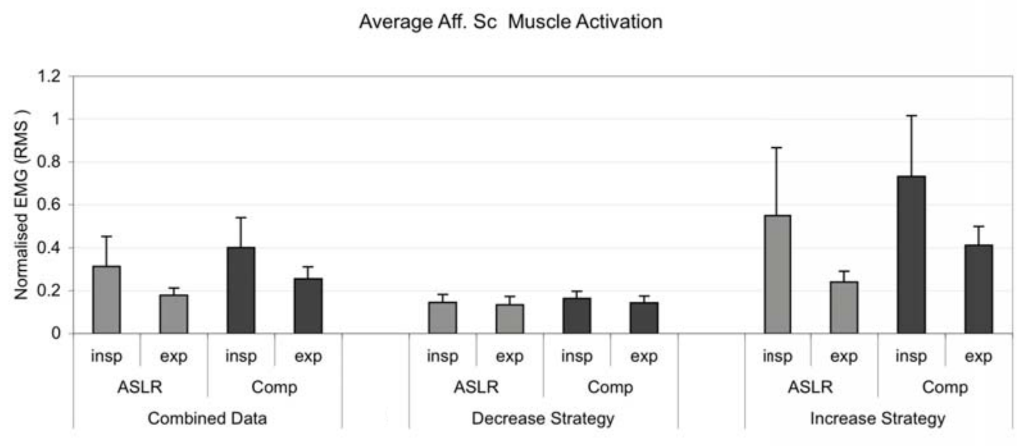
Graph F: Affected RA- as per the non-affected RA



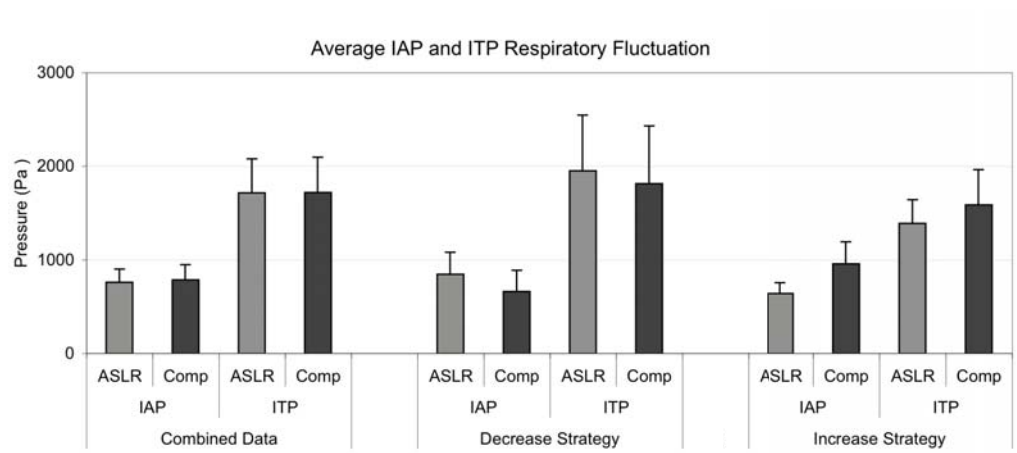
Graph G: Non-Affected Sc- interestingly the decrease strategy group has less Sc activation than the increase strategy group, which appears tonic in the decrease group but phasic in the increase group. Compression appears to have no effect.



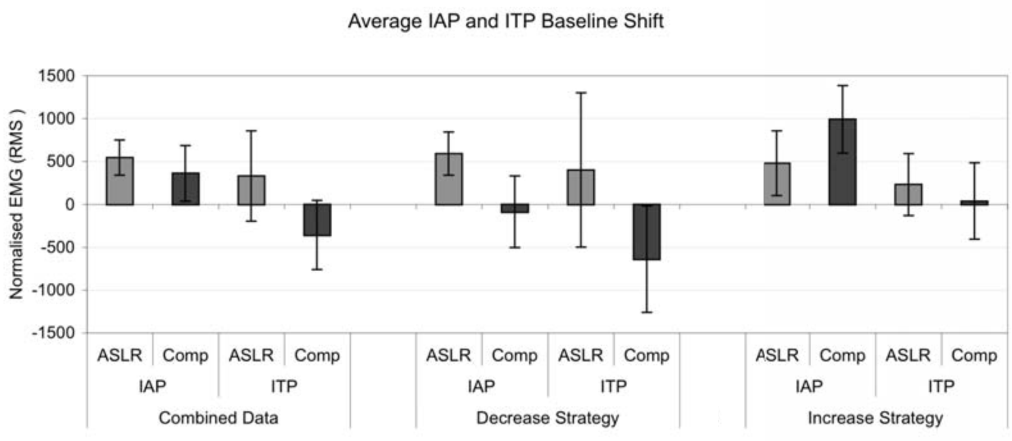
Graph H: Affected Sc- as per the non-affected Sc.



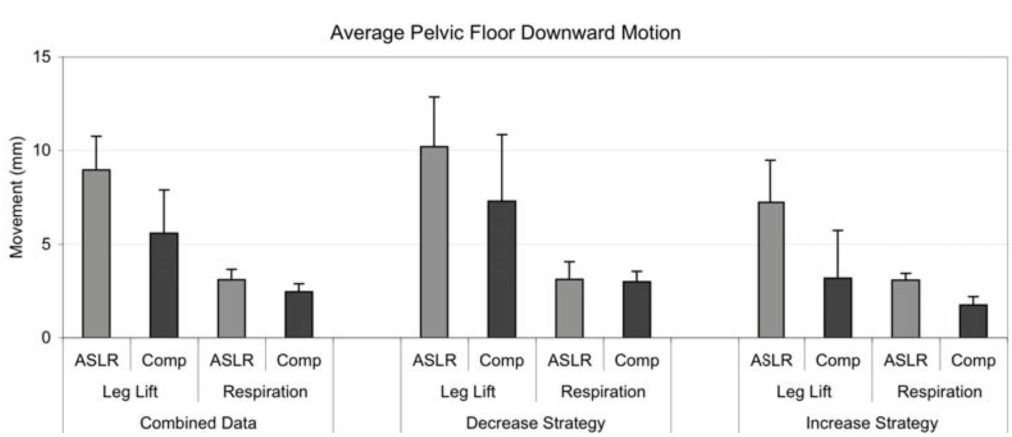
Graph I: IAP and ITP Respiratory Fluctuation- there does appear to be a slight decrease in both IAP and ITP respiratory fluctuation with the ASLR+Comp in the decrease strategy group, but an increase with the increase strategy.



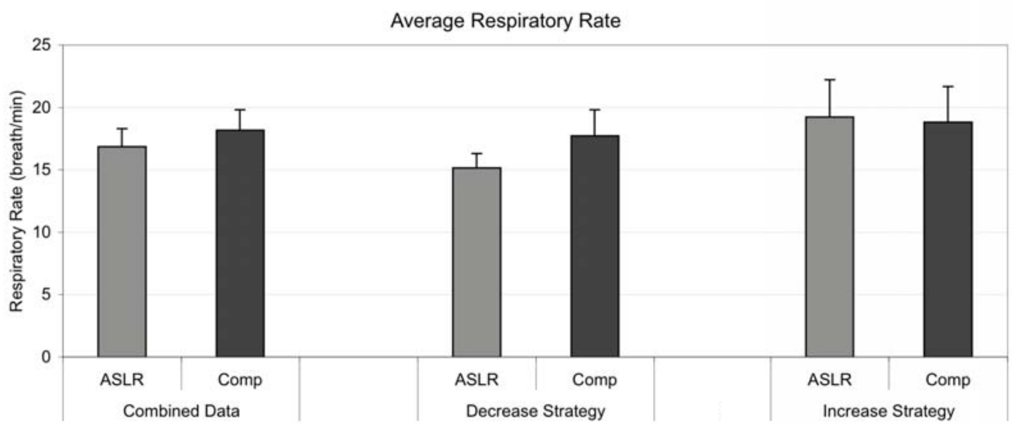
Graph J: IAP and ITP Baseline Shift- IAP baseline shift demonstrates a trend to lower in the decrease strategy group with compression, and vice versa in the increase group. These observation correlate with the observations related to muscle activation. The ITP does not appear to be affected as much by compression in the increase strategy group compared to the decrease group.



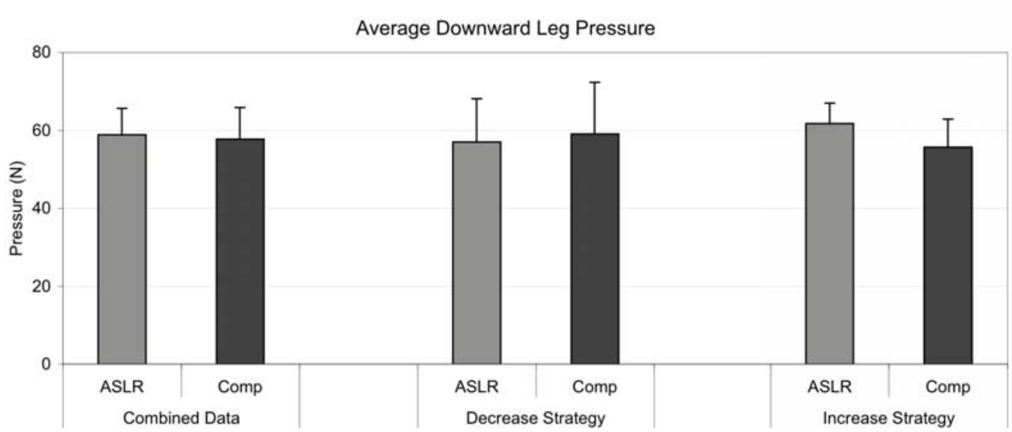
Graph K: PF Motion- there is a trend for decreased PF descent in response to the leg lift during the ASLR+Comp regardless of the overall change in motor strategy. This correlates with previous findings related to PF descent (O'Sullivan et al., 2002).



Graph L: RR- might be slightly increased in the decrease strategy group with ASLR+Comp. This may reflect the observation of the CW shifting from a tonic to a phasic contraction in this group with compression.



Graph M: Downward Leg Pressure- the downward shift in the increase strategy group may reflect a shift from a distal motor strategy to a more local strategy with compression that decreases the need/reliance on the distal strategy.



Chapter 8: Discussion

The body of work in this thesis presents a unique investigation into trunk motor control strategies employed by the central nervous system during an active straight leg raise (ASLR), in both pain free subjects and subjects with chronic pelvic girdle pain (PGP). Additionally it provides insight into the ability of the neuromuscular system to balance simultaneous demands of stability and respiration. To our knowledge this is the first series of studies to provide in-vivo observations of intra-abdominal pressure (IAP) in relation to the ASLR test. Furthermore, to our knowledge this is the first time IAP recording has been performed in subjects with chronic PGP. As such, the work presented in this thesis makes an original contribution to the knowledge base relevant to understanding motor control in PGP.

Specific discussion related to the five studies in this thesis has already been presented (see Chapters 3-7). However, the first part of this section will revisit each of these individual studies separately, directly addressing each research question outlined in Section 2.2. The knowledge gaps addressed by each of these studies and the contribution the findings make to the knowledge base will be addressed.

The second part of the discussion will examine the broader implications of the findings of these studies. Firstly it will discuss how the findings of these studies in pain free subjects relate to contemporary understanding of factors affecting motor control in general, with particular reference to task specificity in motor control and the concept of a neurosignature. Following this will be a discussion of the relationship between aberrant motor control patterns and chronic PGP. In particular this will address how aberrant motor control patterns may act as a primary mechanism driving chronic pain and disability in a specific sub-group of chronic PGP subjects. While none of the studies in this thesis are intervention studies, the findings may have implications for the conservative management of chronic PGP disorders. This will be briefly discussed. While these areas are presented in a segregated and linear fashion here, they should be viewed as interdependent entities (Figure 8.1). Therefore some overlap will exist within the specific sections dedicated to these issues. The discussion will be concluded by addressing limitations in the studies and by making recommendations for future research.

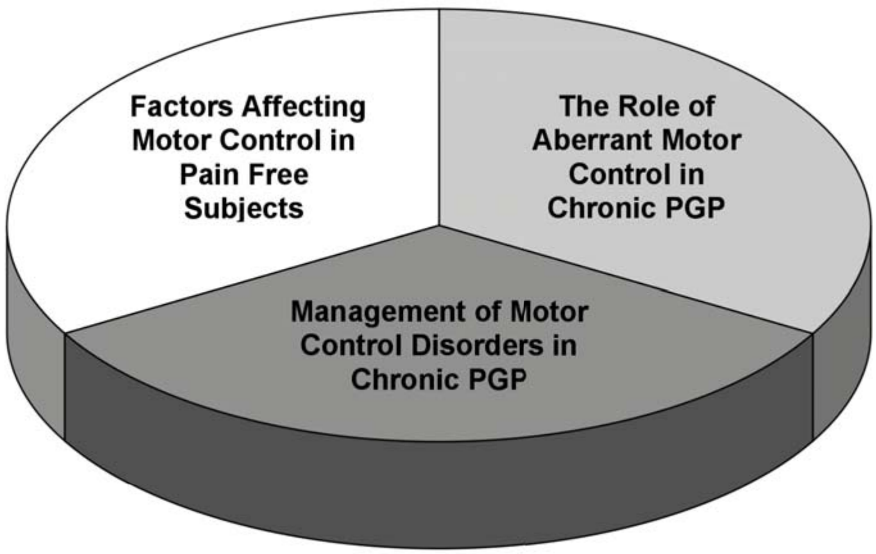


Figure 8.1 A conceptual framework for the broader implication of the studies comprising this thesis. Although they are separate entities, they are symbiotic in nature. (PGP = pelvic girdle pain)

8.1 Research questions revisited

8.1.1 Study 1: What motor control patterns do pain free subjects exhibit during an active straight leg raise?

Background: The ASLR test is a low load activity used to assess load transference through the pelvis (Mens, Vleeming, Snijders, Stam, & Ginai, 1999), and provides insight into motor control strategies adopted by PGP subjects (O'Sullivan, Beales et al., 2002). Pain free pregnant subjects demonstrate symmetrical activation of obliquus externus abdominis (EO) during an ASLR (de Groot, Pool-Goudzwaard, Spoor, & Snijders, 2008), but no studies have investigated motor activation strategies in non-pregnant pain free subjects during an ASLR, nor have any studies investigated activation of trunk muscles other than EO during an ASLR. Of particular interest are the lower fibres of obliquus internus abdominis (IO) which have been acknowledged as important muscles in the provision of pelvic stability (Snijders, Ribbers, de Bakker, Stoeckart, & Stam, 1998; Snijders et al., 1995) given that their direct attachment to the pelvis provides a mechanical advantage to contribute to force closure by compressing the sacroiliac joints. Furthermore, diagonal muscular slings in the anterior and posterior trunk have been described (Mooney, Pozos, Vleeming, Gulick, & Swenski, 2001; Pool-Goudzwaard, Vleeming, Stoeckart, Snijders, & Mens, 1998; Vleeming, Pool-Goudzwaard, Stoeckart, van Wingerden, & Snijders, 1995). It has been proposed that the central nervous system activates these slings to increase force closure (Snijders, Vleeming, & Stoeckart, 1993a, 1993b). No studies have investigated if these slings are activated during an ASLR in pain free subjects.

Findings: In Study 1 a consistent pattern of motor activation was identified during an ASLR in nulliparous pain free subjects, highlighted by greater activation of IO and EO on the side of the leg lift (Figure 8.2). This effect was most pronounced in IO (Figure 3.2). The predominant pattern of right chest wall (CW) activation observed was characterised by tonic recruitment when performing an ipsilateral ASLR, but phasic activation when performing a contralateral ASLR (Figure 3.4 and Figure 8.2). Activation of the anterior scaleni (Sc) was phasic with respiration lifting either leg. While there was a commonality to these patterns across subjects, individual variations in motor control patterns were identified (Figure 3.4). This motor control strategy was associated with a minor increase in IAP in relation to lifting the leg (Figure 8.2), without disruption of IAP or intra-thoracic pressure (ITP) fluctuation related to respiration.

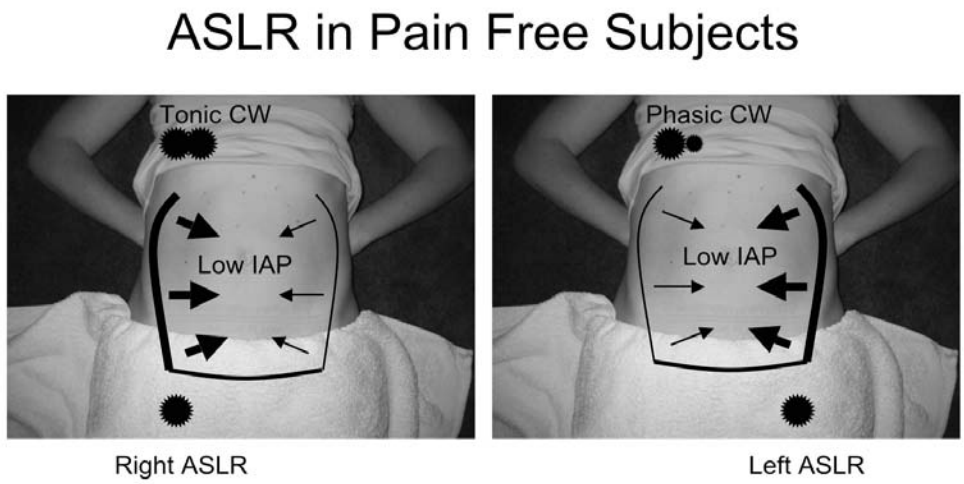


Figure 8.2 Diagrammatic representation of the motor control patterns observed during an active straight leg raise (ASLR) in pain free individuals. The abdominal wall demonstrates greater activation levels on the side of the ASLR, particularly in the obliquus internus abdominis. The right chest wall (CW) shows tonic activation during a right ASLR consistent with a stability role, but phasic activity during a left ASLR consistent with a respiratory role. There is only a small increase in intra-abdominal pressure (IAP) in response to lifting the leg.

<u>Contribution of findings to the literature</u>: The gap in the literature regarding trunk muscle activation during an ASLR in pain free individuals was directly addressed in Study 1. Higher levels of abdominal and CW motor activation on the side ipsilateral to the ASLR were consistent with a discrete activation pattern for an ASLR. This asymmetrical motor pattern differs from the symmetrical pattern of equal side to side activation of the EO observed in pain free pregnant females (between 12 and 40 weeks of pregnancy) during an ASLR (de Groot et al., 2008). This indicates that

motor patterns during an ASLR change during pregnancy in pain free individuals. It is unknown what implications, if any, this change may have in the development of PGP. Furthermore, the finding of greater unilateral activation on the side of the ASLR does not clearly support the model of diagonal anterior slings during this task. The diagonal slings model (Mooney et al., 2001; Pool-Goudzwaard et al., 1998; Vleeming et al., 1995) during the ASLR task would predict greater activation of IO ipsilateral to the ASLR concurrently with greater EO activation on the contralateral side. While a diagonal pattern has been documented during walking and resisted trunk rotation (Mooney et al., 2001), the existence of a diagonal anterior trunk activation pattern during an ASLR is not supported (de Groot et al., 2008) and Study 1). This finding is consistent with task specificity in motor control patterns (see Section 8.2.1 Recognition of multiple factors effecting motor control). Additionally, motor activation was greatest in IO ipsilateral to the ASLR (Figure 3.2). This finding is consistent with previous in-vivo electromyography (EMG) studies in pain free subjects demonstrating a significant contribution from the lower fibres of IO in the provision of force closure in various standing positions (Snijders et al., 1998) and during sitting (Snijders et al., 1995). Individual variations in motor control patterns observed during an ASLR in pain free subjects are consistent with the concept of a neurosignature (discussed in more detail in Section 8.2.2 Recognition of individual motor control patterns: the neurosignature).

Respiratory fluctuations in IAP were similar to those previously reported during quiet breathing (Hodges & Gandevia, 2000b). There was only a slight increase in baseline IAP in response to the ASLR (Figure 3.5). This is consistent with a small increase in IAP observed during isometric lifting tasks, which was associated with motor patterns where the abdominal muscles attended to stability and the chest wall helped maintain respiration (S. M. McGill, Sharratt, & Seguin, 1995). Pain free subjects do not need to generate high levels of IAP to perform an ASLR and can do so without disruption to respiration.

8.1.2 Study 2: How do motor control patterns during an active straight leg raise differ in chronic pelvic girdle pain?

Background: Following on from the documentation of motor control patterns in pain free subjects, motor control patterns during an ASLR were investigated in chronic PGP subjects. These subjects had a very specific diagnosis where; (i) the sacroiliac joint (SIJ) was identified as a peripheral source of symptoms, and (ii) heaviness (+/- pain) during an ASLR was relieved when the ASLR was performed with the addition of manual pelvic compression through the ilia. Aberrant motor control patterns during an ASLR involving depression of the pelvic floor (PF) and altered respiratory patterns with diaphragmatic splinting have previously been identified (O'Sullivan, Beales et al., 2002). It was theorised that these patterns were associated with bracing of the abdominal wall muscles in an attempt by the central nervous system to compensate for impaired load transference through the pelvis (O'Sullivan, Beales et al., 2002). No study has documented muscle activation patterns in non-pregnant chronic PGP subjects during the ASLR test. Increased activation level of the EO muscles has been described during an ASLR in pregnant PGP subjects (de Groot et al., 2008). However, given that motor control patterns during an ASLR differ in pregnant pain free subjects (de Groot et al., 2008 and Study 1), it is not known if this finding is applicable to non-pregnant subjects with chronic PGP. Furthermore, it was theorised that diaphragm splinting and PF descent may be associated with increased levels of IAP (O'Sullivan, Beales et al., 2002), and that increased IAP may be a mechanism contributing to chronic PGP (Mens, Hoek van Dijke, Pool-Goudzwaard, van der Hulst, & Stam, 2006; O'Sullivan, Beales et al., 2002). No studies to date have measured IAP in chronic PGP subjects during an ASLR.

Findings: Subjects with chronic PGP demonstrated symmetrical bilateral activation of IO and EO during an ASLR on the symptomatic side of the body, consistent with a bracing/splinting motor strategy in the abdominal wall (Figure 8.3 and Figure 4.3). Bracing of the CW during an ASLR on the symptomatic side was also observed in most subjects (Figure 8.3), though individual variation was apparent with visual inspection of the motor patterns (Figure 4.5). The activation of Sc was variably tonic or phasic in nature, with individuals demonstrating consistency in this pattern between lifting the leg on either the symptomatic or asymptomatic side. Respiratory fluctuation of IAP and ITP did not differ performing the ASLR on the symptomatic versus the asymptomatic side. There was however an increased baseline shift of IAP when performing an ASLR on the symptomatic side, consistent with the bracing motor strategy observed during this task. This was also associated with a concurrent increase in PF descent (Figure 8.3).

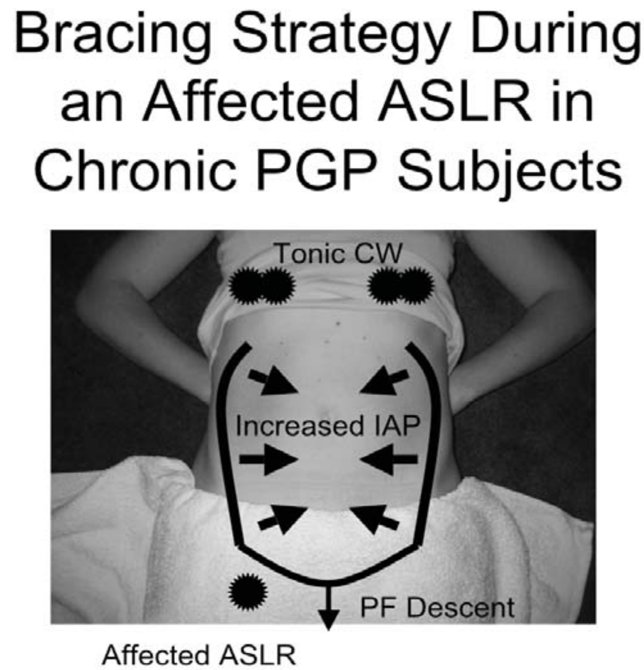


Figure 8.3 Diagrammatic representation of an active straight leg raise (ASLR) performed by a subject with chronic pelvic girdle pain (PGP) on the affected side of the body. There is a bracing contraction of the abdominal wall and chest wall (CW), with concurrent increase in intra-abdominal pressure (IAP) and depression of the pelvic floor (PF).

<u>Contribution of findings to the literature</u>: The documentation of bracing/splinting motor patterns through the abdominal wall and CW in non-pregnant chronic PGP subjects confirms muscle activation patterns previously theorised in these subjects during an ASLR on the symptomatic side of the body (O'Sullivan, Beales et al., 2002). This finding is consistent with the observation of increased bilateral activation of EO in pregnant PGP subjects (de Groot et al., 2008). Additionally,

tonic (ie bracing) CW activation during an ASLR on the symptomatic side is consistent with diaphragmatic splinting observed with ultrasound during an affected ASLR in a similar group of subjects (O'Sullivan, Beales et al., 2002). Bracing strategies have been suggested as an optimum strategy to increase spinal stability (Vera-Garcia, Brown, Gray, & McGill, 2006; Vera-Garcia, Elvira, Brown, & McGill, 2007). However, bracing patterns observed in PGP subjects may reflect a sub-optimal motor control strategy for the provision of force closure (O'Sullivan, Beales et al., 2002; C. A. Richardson et al., 2002), and have the potential to be a mechanism contributing to pain and disability in these subjects (see Section 8.3 The role of aberrant motor control in chronic pelvic girdle pain).

The increased tendency for tonic activation of the Sc in the PGP subjects compared to the phasic respiratory activation that was observed in the pain free subjects in Study 1 demonstrates that changes in motor control strategies in chronic PGP subjects can be widespread. This may reflect a general increase in muscle tone in these subjects, or tonic activation of accessory breathing muscles might be a component of the diaphragm and abdominal wall bracing strategy in some subjects. The development of concurrent cervicothoracic symptoms, which clinical observations denote as a common co-morbidity in subjects with chronic lumbopelvic pain, could in part be related to changes in motor activation around the cervicothoracic region such as that noted in the Sc in these subjects. This premise requires further investigation. Individual variations in motor activation patterns observed during an ASLR in chronic PGP subjects support the concept of an individual neurosignature for motor behaviour (see Section 8.2.2).

The results from this study confirm the presence of increased levels of IAP in response to performing an ASLR on the symptomatic side of the body, that had previously only been theorised (Mens, Hoek van Dijke et al., 2006; O'Sullivan, Beales et al., 2002). To our knowledge this is the first study to record IAP in chronic PGP subjects. While numerous studies have investigated IAP in pain free subjects, very few have measured IAP responses in lumbopelvic pain subjects. One study has shown increased levels of IAP in chronic non-specific low back pain subjects compared to pain free subjects during weight lifting (Fairbank, O'Brien, & Davis, 1980). Alternately though, another study reported no difference in IAP during lifting between chronic low back pain subjects and pain free subjects (Hemborg & Moritz, 1985). Increased IAP in PGP subjects, as observed in this study, has the potential to contribute to the drive of pain and disability in these subjects (see Section 8.3) (Mens, Hoek van Dijke et al., 2006; O'Sullivan, Beales et al., 2002).

Greater depression of the PF observed during ASLR on the symptomatic side was consistent with an earlier study of chronic SIJ pain subjects (O'Sullivan, Beales et al., 2002), and differs from pain free subjects who have less PF movement during an ASLR (O'Sullivan, Beales et al., 2002) and Study 1). This PF depression may have resulted from an inability of PF musculature to resist downward force created by increased baseline IAP (Figure 8.3). Depression of the PF during an ASLR, or with an attempt to voluntarily elevate the PF, has been associated with reports of continence dysfunction (O'Sullivan & Beales, 2007a (Appendix 4); O'Sullivan, Beales et al., 2002; Thompson & O'Sullivan, 2003). Importantly though, the presence of PF depression does not automatically mean that continence will be compromised. Likewise, not all women with continence disorders have depression of the PF during a voluntary PF contraction (Thompson & O'Sullivan, 2003). Five subjects (42%) in this study did not report continence issues despite demonstrating PF depression during an affected ASLR. This figure is consistent with a previous report of PF dysfunction disorders in 52% of women with pregnancy related lumbopelvic pain (Pool-Goudzwaard et al., 2005). This suggests that multiple factors may be associated with the control of continence.

Unaltered respiratory fluctuation of IAP and ITP in this group of PGP subjects, and no change in respiratory rate lifting one leg versus the other, suggests respiration was not disrupted during the ASLR on the affected side of the body. Visual inspection of the respiratory traces confirms that 10 of the 12 subjects had normal respiratory patterns, with the other two demonstrating breath holds not observed when performing an ASLR on the asymptomatic side. In contrast we previously found altered breathing patterns in a similar group of subjects (O'Sullivan, Beales et al., 2002). One explanation for this might be that the subjects in Study 2 had moderate levels of pain and disability, compared to more severe levels of pain and disability in the subjects in the previous study (O'Sullivan & Beales, 2007a (Appendix 3)). Another possibility is that subjects were breathing through a mouthpiece for this series of studies, rather than using a facemask as previously (O'Sullivan, Beales et al., 2002), and this may have influenced breathing patterns (Hirsch & Bishop, 1982). Additionally, the power of the present study may be insufficient to detect changes in respiration.

8.1.3 Study 3: How do pain free subjects adapt to increased physical load during an active straight leg raise?

Background: The findings from pain free subjects in Study 1 were consistent with the ASLR providing a low level physical demand on the neuromuscular system. The motor control patterns observed in PGP subjects during an ASLR suggest that these subjects use a high load strategy for what is usually a low load task (de Groot et al., 2008; O'Sullivan, Beales et al., 2002) and Study 2). No prior studies have directly investigated this premise.

Findings: The response of the neuromuscular system to increased leg load during an ASLR (ASLR+PL) was a general increase in muscle activation through the trunk, increased baseline shift of IAP, descent of the PF in response to lifting the leg, and greater downward pressure of the non-lifted leg (Figure 5.1, Figure 5.2 and Figure 8.4). All these findings are consistent with the notion that adding 6% of body weight around the ankle changed the ASLR from a low load to a high load task (Figure 8.4). In spite of a general increase in abdominal wall muscle activity, the asymmetrical pattern of greater IO activity ipsilateral to the side of the leg lift observed during an ASLR was preserved during the ASLR+PL (Figure 5.1 and Figure 8.4).

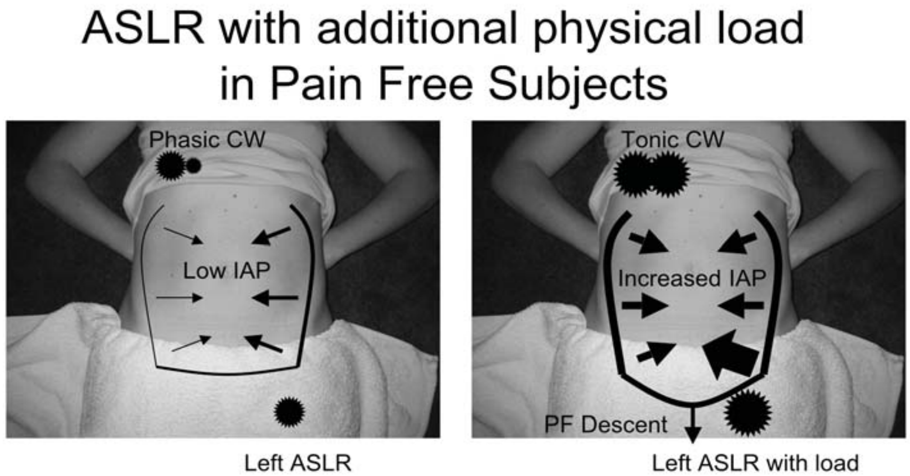


Figure 8.4 Adding physical load to the active straight leg raise (ASLR) resulted in increased motor recruitment. While the abdominal wall showed an overall increase in activation, relatively higher levels of obliquus internus abdominis (IO) activation was maintained on the side of the leg lift versus the contralateral IO (indicated by larger arrow during left ASLR with load). Chest wall (CW) activation showed an overall increase, and a shift from phasic respiratory activity to a tonic stability role. Increased muscle recruitment corresponded to increased intra-abdominal pressure (IAP) and increased descent of the pelvic floor (PF).

<u>Contribution of findings to the literature</u>: Following on from Study 1 and Study 2, in this study we documented a change in neuromuscular strategy utilised by pain free subjects progressing from an unloaded to a loaded ASLR, which has not been previously reported in the literature. The motor control patterns during an ASLR+PL represent an amplified response of that observed during the ASLR. This finding demonstrates that load is an important variable influencing motor control strategies during a specific task (see Section 8.2.1 Recognition of multiple factors effecting motor control).

A key purpose of this study was to compare the motor control strategies observed in pain free subjects during a ASLR+PL with those of chronic PGP subjects during an ASLR on the symptomatic side of the body (Study 2). Increased yet asymmetrical IO activation during a ASLR+PL in pain free subjects contrasts to the increased but symmetrical activation of IO exhibited by chronic PGP subjects (Study 2). Increased motor activity was associated with increased baseline IAP, a trait also observed during an ASLR on the symptomatic side in PGP subjects (Study 2).

Pain free subjects exhibit downward PF movement in response to the leg lift during a ASLR+PL, similar to that observed in PGP subjects in Study 2 and our previous work (O'Sullivan, Beales et al., 2002). This suggests that PF depression may be a response to elevated levels of IAP, in either pain free or PGP subjects. This is consistent with a positive relationship between higher levels of IAP and PF depression during a Valsalva maneuver in both continent and incontinent females (Thompson, O'Sullivan, Briffa, & Neumann, 2006). Further research is required to enlighten the links between PGP, PF descent and PF motor activation levels during an ASLR, and how they might relate to continence control dysfunction.

The subjects in this study also demonstrated a previously unreported increase in respiratory related movement of the PF during the ASLR+PL, a pattern not observed in the pain subjects during an affected ASLR in Study 2. Respiratory modulation of PF motor activation has been reported (Hodges, Sapsford, & Pengel, 2007), but any relationship this may have to respiratory motion of the PF during a ASLR+PL requires further investigation. The finding of increased downward pressure of the leg not being lifted by pain free subjects during the ASLR+PL was not a strategy utilised by the chronic PGP pain subjects in Study 2. Perhaps chronic PGP disorders affect central nervous system processing and motor planning such that there is a reduction in the strategies available for performance of the ASLR. This premise requires further investigation, perhaps with the utilisation of functional brain imaging.

The findings from this study suggest that while PGP subjects tend to use a high load strategy to perform an ASLR on the symptomatic side of the body, there are inherent differences between that pattern and how pain free subjects perform a ASLR+PL. This differentiates PGP subjects from pain free subjects, and supports the notion that PGP subjects have aberrant motor control patterns during an ASLR.

8.1.4 Study 4: How do pain free subjects co-ordinate an active straight leg raise when under a concurrent respiratory load?

Background: Altered respiratory patterns and diaphragmatic splinting have been reported during an ASLR in chronic PGP subjects (O'Sullivan, Beales et al., 2002). While simultaneous control of respiration and lumbopelvic stability has been widely investigated, it has not been investigated during an ASLR. Improved understanding of how pain free subjects co-ordinate respiratory and stability demands during an ASLR is necessary to gain insight into the changes observed previously in PGP subjects.

Findings: Motor control patterns in pain free subjects were compared between resting supine (RS), ASLR, breathing with inspiratory resistance (IR) and during an ASLR with simultaneous inspiratory resistance (ASLR+IR). The IO and EO muscles and the right CW all showed an incremental increase in motor activation during ASLR+IR, compared to performing these tasks in isolation (Figure 6.1, Figure 6.3 and Figure 8.5). The pattern of greater IO activation ipsilateral to the side of the leg lift during an ASLR was preserved during ASLR+IR (Figure 8.5). Baseline IAP also was greater during ASLR+IR compared to ASLR alone (Figure 6.5 and Figure 8.5). In contrast increased rectus abdominis (RA) activation was influenced more by the ASLR than IR. The Sc muscles and the right CW both demonstrated phasic respiratory activation in response to tasks involving IR. This corresponded to greater respiratory fluctuation of ITP during these tasks (Figure 6.6). A similar trend was noted in IAP respiratory fluctuation. While a commonality in the motor patterns was identified with statistical analyses, visual inspection highlighted individual variation in some aspects of the motor control patterns. For example, some subjects had either inspiratory or expiratory activation of the abdominal wall during IR inclusive tasks (Figure 6.2).

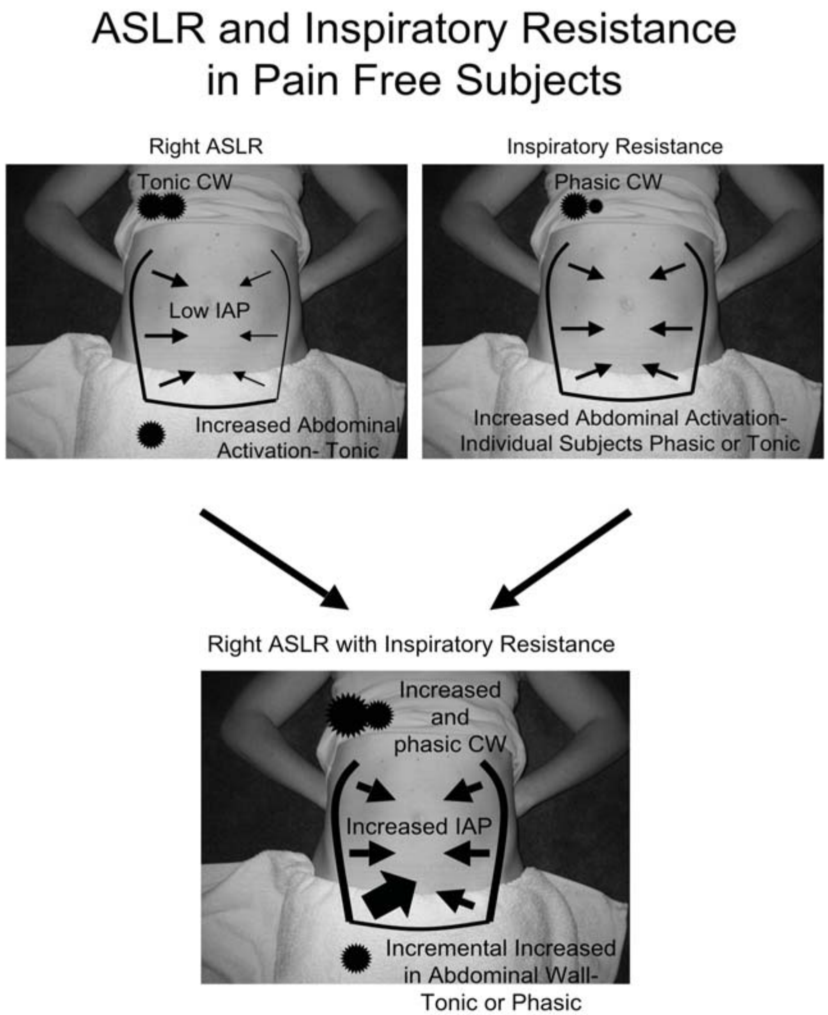


Figure 8.5 Common characteristics of inspiratory resistance (IR) with an active straight leg raise (ASLR). Abdominal wall activation increased during both activities, with an incremental increase when they were performed together suggesting a summation of muscle recruitment. The obliquus internus abdominis had a greater level of activation on the side of the leg lift during both ASLR tasks. Individual differences occurred with respect to tonic or phasic abdominal wall activation during IR inclusive tasks. In contrast all subjects showed phasic chest wall (CW) activation during IR inclusive tasks. Like the abdominal wall, a summation of CW activation occurred when the ASLR and IR were combined. Increase muscle activation with the combined task corresponded to greater baseline shift in intra-abdominal pressure (IAP).

Contribution of findings to the literature: This study documents the neuromuscular control of ASLR+IR in pain free subjects, which has not been previously reported in the literature. The findings illustrate the complex nature of the capacity of the neuromuscular systems to adapt to simultaneous stability and respiratory tasks. The incremental increase in motor activation of IO, EO and the right CW from RS to both ASLR and IR performed in isolation, with a further increase during ASLR+IR, suggests a form of summation in motor recruitment. Consistent with this was the finding of greater baseline shift of IAP performing an ASLR+IR. Thus during an ASLR+IR in pain free subjects, the central nervous system is able to adapt to these simultaneous demands by employing motor control patterns that attend to both stability and respiratory challenges. This is consistent with the finding of discrete motor units for respiratory and stability functions (Hodges & Gandevia, 2000a; Puckree, Cerny, & Bishop, 1998).

Individual variations in motor control patterns were noted, consistent with the concept of individual neurosignatures during these tasks (see Section 8.2.2). Individual variation in this study was consistent with other studies that have reported individual variation in neuromuscular responses to simultaneous stability and respiratory demands (Abraham et al., 2002; Grenier & McGill, 2008; Hodges & Gandevia, 2000b; S. M. McGill et al., 1995; Wang & McGill, 2008) (see Study 4, Section 6.7 Discussion). A wide variety of motor patterns have been described throughout these studies, and observed during the different tasks in this study, supporting the concept of task specificity in motor control patterns (see Section 8.2.1).

8.1.5 Study 5: What effect does manual pelvic compression have on motor control strategies in pelvic girdle pain subjects during an active straight leg raise?

Background: This study directly relates to the finding of altered motor control patterns in chronic PGP subjects during an ASLR from Study 2. Pelvic compression is used in PGP subjects for symptomatic relief (Mens, Damen, Snijders, & Stam, 2006; Mens et al., 1999; Ostgaard, Zetherstrom, Roos-Hansson, & Svanberg, 1994), and has been shown to normalise aberrant motor control strategies observed during the ASLR test (O'Sullivan, Beales et al., 2002). In some subjects though compression may negatively influence or provoke symptoms (Laslett, Aprill, McDonald, & Young, 2005; Mens et al., 1999; Ostgaard et al., 1994). This dichotomy requires further investigation. One study has reported reduced activation of IO and RA (but no effect on EO) with the addition of pelvic compression in erect standing in pain free subjects (Snijders et al., 1998). No study to date has document motor responses in PGP subjects when pelvic compression is added to a positive ASLR test (ASLR+Comp), nor the influence of compression on motor activity in PGP subjects during any other tasks.

Findings: Despite all subjects in this study reporting subjective improvement with ASLR+Comp, there was no consistent pattern of response to this compression based on statistical analyses of the data. However, visual comparison of the motor control patterns performing an ASLR with and without compression revealed two divergent strategies. For some individuals manual compression was associated with reduced trunk muscle activity (Figure 7.1), while in others compression was associated with an increase in trunk muscle activity (Figure 7.2). Baseline IAP shifted up or down in a corresponding manner to the level of motor activity (Figure 7.3). This was supported by supplementary post-hoc examination of the data (see Section 7.8).

Contribution of findings to the literature: To our knowledge, this is the first study of chronic PGP subjects to document in-vivo measurements of trunk muscle activity and IAP during an ASLR+Comp. The hypothesis that chronic PGP subjects would demonstrate a reduction in global muscle activation and a reduction in IAP when performing an ASLR+Comp compared to an unaided ASLR was not supported by the results of this study. Instead divergent strategies of either motor inhibition or facilitation were identified. One previous study has shown an inhibitory effect of compression via a pelvic belt on IO and RA in standing pain free subjects (Snijders et al., 1998). In contrast, another study using a complex biomechanical model predicted facilitation of IO and EO with pelvic compression in standing (Pel, Spoor, Goossens, & Pool-Goudzwaard, 2008). Neither of these studies however anticipated the divergent responses to ASLR+Comp on the symptomatic side of the body observed in Study 5. This finding may represent differences in the underlying mechanisms of the disorder in these subjects (see Section 8.3).

Despite subjective improvement in the ability to perform an ASLR+Comp, the motor patterns exhibited by PGP subjects during this task did not replicate the pattern observed in pain free subjects during an ASLR in Study 1 (see Figure 7.1b and 7.2b compared to Figure 3.2). Thus while providing symptomatic relief, compression did not normalise the motor control pattern in PGP subjects, and alternately may actually reinforce aberrant motor control strategies in a sub-group of subjects. This could explain the clinical observations that some subjects who gain relief initially from a pelvic belt find them less effective with more extended use, while in other cases patients become dependent on the belt and feel worse on removing it. The results of this study support the position of "The European Guidelines for the Diagnosis and Treatment of Pelvic Girdle Pain" that recommends pelvic belts be trialed for symptomatic relief, and if successful only be used for short periods of time (Vleeming, Albert, Ostgaard, Sturesson, & Stuge, 2008). The findings of this study also reinforce the need for active management strategies that promote normalisation of aberrant motor control strategies adopted by chronic PGP subjects (O'Sullivan & Beales, 2007a; Stuge, Veierod, Laerum, & Vollestad, 2004; Vleeming et al., 2008).

8.2 Factors affecting motor control in pain free subjects

8.2.1 Recognition of multiple factors affecting motor control

The literature investigating lumbopelvic motor control, and how it is altered in pain disorders, exposes wide variations in responses (for a review see van Dieen, Selen, & Cholewicki, 2003). As an example, the pattern of greater unilateral abdominal wall activation ipsilateral to the ASLR observed in Study 1 contrasts to the bilateral abdominal wall activation during the same task in the study performed by de Groot and colleagues (2008). Why do two studies examining the same task produce conflicting results? Closer examination reveals one study used pain free nulliparous subjects (Study 1), while the subjects in the other were females between 12 and 40 weeks of pregnancy (de Groot et al., 2008). These two subject groups could portray differences on many levels, such as different body compositions, different muscle length tension relationships and mechanical advantage, different hormonal levels, and perhaps even different psychological factors. Another example is the individual variation in patterns described in pain free subjects performing an ASLR+IR (Study 4). Factors such as cardiovascular fitness levels or inspiratory muscle strength could have influenced individual patterns between subjects. These observations underscore the complexity of central nervous system strategies of motor control in the provision of lumbopelvic stability. The findings from this thesis highlight the need to recognise that many factors have the potential to influence motor control and that a homogenous approach to management may prove to be limiting. Figure 8.6 identifies factors that can potentially influence motor control strategies, either individually or in unison. Some of these factors and how they are related to the findings of the studies performed in pain free subjects for this thesis follow:

<u>The nature of the task</u>

It is intuitive that different tasks require different motor control strategies (Cholewicki & VanVliet, 2002; Cresswell, Grundstrom, & Thorstensson, 1992; Cresswell & Thorstensson, 1989; Grillner, Nilsson, & Thorstensson, 1978; Harman, Frykman, Clagett, & Kraemer, 1988; Kavcic, Grenier, & McGill, 2004; Oddsson & Thorstensson, 1990; Urquhart, Hodges, Allen, &

Story, 2005). The most recent major review of trunk muscle activation patterns concluded that the differences in motor control strategies described in different studies are a result of task dependency (van Dieen et al., 2003). This is reflected in how the pain free individuals in these studies altered their motor control strategies between performing an ASLR, an ASLR+PL, and an ASLR+IR (Studies 1, 3 and 4). Interestingly, despite individual differences, some motor control characteristics were preserved across these three ASLR related tasks. Most noticeable of these was greater activation of IO on the side ipsilateral to the leg being lifted. The consistency of this pattern of IO activation suggests that in pain free subjects there is some common central

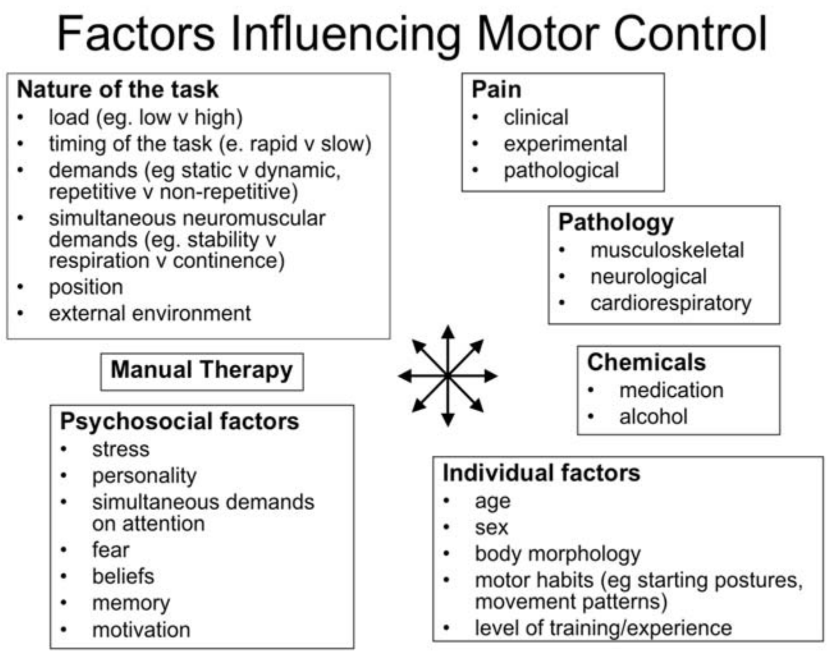


Figure 8.6 Multiple factors may influence motor control related to the lumbopelvic region. Nature of the task, psychosocial factors, individual factors, experimental pain and biochemistry may influence motor control patterns in healthy subjects. These factors, as well as clinical pain, pathology and manual therapy can alter motor control in pain disorders.

nervous system strategy to performing the ASLR that is influenced by simultaneous demands, such as weight on the leg or respiratory loading.

It is well known that increasing physical load will affect motor control. Increasing the load on the leg during an ASLR amplified motor activation and increased baseline IAP (Study 3). This is consistent with studies that have investigated muscle activation levels and IAP during lifting, where increased load also results in increased motor activation and increased IAP (Hagins, Pietrek, Sheikhzadeh, Nordin, & Axen, 2004; Harman et al., 1988; Hemborg & Moritz, 1985; Hemborg, Moritz, Hamberg, Lowing, & Akesson, 1983). Likewise, the effect of simultaneous respiratory and lumbopelvic stability demands on motor control strategies has been demonstrated. The pain free subjects in Study 4 demonstrated an ability to adapt to an ASLR+IR by employing a motor strategy that attended to both of these tasks. On an individual basis though, there was variation in how this incremental increase in trunk muscle activity took form, which could be a result of individual factors (Figure 8.6). This highlights the complex neuromuscular control strategies employed during simultaneous respiratory and physical demands, which can be seen in other studies that have investigated the relationship of stability and respiratory control (Abraham et al., 2002; Aliverti et al., 1997; Aliverti et al., 2002; Grenier & McGill, 2008; Hagins & Lamberg, 2006; Hagins, Pietrek, Sheikhzadeh, & Nordin, 2006; Hodges, Gandevia, & Richardson, 1997; Hodges, Heijnen, & Gandevia, 2001; S. M. McGill et al., 1995; Rimmer, Ford, & Whitelaw, 1995) (see Section 6.7 Discussion).

<u>Individual factors</u>

Individual factors such as age (Hwang, Lee, Park, & Kwon, 2008; Pool-Goudzwaard et al., 2005) and level of experience/practice/training (Chapman, Vicenzino, Blanch, & Hodges, 2008) may all directly affect motor control. Age might have been a confounding factor, though there is not a large variability in the age of the pain free subjects in this thesis (see Section 8.5 Limitations). The ASLR is a simple task that did not require specific training, so level of experience or practice was not likely to be a factor. Also, the order of the individual tasks during testing was standardised to minimise any minor learning effect, and to counter any effect from fatigue.

Lumbopelvic posture is known to affect motor control parameters such as muscle activation levels (Dankaerts, O'Sullivan, Burnett, & Straker, 2006; O'Sullivan et al., 2006; O'Sullivan, Grahamslaw et al., 2002; Sapsford, Richardson, Maher, & Hodges, 2008; Sapsford, Richardson, & Stanton, 2006). The modulation of motor activity secondary to posture is likely to have a carry over effect on movement tasks initiated from that postural position. Interestingly, the influence of posture is powerful enough to influence supposed pre-programmed responses to rapid arm movement in standing (O'Sullivan et al., 2001). While all the testing for this thesis was performed in supine, individual lumbopelvic posture was not monitored nor standardised. Any influence this might have had on motor control patterns is not known.

<u>Psychosocial factors</u>

Stress, personality characteristics and mental processing requirements during lifting tasks may directly alter spinal loading in pain free subjects (Chany, Parakkat, Yang, Burr, & Marras, 2006; Davis, Marras, Heaney, Waters, & Gupta, 2002; Marras, Davis, Heaney, Maronitis, & Allread, 2000), and are likely to simultaneously affect pelvic loading given the shared anatomy of these regions. These factors were not monitored in the pain free subjects in this series of studies.

In summary, the findings of this thesis support the formation of a model that recognises the multitude of factors that can alter motor control strategies (Figure 8.6). Recently a model for the computational neuroanatomy of motor control has been proposed (Shadmehr & Krakauer, 2008). In brief, this model is based on the assumption that prior to the performance of a motor task the central nervous system determines the expected cost and reward of that motor task. In the performance of a motor task, the central nervous system predicts the sensory outcome of the motor task (*system identification*), combines predictions with sensory feedback (*state estimation*) and acts on this information to optimise motor performance (*optimal* *control*). The factors that can potentially influence motor control strategies employed by the central nervous system (Figure 8.6) may have a direct impact on system identification and state estimation. In terms of system identification for example, in Study 3 although speculative, load added to the ASLR could influence central nervous system prediction of the way the ASLR+PL should be performed. Or in terms of state estimation, sensory recognition of increased IAP during the ASLR+IR could be utilised to modify/adjust motor output during this task. Hence, the model presented here for factors that may influence motor control (Figure 8.6) supplements contemporary understanding of central nervous system planning and performance of motor tasks.

8.2.2 Recognition of individual motor control patterns: the neurosignature

Statistical analysis of the data collected for Studies 1-4 identified commonality in motor patterns adopted by the subjects. However, a limitation of statistical analyses investigating mean differences between groups is the potential to wash out individual variation. Visual inspection of the motor control patterns from all the studies in this thesis identified individual variation within gross patterns. Individual variations in motor control patterns are commonly reported in the related literature (Abraham et al., 2002; Grenier & McGill, 2008; Hodges & Gandevia, 2000b; Marshall & Murphy, 2003; S. M. McGill et al., 1995; O'Sullivan, Beales et al., 2002; Wang & McGill, 2008).

It is possible that individual variations represent unique motor control footprints. This assumption aligns itself well to the concept of a *neurosignature* (Melzack, 1999, 2001, 2005). Melzack describes the *neuromatrix* as an "anatomical substrate of the body-self" (Melzack, 2005, pg 86). The neuromatrix constitutes widespread networks of neurons. The make up of the neuromatrix is genetically determined, but molded by experience. The neurosignature is an imprint of the output from the neuromatrix: "The repeated cyclical processing and synthesis of nerve impulses through the neuromatrix imparts a characteristic pattern: the neurosignature" (Melzack, 2005, pg 86). The concepts of the neuromatrix and neurosignature compliment the recent proposal of a computational neuroanatomy for motor control, where the neurosignature would reflect a footprint of *optimal control* (Shadmehr & Krakauer, 2008) (see above Section 8.2.1 for a fuller description of this model). The individual motor control patterns observed in this series of studies may well represent the unique neurosignature of the individual performing the tasks, a reflection of that individual's optimal control. The consistency of the motor activation patterns demonstrated by the repeatability data supports this notion. Studies utilising functional magnetic resonance imaging of the brain would be useful to gain insight into this theory, by potentially mapping the neurosignature for ASLR related tasks.

8.3 The role of aberrant motor control in chronic pelvic girdle pain

The trunk motor control patterns observed in chronic PGP subjects for this thesis expand prior knowledge of aberrant motor control patterns in these subjects (Section 8.1). The central characteristics of this pattern during an ASLR on the symptomatic side of the body are increased bilateral trunk motor activation in the form of a bracing/splinting contraction, with increased baseline IAP and depression of the PF (Study 2). This pattern is aberrant in as much as it differs from motor control patterns adopted by pain free subjects during either an ASLR or an ASLR+PL (Studies 1 and 3). It has been shown that the finding of aberrant motor patterns is consistent with other studies that have identified changes in motor control in subjects with chronic PGP (de Groot et al., 2008; O'Sullivan & Beales, 2007a; O'Sullivan, Beales et al., 2002; Pool-Goudzwaard et al., 2005) (Section 8.1). Two major questions with regard to the relationship between aberrant motor control and chronic PGP are; (i) What is the origin of aberrant motor control patterns in chronic PGP subjects?, and (ii) Are aberrant motor control strategies adaptive or maladaptive? How do they relate to ongoing pain and disability in these subjects?

8.3.1 Factors contributing to aberrant motor control patterns in pelvic girdle pain in the initial phase of the disorder

The origin of aberrant motor patterns in chronic PGP is open for debate. It could be argued that the motor control patterns found in chronic PGP subjects (de Groot et al., 2008; Hungerford, Gilleard, & Hodges, 2003; O'Sullivan & Beales, 2007a; O'Sullivan, Beales et al., 2002; Pool-Goudzwaard et al., 2005 and Study 2) existed prior to the onset of symptoms, and predispose those people to pelvic pain disorders. However, the motor control patterns seen in chronic PGP subjects clearly differ from pain free subjects (de Groot et al., 2008; Hungerford et al., 2003; O'Sullivan, Beales et al., 2002; Pool-Goudzwaard et al., 2005 and Study 2). While cross sectional studies can not inform of the origin of aberrant motor control, these inherent differences between pain free subjects and PGP subjects suggests that the aberrant motor control strategies observed in chronic PGP subjects are not likely to precede the onset of the PGP disorder. Longitudinal studies are required to investigate this.

For most subjects then it is likely that changes in trunk motor control strategies occur following the onset of PGP. All of the pain subjects in this thesis had a physical presentation consistent with the SIJ as a peripheral source of symptoms; that is a primary area of symptoms over the SIJ, three out of five positive SIJ pain provocation tests and an absence of lumbar spine symptoms (normal lumbar range of motion and negative lumbar spine pain provocation tests) (see Section 1.3). For 10 of the 12 subjects, the onset of their disorder was related to either a traumatic incident or late pregnancy (Table 4.3). A traumatic incident could have resulted in sensitisation to SIJ and/or surrounding ligamentous and myofascial structures, creating a peripheral nociceptive drive for pain. Some cases of pregnancy related PGP might be related to trauma during the birthing process. One subject in this thesis reported this type of onset. Another had a fall during pregnancy that amplified earlier pelvic discomfort. In these cases a traumatic incident during pregnancy may have resulted in tissue strain and sensitisation in a similar manner to non-pregnancy related traumatic onset of PGP. Non-traumatic causes of PGP during pregnancy are less obvious. There may well be a physical component to the development of symptoms in these subjects. Asymmetrical SIJ laxity in pregnancy (Damen et al., 2001) and changes in posture and movement patterns during pregnancy (W. Gilleard, Crosbie, & Smith, 2008; W. L. Gilleard, Crosbie, & Smith, 2002), coupled with hormonal effects that appear to be associated with changes in collagen synthesis (Kristiansson, Svardsudd, & von Schoultz, 1999), may all point to altered pelvic loading and the potential for repetitive strain leading to the development of symptoms. However, it is important to note that these physical factors taken in isolation do not consistently correlate with pain and disability levels. For example, postural changes in standing during pregnancy do not correlate with the development of PGP symptoms during pregnancy (Franklin & Conner-Kerr, 1998), nor does a general increase in SIJ laxity (Damen et al., 2001). This suggests that the mechanisms resulting in the development of pregnancy related PGP are multifactorial, with complex interactions between these factors likely (O'Sullivan & Beales, 2007b) (Figure 1.12).

In the early stage following the onset of symptoms, the central nervous system may employ motor control strategies that serve to protect the sensitised area and facilitate recovery (Figure 8.7). Central nervous system strategies of motor control will be influenced by numerous factors (Section 8.2). For most people symptoms resolve, but it is unknown if motor control strategies normalise with symptom resolution. It is known that muscle function does not necessarily normalise after the resolution of first episode low back pain, leading to increased recurrent episodes of symptoms (Hides, Jull, & Richardson, 2001; Hides, Richardson, & Jull, 1996). Further research is required to investigate for this occurrence in PGP subjects.

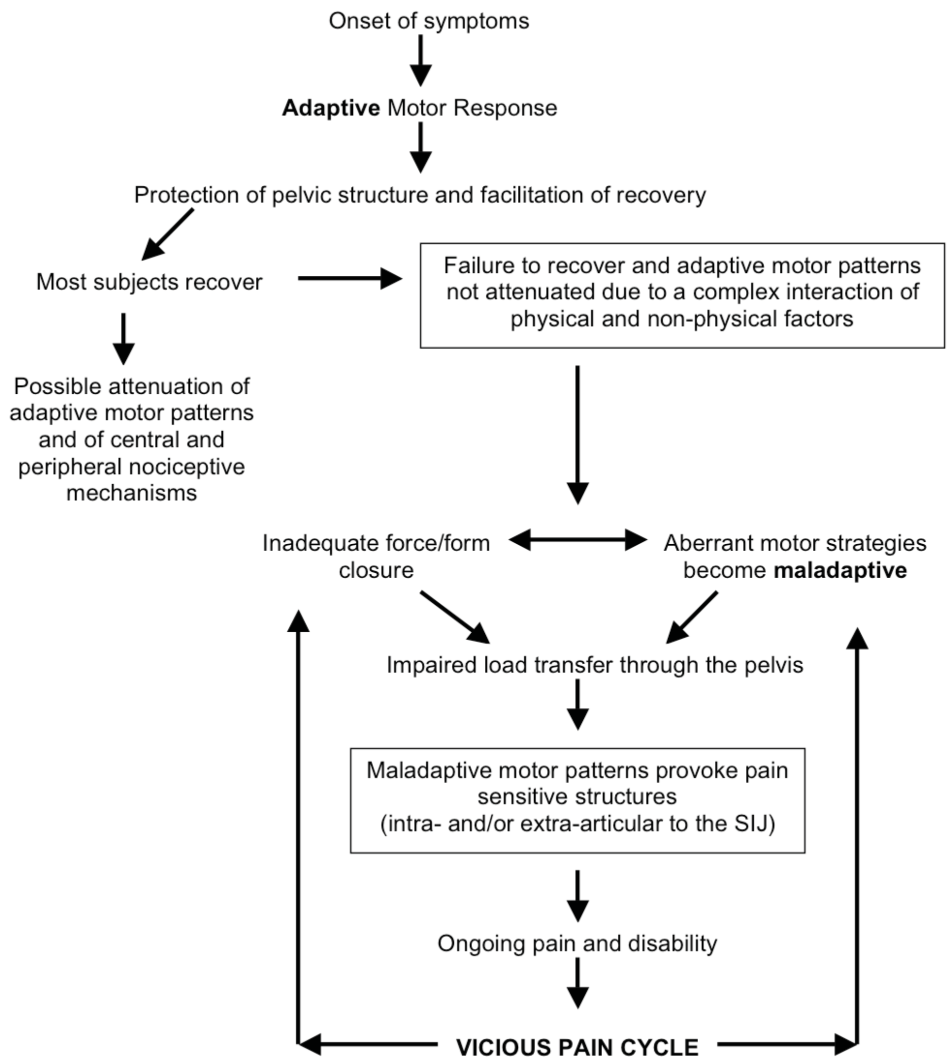


Figure 8.7 A vicious pain cycle model for chronic pelvic girdle pain subjects with the sacroiliac joint identified as a painful structure and a positive active straight leg raise test where compression reduces heaviness of the leg and pain (reduced force closure). Initially there is a motor response to injury that is adaptive in nature, to protect the subject from further injury and facilitate healing. While for the majority of subjects the disorder resolves at this stage, some develop motor control strategies that are maladaptive, provoking symptoms and contributing to ongoing vicious cycle of pain and disability.

8.3.2 Factors that may contribute to aberrant motor control patterns in the chronic stage of pelvic girdle pain

For roughly 10% of PGP subjects, symptoms persist beyond the early onset of symptoms, leading to chronic pain and disability (Albert, Godskesen, & Westergaard, 2001; Petersen et al., 2004; Rost, Jacqueline, Kaiser, Verhagen, & Koes, 2006; Schwarzer, Aprill, & Bogduk, 1995; Wu et al., 2004). As outlined in Section 1.4 The multifactorial nature of chronic pelvic girdle pain, many factors may contribute to the maintenance of these disorders (Figure 1.12). These factors may also have directly influenced patterns of motor control (Figure 8.6) observed in chronic PGP in Studies 2 and 4.

Pain

It is well known that either experimental or clinical pain can alter central nervous system motor programming, affecting lumbopelvic motor control patterns (for reviews see (Hodges & Moseley, 2003; van Dieen et al., 2003). Pain itself could be the central factor driving motor control changes observed during the ASLR in the chronic PGP subjects. However, the primary symptom during an ASLR for these subjects is heaviness of the leg, not necessarily pain. This implies that there is not a simple cause and effect relationship between the motor patterns described in Study 2 and pain. Neither individual pain levels nor use of pain relieving medication were specifically assessed during the testing procedure, although there were no reports of significant pain during testing. Either of these factors may have influenced motor control patterns observed in PGP subjects, and perhaps contributed to some of the individual variations observed during Study 2 and Study 5. It should be noted though that the primary complaint during an ASLR is heaviness of the leg rather than pain, suggesting pain levels are not solely responsible for the observations made in chronic PGP subjects. It is likely that these findings are part of the vicious pain cycle (Figure 8.7).

Neurophysiological changes

Central nervous system changes in response to pain, such as plastic changes associated with central sensitisation (Woolf, 2004) or glial cell activation

(Hansson, 2006), can drive pain, disability and changes in motor control. However, there were not dominant clinical features of neuropathic changes in the pain subjects, ruling out the likelihood that central neurophysiological changes were solely driving the motor control changes.

Psychosocial factors

While psychosocial factors have been recognised as an important potential mechanism in the development and maintenance of chronic PGP disorders (Bastiaenen et al., 2008; Bastiaenen et al., 2004; Bastiaenen et al., 2006; Gutke, Josefsson, & Oberg, 2007; O'Sullivan & Beales, 2007b, 2007c; Van De Pol, Van Brummen, Bruinse, Heintz, & Van Der Vaart, 2007), they may also directly influence motor control patterns (Chany et al., 2006; Davis et al., 2002; Marras et al., 2000). While fear avoidance levels measured by the Tampa Scale for Kinesiophobia were within normal limits for PGP subjects during an ASLR on the symptomatic side of the body (Study 2), other psychological factors like depression, anxiety, stress levels and faulty beliefs could have potentially influenced the motor control patterns observed in chronic PGP subjects. Further, it has recently been proposed that sustained associatively learned memory for pain influences movement patterning (Zusman, 2008). Further research examining the direct influence of psychosocial influences on motor control, and thus pelvic loading, will provide valuable knowledge in this area.

All the chronic PGP subjects in this thesis presented in a manner consistent with a peripherally mediated pain disorder, as their pain was intermittent in nature and clearly provoked and relieved with specific movements and postures. It could be argued that the motor control changes observed in these subjects during an ASLR test could be an adaptive or maladaptive central nervous system response to this pain disorder.

8.3.3 Aberrant motor control patterns in chronic pelvic girdle pain as an adaptive behaviour

Adaptive motor control behaviour has been defined as the outward expression of a central nervous system strategy attempting to protect pain sensitive structures (O'Sullivan, 2005). It has been suggested that all motor changes in the trunk muscles of lumbopelvic pain subjects are adaptive in nature (van Dieen et al., 2003). Alternately, it has been proposed that only specific sub-groups of lumbopelvic pain subjects display characteristics of adaptive motor behaviours (O'Sullivan, 2005).

Pool-Goudzwaard et al (2005) investigated PF function in two sub-groups of chronic PPG subjects. One sub-group had difficulty performing an ASLR, the other did not. The effect of adding pelvic compression was not reported. While PF activity was increased in both of these sub-groups compared to healthy controls, the authors suggested that this was part of a successful strategy (ie. adaptive behaviour) to stabilise the pelvis for load transference in subjects who did not have difficulty performing an ASLR (Pool-Goudzwaard et al., 2005). It was proposed however that consequences of this adaptive behaviour were a higher incidence of urgency, stress incontinence and sexual dysfunction in this sub-group. In contrast, it was theorised that those who had difficulty performing an ASLR employed motor strategies that were not successful in improving load transference through the pelvis (Pool-Goudzwaard et al., 2005), namely bracing strategies with diaphragmatic splinting as previously described (O'Sullivan, Beales et al., 2002).

Similarly, it could be argued that the aberrant motor control strategies observed in the chronic PGP subjects in Study 2 during an ASLR on the symptomatic side of the body are adaptive. The neuromuscular system may adopt a bracing strategy to enhance spinal stability (Grenier & McGill, 2008; Kavcic et al., 2004; Vera-Garcia et al., 2006; Vera-Garcia et al., 2007). Pain subjects may adopt bracing/splint strategies in an effort to improved load transference during the ASLR (and functional tasks), with the pay-off being changes to respiration or continence control is some sub-groups of subjects (O'Sullivan, Beales et al., 2002), or increased IAP (Study 2).

8.3.3 Aberrant motor control patterns in chronic pelvic girdle pain as a maladaptive behaviour

Where adaptive motor control behaviour is protective in nature, it has been proposed that *maladaptive* motor behaviours are provocative of the pain disorder (O'Sullivan, 2005). In terms of the chronic PGP subjects in this thesis, symptom provocation from aberrant motor control patterns might occur via direct mechanical provocation of pain sensitised structures resulting in a peripheral nociceptive drive for pain, mediated by; (i) increased activation of the abdominal muscles involved in the bracing/splinting strategies, by virtue of their direct attachment to the pelvis or via fascial connections, excessively loading and potentially mechanically provoking sensitised structures, (ii) increased levels of IAP that are associated with bracing motor strategies directly contributing to increased mechanical load on pain sensitised structures (Mens, Hoek van Dijke et al., 2006), and (iii) sub-optimal/reduced force closure, inherent to bracing motor strategies (C. A. Richardson et al., 2002), leaving pain sensitive pelvic structures vulnerable to mechanical stressors during load transference tasks (ASLR, functional tasks). Via these processes aberrant motor control patterns may also directly and/or indirectly contribute to ongoing microtrauma of sensitised pelvic structures. Microtrauma could; (i) maintain nociceptive sensitivity in local pelvic structures, and (ii) disrupt proprioceptive function in the affected peripheral structures (Sjolander, Johansson, & Djupsjobacka, 2002; Solomonow, 2006) that may potentially have a negative influence on motor programming in the central nervous system.

This model of direct involvement of aberrant motor control strategies in the peripheral mediation of chronic PGP is consistent with other descriptions in the literature (Mens, Vleeming, Stoeckart, Stam, & Snijders, 1996; O'Sullivan & Beales, 2007a; O'Sullivan, Beales et al., 2002; Snijders et al., 1993a, 1993b; Vleeming et al., 1996; Vleeming, Volkers, Snijders, & Stoeckart, 1990). In this manner, aberrant motor control patterns could potentially contribute to a vicious pain cycle (Figure 8.7), and as such be maladaptive in nature.

There are a number of lines of reasoning that support the proposal that aberrant motor control patterns in this sub-group of chronic PGP represent maladaptive behaviour. The findings that; (i) the addition of compression during an ASLR reduces symptoms (O'Sullivan, Beales et al., 2002 and Study 5), (ii) bracing strategies through the abdominal wall are sub-optimal for enhancing pelvic stability/force closure (C. A. Richardson et al., 2002), and (iii) interventions normalising aberrant motor control strategies relieve pain and disability (O'Sullivan & Beales, 2007a; Stuge, Laerum, Kirkesola, & Vollestad, 2004; Stuge, Veierod et al., 2004) while those reinforcing aberrant motor control strategies are ineffective for reducing pain and disability (Mens, Snijders, & Stam, 2000). All these findings support the concept that the aberrant motor control strategies observed with the positive ASLR may be maladaptive in nature.

8.4 Management of motor control disorders in chronic pelvic girdle pain

This thesis has not investigated intervention in chronic PGP. However, the findings enhance understanding of the motor control strategies in PGP subjects and therefore provide insights for the potential management of chronic PGP disorders.

Recognition of individual variation in motor control during intervention: The "European guidelines for the diagnosis and treatment of pelvic girdle pain" recommend "an individualized treatment program, focusing specifically on stabilizing exercises for control and stability" for PGP (Vleeming et al., 2008, pg 813). Such a program should be focused upon the underlying mechanisms driving the disorder, within a biopsychosocial framework (O'Sullivan & Beales, 2007b, 2007c). The findings of individual variation in motor control patterns in this thesis, and the probability of different underlying mechanisms driving the disorder (O'Sullivan & Beales, 2007b, 2007c; O'Sullivan, Beales et al., 2002; Pool-Goudzwaard et al., 2005 and Study 5), highlights the need for motor control intervention to be based on individual presentations.

Management that normalises aberrant motor patterns: For chronic PGP subjects with a presentation consistent with reduced force closure (positive SIJ pain provocation tests and a positive ASLR test relieved with the addition of pelvic compression), there is evidence that a motor learning intervention that addresses aberrant motor control patterns observed during the ASLR test can be part of an effective management strategy (O'Sullivan & Beales, 2007a; Stuge, Laerum et al., 2004; Stuge, Veierod et al., 2004). There is some initial evidence that aberrant motor control patterns observed during the ASLR in chronic PGP can be reversed with this type of approach (O'Sullivan & Beales, 2007a). Consistent with this, the ASLR heaviness score has also been shown to improve with this type of intervention (Stuge, Laerum et al., 2004). In those studies, improved motor control patterns and an improved ASLR test were associated with improvements in pain and disability (O'Sullivan & Beales, 2007a; Stuge, Laerum et al., 2004). It is possible that normalisation of aberrant motor control patterns reduced pain and disability by decreasing excessive load/stress on pain sensitised structures, leading to reprogramming of the neuromatrix (Kelly, Foxe, & Garavan, 2006). However, not all subjects responded to this approach (Stuge, Morkved, Haug Dahl, & Vollestad, 2006). This could reflect differences in the underlying mechanism driving the disorder (O'Sullivan, Beales et al., 2002; Pool-Goudzwaard et al., 2005 and Study 5), again highlighting the need for an approach that identifies and classifies patients according to the underlying mechanisms, which will facilitate targeted interventions (O'Sullivan & Beales, 2007b, 2007c). Further research is required to clarify the existence of other sub-groups, such as subjects with a primary peripheral nociceptive drive that is related to excessive force closure (O'Sullivan & Beales, 2007b, 2007c; Pool-Goudzwaard et al., 2005). Once the existence of other specific sub-groups has been clarified, further research to test the efficacy of specific treatment programs for those sub-groups can be tested.

Management that reinforces aberrant motor patterns: Treatment that appears to reinforce bracing motor activation strategies via exercise aimed at the trunk muscles is ineffective in the management of pregnancy related PGP, and may actually provoke symptoms (Mens et al., 2000). It was suggested that this type of exercise might adversely load passive structures (Mens et al., 2000). The main rationale for the approach used in the Mens et al (2000) study was to enhance function of the diagonal muscular slings (Mooney et al., 2001; Pool-Goudzwaard et al., 1998; Vleeming et al., 1995). As outline above (Section 8.1.1) though, the activation of diagonal slings was not supported by investigation of the ASLR in pain free subjects (Study 1). Diagonal muscular activation patterns are more likely a reflection of task specificity in motor control patterns rather than a singular central nervous system strategy to provide force closure at all/any times. This underscores the need for consideration of task specificity of motor control when designing intervention programs. Additionally, exercise prescription in the Mens et al (2000) study was carried out via videotape. So another limitation of that study was that the intervention was not matched to specific presentations of individual subjects.

Recognition of task specificity of motor control patterns in motor learning interventions: A common feature of contemporary approaches to motor learning interventions is an assumption that one motor control strategy serves the body across all functional tasks. This motor strategy is then trained across tasks (S. McGill, 2002; C.A. Richardson, Jull, Hodges, & Hides, 1999). The findings from this thesis highlight that the central nervous system uses different motor control strategies dependent upon multiple factors, not least of which is task. Attempting to train one strategy for all tasks and all individuals could represent one factor that reduces the effectiveness of these types of approaches (Macedo, Maher, Latimer, & McAuley, 2009), and limiting their efficacy in some subjects with chronic PGP (Mens et al., 2000; Stuge et al., 2006). The development of intervention strategies that recognise the inherent complexity of the motor control patterns observed in both pain free and chronic lumbopelvic subjects, that acknowledges the individual variations seen in these motor control patterns (Section 8.2.2), and appreciates the multitude of factors that may influence motor control strategies (Section 8.2.1) may be required to advance the management of chronic PGP disorders. Approaches which are more functionally based (O'Sullivan, 2005; O'Sullivan & Beales, 2007b, 2007c), rather than muscle based (S. McGill, 2002; C.A. Richardson et al., 1999), may better address these issues. Another distinct advantage of a functional approach may be that the cognitive demands on the subject are more closely in line with central nervous system adaptations in motor learning (Kelly et al., 2006).

8.5 Limitations

A number of limitations must be recognised with the studies presented:

<u>Specificity of findings to the active straight leg raise test</u>

Given the complexities of neuromuscular control of the lumbopelvic region (inherent in Figure 8.6), care must be taken in extrapolating the results of these experiments to tasks other than the ASLR. However, despite the capacity for many factors to influence the motor control patterns observed in these studies, from a clinical perspective, subjects with chronic pain disorders where maladaptive motor control strategies appear to be a dominant feature of the disorder have a propensity to adopt stereotypical motor strategies across various tasks (O'Sullivan, 2005; O'Sullivan & Beales, 2007b, 2007c). Thus while not directly applicable to functional tasks, motor control patterns during the ASLR may provide insight into an overall motor control profile for any individual. Further research is needed to validate this concept.

<u>Sample size</u>

The invasive nature of the test procedures, and the very specific diagnostic criteria, limited the number of subjects that could be recruited for these studies. This was primarily an issue for Study 5 where two divergent motor control strategies were identified in PGP subjects performing an ASLR with the addition of manual pelvic compression. For most of the variables in the other studies the power was sufficient for statistical inferences to be made. One exception to this was recording from only the right chest wall in the pain subjects. Only the right CW was recorded in all subjects as it was thought recording from the left CW would be excessively contaminated by electrocardiography. Half the PGP subjects had left sided symptoms versus half having right sided symptoms. Thus the right chest wall was the affected chest wall for six subject, and non-affected for the other six, a number we considered too small for meaningful statistical comparison. Bilateral recordings of the chest wall would be useful in future studies if the electrocardiography can be successfully removed from the EMG data.

The sample size did mean that adjustment for confounding factors such as age, physical fitness levels and parity could not be examined. The age range for the pain free subjects was 22-44 years and for the PGP subjects 28-65 years. Thus age may have been a confounding factor, more so in the PGP subject group. While all the pain free subjects were nulliparous, 7 of the 12 pain subjects had children, which could potentially have been a confounding factor also. Fitness levels of the subjects were not ascertained.

Fine-wire versus surface electromyography

Surface EMG was chosen for these studies because:

- it is less invasive than fine-wire EMG
- motor patterns that might be detectable by clinicians were our primary interest.

The use of surface EMG could possibly oversimplify the motor control patterns found in these studies as the muscles observed are known to have different motor units for respiratory and stability tasks, which may act concurrently (Hodges & Gandevia, 2000a; Puckree et al., 1998). In contrast, the use of fine-wire EMG would have recorded from a limited number of motor units, and as such could have failed to fully reflect the overall muscle recruitment pattern. Fine-wire EMG would offer the benefit of recording muscle activity from deep muscles, like transversus abdominis and the costal diaphragm, which would contribute to the production of IAP. However synergies between transversus abdominis and the lower fibres of IO (Hungerford et al., 2003) and the CW and the costal diaphragm (Rodarte & Shardonofsky, 2000) mean that activity of these muscles is still likely to be represented in our data.

Use of ultrasound to measure pelvic floor movement

Real time ultrasound provides a non-invasive, reliable tool for the measurement of PF movement (O'Sullivan, Beales et al., 2002; Sherburn, Murphy, Carroll, Allen, & Galea, 2005; Thompson, O'Sullivan, Briffa, Neumann, & Court, 2005). However, there is some question over the validity of this approach as movement measured trans-abdominally may represent a combination of bladder movement and movement of the abdominal wall against the probe. This may be problematic where the determination of the exact magnitude of PF movement is critical. However, trans-abdominal measurements of PF motion correlates well with trans-perineal ultrasound measurements (Thompson et al., 2005), and both of these dimensions reflect adaptation of the abdominal pressure cylinder related to changes in IAP and muscle activation. We considered trans-abdominal RTUS an appropriate indicator of PF movement in the context of these studies.

Influence of psychosocial factors on motor patterns

Fear of movement was not a dominant factor for the pain subjects in these studies as the Tampa Scale for Kinesiophobia scores were within a reasonable range (Table 4.3). However, psychosocial factors other than kinesiophobia might have contributed to the observed motor control patterns in these subjects. Broader screening of psychosocial factors, such as anxiety, stress, depression and beliefs would be advantageous in future studies.

Test procedure

The test procedure is outlined in Appendix 5: Methodological Issues, Section G: Test procedure. The order of testing was standardised to allow for a consistent effect of fatigue. Never the less, fatigue may be a confounding factor for test preformed during the later stages of this procedure. The effect of fatigue on motor control patterns is worthy of further investigation.

8.6 Recommendations for future research

A number of areas for further research have been suggested already within this thesis. Priorities for further research include:

- investigation of motor control patterns in PGP subjects during functional tasks, and how this might be influenced by the level of disability that these subjects present with as well as the influence of fatigue and changes in motor control during sustained activities
- further investigation of PF muscle function and dysfunction in chronic PGP

- investigation of how PGP subjects cope with respiratory loading during an ASLR
- further investigation into the effect of pelvic compression on aberrant motor control strategies
- further evidence for the model of a multifactorial mechanism based classification system (O'Sullivan & Beales, 2007b, 2007c)
- documentation of motor control patterns in other sub-groups of chronic PGP subjects, such as those with excessive force closure as opposed to the classification of reduced force closure which the subjects in this study represented (O'Sullivan & Beales, 2007b, 2007c)
- intervention studies targeting specific sub-groups of PGP subjects with specific intervention strategies targeting both the mechanisms driving the disorder and specific motor control deficits as applicable
- the ASLR might be a suitable task for use in brain imagining studies

8.9 References: Discussion

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Chapter 9: Summary and Conclusion

The series of studies presented in this thesis are the first to document motor activation patterns and intra-abdominal pressure (IAP) during an active straight leg raise (ASLR), in either pain free or chronic pelvic girdle pain (PGP) subjects. The PGP subjects are from a very specific group of subjects where the sacroiliac joint and surrounding structures were symptomatic with a positive ASLR test, consistent with a classification of reduced force closure. The specific conclusions from these studies are:

Study 1: Motor control patterns during an active straight leg raise in pain free subjects.

This study refutes the theory of activation of the anterior diagonal slings for the provision of pelvic stability/force closure during an ASLR in pain free subjects. Instead a pattern of greater anterior trunk muscle activation ipsilateral to the side of the leg lift was identified. The findings of this study highlight the flexibility of the neuromuscular system in controlling load transference during an ASLR, and the plastic nature of the abdominal cylinder.

Study 2: Motor control patterns during an active straight leg raise in chronic pelvic girdle pain subjects.

This is the first study to document bilateral bracing trunk muscle activation strategies with increased levels of IAP during an ASLR in chronic PGP subjects. Increased levels of IAP could have negative consequences and be provocative to the disorder, supporting the notion that aberrant motor activation patterns exist in this group of subjects.

Study 3: The effect of increased physical load during an active straight leg raise in pain free subjects.

During a loaded ASLR pain free subjects maintain a pattern of greater muscle activation ipsilateral to the ASLR despite an overall increase in motor activation. In contrast, while chronic PGP subjects tend to use a high load strategy to perform an ASLR on the symptomatic side of the body, they have bilateral muscle activation. This supports the notion that PGP subjects have aberrant motor control patterns during an ASLR.

Study 4: The effect of resisted inspiration during an active straight leg raise in pain free subjects.

Pain free subjects are able to adapt to the multiple demands of an ASLR and inspiratory resistance by an incremental increase/accumulative summation of the patterns utilised when these tasks are performed independently. This is achieved while still maintaining relatively greater motor activation ipsilateral to the ASLR during the combined task.

Study 5: Non-uniform motor control changes with manually applied pelvic compression during an active straight leg raise in chronic pelvic girdle pain subjects.

Trends for either trunk muscle facilitation or inhibition with the addition of manual pelvic compression to an ASLR on the affected side of the body suggest that there may be differences in the underlying mechanism of these subjects and variable responses to pelvic compression.

While commonalities in motor patterns were seen during these experiments with statistical analyses of the data, individual differences in the motor control strategies were found with visual inspection of the data in both pain free and chronic PGP subjects.

These findings show that pain free subjects adopt a predominant pattern of greater motor activation ipsilateral to the side of the leg lift during an ASLR, an ASLR with additional physical load, and an ASLR with simultaneous inspiratory resistance. In contrast, chronic PGP subjects adopt bilateral bracing/splinting motor control patterns with increased IAP. These aberrant motor control strategies in chronic PGP subjects have the potential to be maladaptive, driving ongoing pain and disability, with negative consequences on pelvic loading and stability, respiration, continence and pain.

In addition the findings of this thesis demonstrate the complexity of the underlying mechanisms driving chronic pelvic girdle pain disorders, and highlight that multiple factors have the potential to influence motor control strategies in these subjects. It must be noted though that at this stage the findings from the chronic PGP subjects are very specific to that group. Also they are specific to the ASLR task. Care must be taken extrapolating these results to other symptomatic subject groups and to other tasks. Further research investigating motor control strategies during functional tasks and in different sub-groups of PGP subjects is required.

Overall, this thesis has added substantially to the knowledge of motor control in chronic PGP disorders, a research area in its infancy compared to the investigation of motor control in the lumbar and cervical regions of the spine. Now that PGP has been recognised as a separate diagnostic entity to LBP, greater understanding of this region is essential for the identification of sub-groups within the diagnosis of PGP, and for the development of specific intervention strategies that target the underlying pain mechanisms driving these disorders.

Appendices

Appendix 1: Diagnosis and classification of pelvic girdle pain disorders- Part 1: A mechanism based approach within a biopsychosocial framework

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Diagnosis and classification of pelvic girdle pain disorders—Part 1: A mechanism based approach within a biopsychosocial framework

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Abstract

The diagnosis and classification of pelvic girdle pain (PGP) disorders remains controversial despite a proliferation of research into this field. The majority of PGP disorders have no identified pathoanatomical basis leaving a management vacuum. Diagnostic and treatment paradigms for PGP disorders exist although many of these approaches have limited validity and are uni-dimensional (i.e. biomechanical) in nature. Furthermore single approaches for the management of PGP fail to benefit all. This highlights the possibility that 'non-specific' PGP disorders are represented by a number of sub-groups with different underlying pain mechanisms rather than a single entity.

This paper examines the current knowledge and challenges some of the common beliefs regarding the sacroiliac joints and pelvic function. A hypothetical 'mechanism based' classification system for PGP, based within a biopsychosocial framework is proposed. This has developed from a synthesis of the current evidence combined with the clinical observations of the authors. It recognises the presence of both specific and non-specific musculoskeletal PGP disorders. It acknowledges the complex and multifactorial nature of chronic PGP disorders and the potential of both the peripheral and central nervous system to promote and modulate pain. It is proposed that there is a large group of predominantly peripherally mediated PGP disorders which are associated with either 'reduced' or 'excessive' force closure of the pelvis, resulting in abnormal stresses on pain sensitive pelvic structures. It acknowledges that the interaction of psychosocial factors (such as passive coping strategies, faulty beliefs, anxiety and depression) in these pain disorders has the potential to promote pain and disability. It also acknowledges the complex interaction that hormonal factors may play in these pain disorders. This classification model is flexible and helps guide appropriate management of these disorders within a biopsychosocial framework. While the validity of this approach is emerging, further research is required.

Keywords: Pelvic girdle pain; Sacroiliac joint; Classification; Pain mechanisms; Motor control

1. Pelvic girdle pain disorders

Pelvic girdle pain (PGP) disorders represent a small but significant group of musculoskeletal pain disorders. Pain associated with the sacroiliac joints (SIJs) and/or the surrounding musculoskeletal and ligamentous structures represent a sub-group of these disorders. *Specific* inflammatory pain disorders of the SIJs, such as sacroiliitis, are the most readily identified PGP disorders (Maksymowych et al., 2005). However, PGP disorders more commonly present as '*non-specific*' (no identified pathoanatomical basis), often arising during or shortly after pregnancy (Berg et al., 1988; Ostgaard et al., 1991; Bastiaanssen et al., 2005) or following traumatic injury to the pelvis (O'Sullivan et al., 2002a; Chou et al., 2004). Frequently these pain disorders are misdiagnosed and managed as lumbar spine disorders, as pain originating from the lumbar spine commonly refers to the SIJ region. However, there is growing evidence that PGP disorders manifest as a separate sub-group with a unique clinical presentation and the need for specific management.

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A number of PGP disorders do not resolve (Ostgaard et al., 1996; Larsen et al., 1999; Albert et al., 2001; Noren et al., 2002; To and Wong, 2003), becoming chronic despite the absence of pathoanatomical abnormalities on radiological examination or signs of a systemic or inflammatory disorder from blood screening (Hansen et al., 2005). This leads to a broad diagnosis of a 'non-specific' PGP disorder and leaves a diagnostic and management vacuum. These PGP disorders are commonly associated with signs and symptoms indicating that the pain originates from the SIJs and/or their surrounding connective tissue and myo-fascial structures (Berg et al., 1988; Kristiansson and Svardsudd, 1996; Mens et al., 1999; Albert et al., 2000; Damen et al., 2001; Vleeming et al., 2002; O'Sullivan et al., 2002a; Laslett et al., 2003). However, identification of a painful structure does not provide insight into the underlying mechanism(s) that drives the pain (O'Sullivan, 2005a).

A number of theoretical models have been proposed with regard to potential underlying pain mechanisms in PGP. Chiropractic, Osteopathic and Manual Therapy models commonly propose that the SIJs can become 'fixated' or 'displaced' leading to positional faults. There are a series of complex clinical procedures proposed to identify these so-called 'positional faults' and treatment with manipulation, mobilisation and/or muscle energy techniques has been suggested to rectify them (Don-Tigny, 1990; Sandler, 1996; Kuchera, 1997; Oldreive, 1998; Cibulka, 2002). Although manual and manipulative techniques can result in short term pain modulation (Wright, 1995), there is little evidence for the long term benefits of SIJ manipulation or other passive treatments used in isolation for the management of chronic PGP disorders (Stuge et al., 2003). The selection of these techniques is often directed by treating the signs and symptoms of the disorder rather than a valid and clear diagnostic and classification paradigm based on the mechanisms that underlie the pain disorder.

More recently emphasis has been placed on enhancing motor control deficits in PGP disorders. This is based on the premise that deficits in lumbo-pelvic motor control result in impaired load transference through the pelvis and thereby contribute to a peripheral nociceptive drive of symptoms (Mens et al., 1996; Vleeming et al., 1996, 1990b; O'Sullivan et al., 2002a; O'Sullivan and Beales, 2007). There is growing evidence based on outcome studies that some PGP disorders do indeed respond well to specifically targeted motor training interventions (Stuge et al., 2004a, b; O'Sullivan and Beales, 2007). However, not all PGP disorders respond to these interventions (Stuge et al., 2006). Relevant to this inconsistency in outcome, is the existence of different patterns of motor control impairments in PGP subjects. For instance increased pelvic floor activation has been documented in subjects with peripartum PGP consistent with SIJ involvement (Pool-Goudzwaard et al., 2005), while another group of subjects with SIJ pain (with a positive active straight leg raise test (ASLR)) demonstrate impaired control of the pelvic floor (O'Sullivan et al., 2002a; O'Sullivan and Beales, 2007). These findings highlight that; (i) there may be various underlying mechanisms that drive different PGP disorders, and (ii) the need for a classification based approach which guides targeted interventions for sub-groups of subjects with PGP, which is based upon the underlying pain mechanism(s) that drives the disorder.

2. Challenging the beliefs regarding the sacroiliac joints and the pelvis

The SIJ perhaps more than any other joint complex in the body has been shrouded by an enormous amount of mystique within the field of Manual Therapy—with complex, poorly validated and often confusing theories and treatment approaches associated with it. Beliefs of the clinician (that the pelvis is 'displaced' or 'unstable') commonly become the beliefs of the patients. For many patients these clinical labels can be detrimental with the potential to render the patient passively dependent on someone to 'fix them', elevating anxiety levels, reinforcing avoidance behaviours and promoting disability. Increased passive dependence and fear/anxiety has the potential to further increase the central drive of pain, contributing to disability and the chronic pain cycle. It is therefore important to be clear on the *'facts'* regarding the SIJs and put them into the context of current knowledge. The basic anatomy, biomechanics and stability models proposed for the SIJ are documented elsewhere and as such will not be reviewed in full here (Pool-Goudzwaard et al., 1998; Lee and Vleeming, 2000; Vleeming et al., 2006).

2.1. The facts regarding the SIJs

- The SIJs are inherently stable (Vleeming et al., 1990a, b; Snijders et al., 1993a).
- The joints are designed for load transfer (Kapandji, 1982; Gray and Williams, 1989) and can safely transfer enormous compressive loading forces under normal conditions (Snijders et al., 1993a).
- The SIJ has little movement in non-weight bearing (average 2.5 degrees rotation) (Sturesson et al., 1989; Brunner et al., 1991; Jacob and Kissling, 1995; Vleeming et al., 1992a, b), and even less in weight bearing (average 0.2 degrees rotation) (Sturesson et al., 2000).
- Movement of the SIJ cannot be reliably assessed by manual palpation, particularly in weight bearing (Sturesson et al., 2000; van der Wurff et al., 2000a, b).
- Due to its anatomical makeup, intra-articular displacements within the SIJs are unlikely to occur. No

study utilising a valid measurement instrument has identified positional faults of the SIJ—in fact the converse is true (Tullberg et al., 1998).

- Distortions of the pelvis observed clinically are likely to occur secondary to changes in pelvic and trunk muscle activity, resulting in directional strain and not positional changes within the SIJs themselves (Tullberg et al., 1998).
- No study utilising a valid measurement tool has demonstrated that pelvic manipulation alters the position of the pelvic joints (Tullberg et al., 1998)—pain relief from these procedures is likely to result from nociceptive inhibition based on neuro-inhibitory factors and/or altered patterns of motor activity (Wright, 1995; Pickar, 2002).
- Asymmetrical laxity of the SIJs, as measured with Doppler imaging, has been shown to correlate with moderate to severe levels of symptoms in subjects with peripartum PGP (Damen et al., 2001). Generalised SIJ laxity is not associated with peripartum pelvic pain (Damen et al., 2001).
- When clinical signs of reduced force closure have been identified (positive ASLR), the increased movement is identified at the symphysis pubis—not the SIJs (Mens et al., 1999). It is likely that the torsional forces occurring at the SIJs can cause strain across pain sensitised tissue.
- Pain from the SIJ is located primarily over the joint (inferior sulcus) and may refer distally, but not to the low back (Fortin et al., 1994a, b; Schwarzer et al., 1995; Dreyfuss et al., 1996; Maigne et al., 1996; Slipman et al., 2000; Young et al., 2003; van der Wurff et al., 2006).
- SIJ pain disorders can be diagnosed using clinical examination (Laslett et al., 2003; Young et al., 2003; Petersen et al., 2004; Laslett et al., 2005a, b). This includes the finding of pain primarily located to the inferior sulcus of the SIJs, positive pain provocation tests for the SIJs and an absence of painful lumbar spine impairment.
- The SIJ has many muscles that act to compress and control it (force closure), thereby enhancing pelvic stability (creating stiffness) allowing for effective load transfer via the pelvis during a variety of functional tasks (Vleeming et al., 1990a, b, 1995; Snijders et al., 1993a, b; ; Snijders et al., 1998; Damen et al., 2002; Richardson et al., 2002; O'Sullivan et al., 2002a; Pool-Goudzwaard et al., 2004; van Wingerden et al., 2004; Mens et al., 2006; Snijders et al., 2006).
- PGP disorders may be associated with 'excessive' as well as 'insufficient' motor activation of the lumbopelvic and surrounding musculature (O'Sullivan et al., 2002a; Hungerford et al., 2003; Pool-Goudzwaard et al., 2005; O'Sullivan and Beales, 2007).

3. Classification of pelvic girdle pain disorders

Chronic pain disorders are complex, multifactorial and need to be considered within a biopsychosocial framework. A different cluster of potential physical, pathoanatomical, psychosocial, hormonal and neurophysiological factors is associated with each disorder (Fig. 1). Needless to say the interactions between these factors are very complex. This highlights the need for a flexible classification and management approach for each disorder.

Although the SIJs and the surrounding ligamentous and myofascial structures are potentially nociceptive structures (Fortin et al., 1994a, b; Vilensky et al., 2002), from a neurophysiologic perspective it is well known that ongoing pain can be mediated both peripherally and centrally, and the forebrain can greatly modulate this process (Zusman, 2002; Woolf, 2004). It is therefore logical that PGP disorders can potentially be both peripherally or centrally induced/maintained, with a different balance or dominance of peripheral and central factors associated with each disorder (Elvey and O'Sullivan, 2005).

Furthermore with PGP there is the potential contributing role of sex hormones. There are a number of possible pathways by which hormones may influence PGP (Fig. 2). There is some evidence that sex hormones are active in pain modulation (Aloisi and Bonifazi, 2006). Sex hormones are also known to influence the inflammatory process in inflammatory pain disorders (Schmidt et al., 2006). Furthermore sex hormones may alter collagen synthesis (Kristiansson et al., 1999), thereby effecting the load capacity of the pelvis. There is some evidence to support the role of hormones in PGP disorders, with higher serum levels of progesterone and relaxin in early pregnancy being found in subjects who develop peripartum PGP compared to those who do not (Kristiansson et al., 1999). Via these processes sex hormones have the potential to contribute to PGP in different clinical presentations (Fig. 2). Further research is required to clarify how the role of hormones may differ in these various presentations of PGP.

The proposed classification model for PGP disorders is based on the potential mechanisms that can drive the PGP. This classification approach is not exhaustive but rather provides a framework to guide the clinician. Based on the mechanism(s) that underlie these disorders and operating within a biopsychosocial framework, the classification model aims to facilitate the diagnosis, classification (Fig. 3), and targeted management of these disorders.

3.1. The clinical examination

The clinical examination is critical to the clinical reasoning process that underpins this diagnosis and

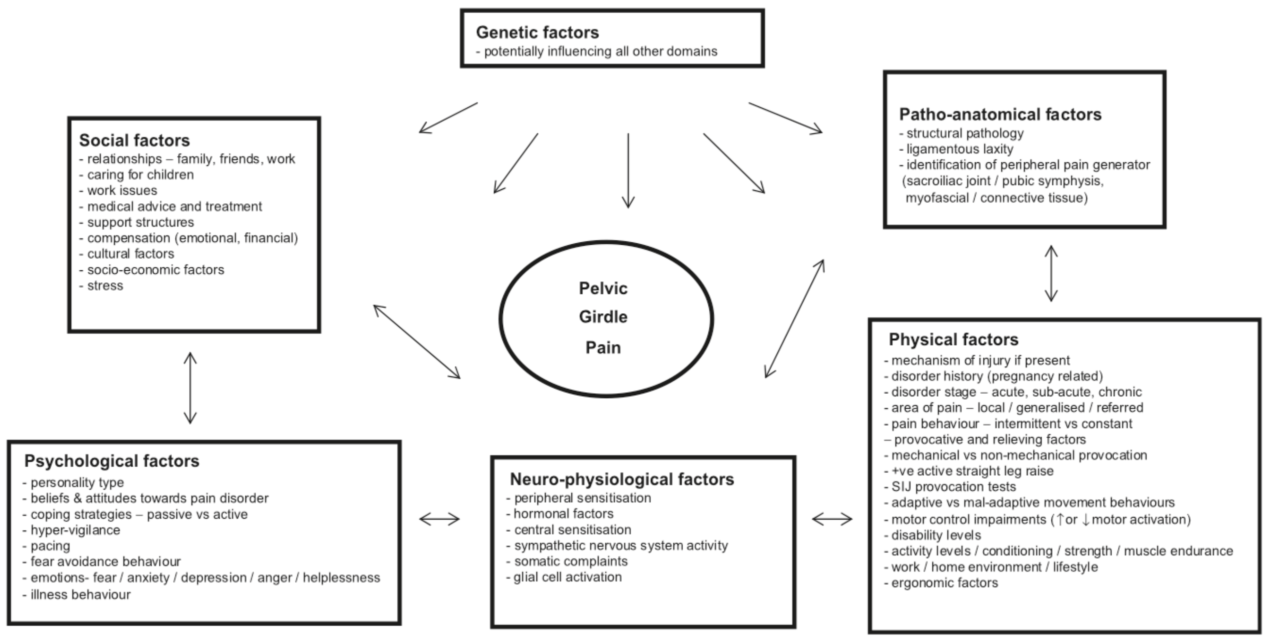

Fig. 1. Factors that need consideration within a biopsychosocial framework for the diagnosis and classification of chronic pelvic girdle pain disorders.

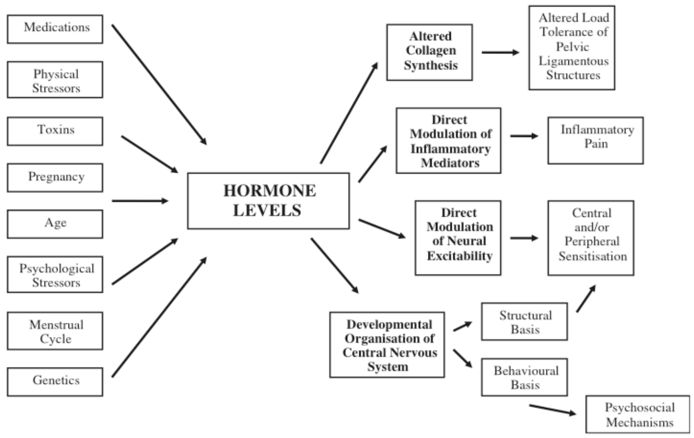

Fig. 2. Possible actions of hormones in the development and maintenance of pelvic girdle pain. Factors affecting hormone levels are also presented.

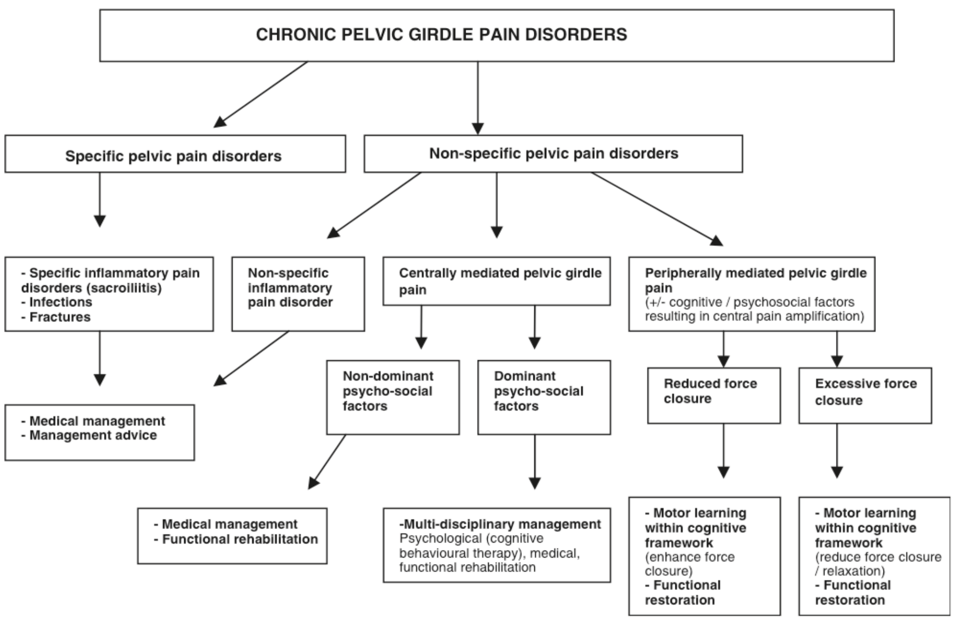

Fig. 3. Mechanism based classification and management of chronic pelvic girdle pain disorders.

classification framework. In the interview process all the following need to be considered:

- the pain area (localised versus generalised pain can indicate peripheral from central pain drive),
- pain pattern (intermittent versus constant, 24 hour pain pattern, sleep disturbances),
- pain intensity,
- pain behaviour (specific movements and postures that provoke and relieve pain),

- levels of disability and impairment,
- specific pain history (specific and surrounding events that may have contributed to the development of symptoms),
- family history of PGP,
- the patient's pain coping strategies (active versus passive coping),
- the patient's pain beliefs,
- presence of avoidant behaviours due to fear of movement and other psychosocial factors including present and past history of anxiety and depression,
- pacing patterns and
- concurrent presence of disorders of continence and/or sexual dysfunction.

Review of radiology if present and screening for specific causes of PGP may be indicated from this process. This allows for a determination as to the area and nature of the pain.

A thorough physical examination is then required to determine the pain source and behaviour in relationship to the patient's movement behaviour. Physical tests should include:

- Palpation of the inferior sulcus of the SIJ and surrounding pelvic ligamentous and myo-fascial structures.
- Provocative tests for the SIJ and surrounding ligamentous and myofascial structures (Laslett et al., 2003, 2005a, b; Young et al., 2003; Petersen et al., 2004).
- The ASLR test in supine and prone as a test of load transfer, with a positive test resulting in normalisation of ASLR with the addition of pelvic compression (Mens et al., 1999; O'Sullivan and Beales, 2007).
- Careful analysis of the pain provoking and relieving activities and postures (functional impairments) highlighted from the interview to identify the presence of impairments of movement and motor control as well as avoidance behaviours and to determine their relationship to the pain disorder. Determining whether altered motor patterns are adaptive/protective (pain is aggravated when motor control patterns are normalised) or mal-adaptive (pain is relieved when motor control deficits are normalised) is essential.
- Tests for specific muscle function for the pelvic floor, the abdominal wall, the back muscles, iliopsoas, quadratus lumborum, the gluteal muscles and piriformis.

In addition the adjacent areas of the lumbar spine (including neural tissue) and hip joints should be thoroughly investigated to rule out involvement of these areas or to assess for coexisting pathology/dysfunction in these regions.

Correlating the patient's reported pain behaviour, beliefs and levels of impairment with his/her clinical presentation (observing for avoidance behaviours, catastrophising, etc.) is important to determine whether cognitive issues such as fear of movement are present and dominant. On synthesis of this material a diagnosis and classification of the PGP disorder can be made.

4. Specific pelvic girdle pain disorders

Pelvic girdle pain disorders associated with *specific* pathological processes include inflammatory arthritis, sacroiliitis, infections and fractures. These disorders are amenable to specific diagnosis with appropriate blood screening and radiological investigation. They can be associated with altered patterns of motor control behaviour that are *'adaptive'* and/or protective of the underlying disorder. Treating the signs and symptoms of these disorders by manual therapy and/or specific exercise interventions is generally not appropriate as it does not address the underlying pain mechanism of the disorder. Physiotherapy may be limited to management of the sequelae of the underlying disease/pathological processes especially in disorders such as ankylosing spondylitis.

5. Non-specific pelvic girdle pain disorders

5.1. Non-specific inflammatory pelvic girdle pain disorders

There appears to be a group of PGP disorders that present as being inflammatory in nature, rather than mechanical. They are characterised by constant, disabling and non-remitting pain, located in the SIJs, that is provoked with weight bearing, pelvic compression (such as a SIJ belt) and with SIJ pain provocation tests. These disorders may show areas of increased uptake on bone scan but are not linked to a specific inflammatory disorder diagnosis based on blood screening. They may be relieved with rest, anti-inflammatory medications and local steroid injections to the SIJ, but are resistant to physical interventions.

Although the exact underlying mechanism for these PGP disorders is unknown it is possible that hormonal factors play a role, particularly given their common onset in the first trimester of pregnancy or pain modulation with hormonal cycles or changes. Although the role of sex hormones is purely speculative in this group of patients, further research into their effect is warranted.

5.2. Peripherally mediated (mechanically induced) pelvic girdle pain disorders

These disorders are characterised by localised pain that has a defined anatomical location (SIJ and associated connective tissue and myofascial structures +/−symphysis pubis). The pain is intermittent in nature and is provoked and relieved by specific postures and activities related to vertical or directional loading in weight bearing positions. They are not usually associated with spinal movement related pain and/or spinal movement impairment. A specific pain source at the SIJ and its surrounding structures can usually be identified by specific provocative manual tests (Laslett et al., 2003, 2005a, b; Young et al., 2003; Petersen et al., 2004). These disorders are usually associated with consistent local motor control changes (inhibition or excitation). These disorders usually have a clear mechanism or time of onset (either repeated strain or direct trauma to the pelvis or peripartum PGP). It is proposed that these

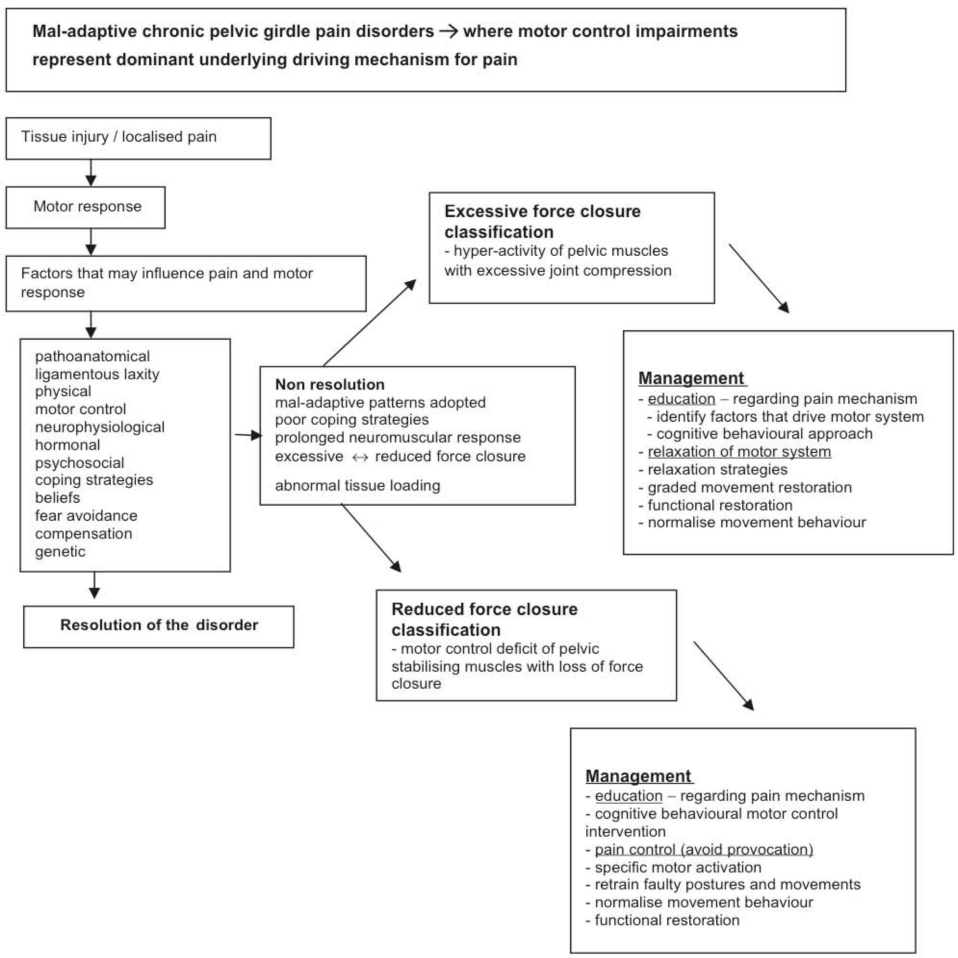

Fig. 4. Sub-classification of pelvic girdle pain disorders with a primary peripheral nociceptive drive. Peripheral drive is perpetuated by mal-adaptive motor control dysfunctions.

disorders may be classified into two clinical subgroups (Fig. 4).

5.2.1. Reduced force closure

The first group represents disorders where the peripheral pain drive is associated with excessive strain to the sensitised SIJs and/or surrounding connective tissue and myofascial structures secondary to ligamentous laxity (Damen et al., 2001), coupled with *motor control deficits* of muscles that control force closure of the SIJs (O'Sullivan et al., 2002a; Hungerford et al., 2003; O'Sullivan and Beales, 2007). These motor control deficits may have originally developed secondary to the pain disorder, but now their presence is *mal-adaptive* as the resultant 'reduced forced closure' leads to impaired load transfer through the pelvis, acting as a mechanism for ongoing strain and peripheral nociceptive drive for the pain disorder. Hormonal influences on collagen synthesis may be an important factor in this group.

These disorders are commonly associated with post-partum PGP and present with a positive ASLR test (normalised with pelvic compression) (O'Sullivan et al., 2002a; Stuge et al., 2004a). The motor control deficits that present in these disorders are variable and are linked to a loss of functional patterns of co-contraction of the local force closure muscles of the pelvis (such as the pelvic floor, the transverse abdominal wall, the lumbar multifidus, iliopsoas and the gluteal muscles). This is commonly associated with attempts to stabilise the lumbopelvic region via co-activation of other trunk muscles (quadratus lumborum, thoracic erector spinae, diaphragm, external oblique, rectus abdominis and vertical fibres of internal oblique). Their primary functional impairments are associated with pain in weight bearing postures such as sitting, standing and walking, or loaded activities inducing rotational pelvic strain associated with coupled spine/hip loading activities (i.e. cycling and rowing resulting in posterior rotational strain on ilium). These patients commonly assume postures that are associated with inhibition of the local pelvic muscles (pelvic floor, transverse abdominal wall, lumbar multifidus and the gluteal muscles) such as 'sway' standing, 'hanging off one leg', 'slump' sitting or 'thoracic upright' sitting (O'Sullivan et al., 2002b, 2006; Dankaerts et al., 2006; Sapsford et al., 2006) and present with a loss of lumbopelvic control (inability to disassociate pelvic from thoracic movement). These disorders may be relieved with a SIJ belt (Ostgaard et al., 1994; Mens et al., 2006), training optimal alignment of their spino-pelvic posture and functional enhancement of local co-contraction strategies across the pelvis with relaxation of the thoraco-pelvic musculature (O'Sullivan and Beales, 2007). These disorders may gain short term relief from mobilisation, muscle energy techniques, soft tissue massage and manipulation of the SIJs (clinical observation) although these in isolation tend not to benefit the long term outcome of the disorder. There is evidence that long lever exercise regimes may aggravate these disorders (Mens et al., 2000). These disorders can be further sub-grouped based on their pattern of motor control dysfunction. Different combinations of motor control deficits may be found within the local lumbopelvic muscles such as is observed in low back pain disorders that result in different directional (vertical, rotational) strain patterns within the pelvis (O'Sullivan, 2005b).

Management of these disorders focuses on functionally enhancing force closure across the pelvic structures based on the specific motor control deficits present. The aim of the intervention is to provide functional activation of the motor system in order to control pain and restore functional capacity (Fig. 4). There is good evidence to support the efficacy of this type of approach in these disorders (Stuge et al., 2004a, b; O'Sullivan and Beales, 2007).

5.2.2. Excessive force closure

The second group is defined by a group of PGP disorders where the peripheral nociceptive drive is based on excessive, abnormal and sustained loading of sensitised pelvic structures (SIJs and surrounding connective tissue and/or myofascial structures) from the *excessive activation of the motor system local to the pelvis (excessive force closure).* This patient group presents with localised pain to the SIJs and commonly also the surrounding connective tissue and myo-fascial structures (such as the pelvic floor and piriformis muscles) as well as positive pain provocation tests. However this group of patients has a negative ASLR (no feeling of heaviness). Compression (manual or using a SIJ belt), is often provocative, as is local muscle activation (pelvic floor, transverse abdominal wall, back muscles, iliopsoas, gluteal muscles). They commonly hold habitual erect lordotic lumbopelvic postures associated with high levels of co-contraction across various muscles such as the abdominal wall, pelvic floor, local spinal muscles (lumbar multifidus, psoas major) and in some cases the gluteal and piriformis muscles which may become pain sensitised. These motor control responses often become habitual secondary to excessive cognitive muscle training and/or muscle guarding of the lumbopelvic muscles, and are themselves *mal-adaptive* (provocative). These patients report pain relief from cardiovascular exercise, relaxation, assuming passive spinal postures (which they seldom do), as well as short-term relief with stretching, soft tissue massage, manipulation, muscle energy techniques and cessation of stabilisation exercises. These disorders are commonly associated with the patient's belief that their pelvis is 'unstable' or 'displaced' and that more muscle contraction or 'pelvic re-alignment' is beneficial. This is commonly reinforced by the treating therapist's beliefs. These disorders may be induced by intensive 'stabilisation exercises', Pilates, ball exercise, and cognitive muscle exercise training of the abdominal wall, lumbar multifidus and pelvic floor. Patients with these disorders are commonly anxious, under high levels of stress, highly active and seldom rest.

Management of these disorders focuses on reducing force closure across the pelvic structures (Fig. 4). This is carried out with a combination of approaches such as: general as well as targeted relaxation strategies, breathing control, muscle inhibitory techniques, enhancing passive/relaxed spinal postures, pacing strategies, hydrotherapy, cessation of stabilisation exercise training, and a focus on cardiovascular exercise. Anecdotally this approach appears very effective although clinical studies are required to validate this.

5.2.3. Psychosocial influences on peripherally mediated pelvic girdle pain

It is known that chronic pain and PGP disorders are commonly associated with not only physical but also psychosocial and cognitive impairments (Main and Watson, 1999; Bastiaenen et al., 2004, 2006; Linton, 2000, 2005) (Fig. 1). Even in the presence of a dominant peripheral nociceptive drive to PGP (such as described above), cognitive and psychosocial factors are invariably linked to these disorders influencing pain amplification and disability levels to varying degrees. This highlights the need for a biopsychosocial (behavioural) approach to understanding and managing chronic PGP disorders even when they are peripherally mediated in nature.

Psychosocial factors have the potential to both 'up' regulate or 'down' regulate pain. For example, a classification of 'reduced force closure' may be associated with cognitive impairments such as faulty beliefs, elevated anxiety levels and passive coping strategies that amplifies pain via the central nervous system and promotes high levels of disability associated with the pain disorder. In this case the intervention must address the cognitive impairments associated with the disorder within the motor learning intervention such as by promoting accurate beliefs, relaxation techniques and active coping strategies. On the other hand, if the same 'reduced force closure' classification is associated with positive beliefs, active coping strategies and limited functional impairments, then the primary focus can be placed more on the physical impairments of the disorder to establish pain control.

Similarly a classification of 'excessive force closure' may be associated with underlying stress and anxiety. In this case dealing with these cognitive factors with relaxation, breathing strategies, pacing and cardiovascular exercise is a critical adjunct to the motor learning management of these disorders. Where the psychosocial/cognitive components of the disorders are resistant to change, complementary psychological and/or medical intervention may be essential.

5.3. Central nervous system driven pelvic girdle pain disorders

The mechanisms of central nervous system sensitisation and/or glial cell activation and their involvement in the maintenance of chronic pain states are well known (Woolf, 2004; Hansson, 2006), and may persist even once a peripheral nociceptive drive is removed or has resolved. In this way chronic PGP can be potentially mediated largely or entirely via the central nervous system. In these disorders, the pain may have initially presented as a peripherally driven disorder, but once chronic, the pain does not have a presentation consistent with a peripheral pain source. These pain disorders are commonly associated with widespread, severe, and constant pain that is non-mechanical in nature. They lack a specific detectable peripheral nociceptive drive or pathological basis and are commonly associated with widespread allodynia. These disorders are associated with high levels of physical impairment and social impact, and may be associated with widespread and inconsistent motor control disturbances and abnormal pain behaviours that are secondary to the pain state and do not clearly drive the pain disorder. These disorders are often associated with dominant psychosocial factors (somatisation, catastrophising, pathological fear and/or elevated anxiety, depression, as well as significant social factors such as past history of sexual abuse etc).

Although these disorders appear to represent a small sub-group of chronic PGP disorders, they are highly disabling and resistant to physical interventions. Management of these disorders must be multidisciplinary involving medical and psychological management as a primary approach. Functional rehabilitation should aim to enhance normal general body function and address abnormal pain behaviours without a focus on pain. Passive treatments and rehabilitation that focuses on specific muscle control strategies may simply act to reinforce abnormal pain behaviours and hyper-vigilance in these patients.

5.4. Genetics and pelvic girdle pain

The role that genetics play with non-specific PGP disorders is largely unknown although its potential must be recognised. Subjects with PGP are more likely to have a mother or sister who also has PGP (Mogren and Pohjanen, 2005; Larsen et al., 1999) which may implicate a genetic link although social influences may also mediate this effect. A genetic predisposition in PGP patients related to changes in action of relaxin is proposed as one mechanism of genetic influence on PGP (MacLennan and MacLennan, 1997). Clearly further research into genetic influences is required.

6. Summary

This paper provides a broad clinical classification model for the management of chronic PGP disorders. It is a flexible, mechanism-based approach within a multi-factorial biopsychosocial framework. The classification model directs appropriate management based on the underlying mechanism/s that drives the pain. Although there is growing support for the validity of this approach, further research is required into this area.

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Note

Part 2 of this Masterclass can be viewed online only at doi:10.1016/jmath.2007.03.003.

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Appendix 2: Diagnosis and classification of pelvic girdle pain disorders- Part 2: Illustration of the utility of a classification system via case studies

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Diagnosis and classification of pelvic girdle pain disorders, Part 2: Illustration of the utility of a classification system via case studies

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Abstract

Pelvic girdle pain (PGP) disorders are complex and multi-factorial and are likely to be represented by a series of sub-groups with different underlying pain drivers. Both the central and peripheral nervous systems have the potential to mediate PGP disorders. Even in the case of a peripheral pain disorder, the central nervous system can modulate (to promote or diminish) the pain via the forebrain (cognitive factors).

It is hypothesised that the motor control system can become dysfunctional in different ways. A change in motor control may simply be a response to a pain disorder (adaptive), or it may in itself promote abnormal tissue strain and therefore be 'mal-adaptive' or provocative of a pain disorder. Where a deficit in motor control is 'mal-adaptive' it is proposed that it could result in reduced force closure (deficit in motor control) or excessive force closure (increased motor activation) resulting in a mechanism for ongoing peripheral pain sensitisation. Three cases are presented which highlight the multi-dimensional nature of PGP. These cases studies outline the practical clinical application of a classification model for PGP and the underlying clinical reasoning processes inherent to the application of this model. The case studies demonstrate the importance of appropriate classification of PGP disorders in determining targeted intervention directed at the underlying pain mechanism of the disorder.

Keywords: Pelvic girdle pain; Sacroiliac joint; Classification; Pain mechanisms; Motor control; Case studies

1. Introduction

Pelvic girdle pain (PGP) of musculoskeletal origin has become recognised as a clinical entity distinct from that of low back pain. Not unlike low back pain though, clarity in the classification of PGP disorders is regularly lacking in both research and clinical settings. Failure to effectively classify these disorders in a meaningful manner has resulted in confusion about PGP disorders in the same way that a lack of classification of back pain has contributed to the problems surrounding the diagnostic label of 'non-specific' low back pain. The failure to meaningfully classify PGP disorders based on their underlying pain mechanism ultimately leads to difficulties in providing appropriate care for the patient, as the treatment may not be directed at the mechanism/s that drive the pain disorder.

In the accompanying article to this paper, a non-exclusive classification system based on a biopsychosocial approach has been presented (O'Sullivan and Beales, 2007a). The underlying basis of this model is one of understanding the mechanism/s involved in the development and maintenance of PGP disorders. It recognises the multi-faceted nature and complex interaction of these mechanisms. This mechanism-based approach directly leads to and facilitates the uptake of appropriate management strategies.

To demonstrate the utility of this classification system three case studies are presented. Note: Where not else stated, subjective data presented in the case studies (fear, beliefs, anxiety, depression scales, etc.) represent a 10-point numerical rating score from data collected from the Orebro Musculoskeletal Pain Questionnaire (Linton, 2005).

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2. Case studies

2.1. Case 1: Centrally mediated PGP

2.1.1. Subjective examination findings

39-year-old female; married; two children

Work: home duties

History: 5 year history of chronic PGP that began during her second pregnancy and did not resolve. She reported that after the birth of her second child she became disabled and sought various treatments to manage her disorder. These interventions included manipulation, stabilisation exercises and a pelvic belt. She reported little benefit from these treatments over a period of 2 years. Over this time she had become inactive and very disabled. She was then referred to a clinic that specialised in PGP disorders. As she had great difficulty performing the active straight leg raise (ASLR) test, and pelvic compression did not reduce the pain and heaviness, she was advised that her pelvis was 'very unstable' and that she required surgical fusion. Initially she underwent fusion of the symphysis pubis and when this was not successful, she also underwent fusion of both sacroiliac joints (SIJs) (Fig. 1). When this did not benefit her she was referred to a multi-disciplinary pain management clinic for psychological, medical and physical management. She was still disabled with PGP and was attending active rehabilitation sessions three times per week.

Family history: nil

Pain: constant pain over the posterior pelvis as well as pubic area (left side bias)

Aggravating postures: all postures—sitting, standing, lying

Aggravating activities: all activities—walking, lifting, bending, activities of daily living

Easing postures/activities: no symptom relief during weight bearing or non-weight bearing

Activity levels: low

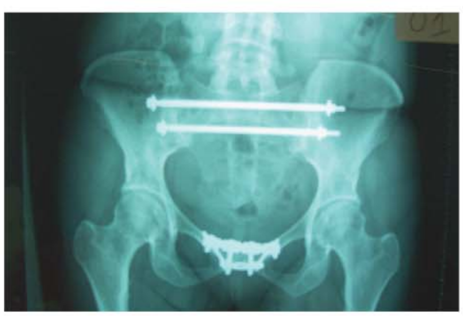

Fig. 1. X-ray of subject in Case 1 depicting surgical fusion of both sacroiliac joints and the symphysis pubis.

Coping strategies: rest, spends much of the day lying down

Beliefs:

1. Back pain likely to become persistent 10/10
2. Activity aggravates back pain 10/10
3. Activities that aggravate back pain are likely to be damaging 10/10
4. Work likely to aggravate back pain 10/10
5. Basis of the pain—not known

Pain-intensity (VAS): 8/10 (day intake examination); 8/10 (average pain week); 8/10 pain (average over 3 months)

Disability scale score: revised-Oswestry (Fairbank et al., 1980): 50%

Fear avoidance: high levels of fear avoidance behaviour

Psycho-social risk factors ('yellow' flags):

1. Stress levels (7/10)
2. Depression (7/10)

Medical imaging: X-rays—successful fusion of the pelvis

Medication: Strong analgesics, pain modulation medication

2.1.2. Key subjective features

- Widespread symptoms
- Constant pain
- Pain is of a high level and non-mechanical in nature
- High levels of disability
- High levels of stress and anxiety
- High levels of fear avoidance behaviour
- Belief that something is damaged and disorder is unlikely to resolve
- Fused pelvis

2.1.3. Plan for physical examination

- Examine for the presence of consistent clinical patterns—organic vs non-organic signs
- Investigate relationship between movement behaviour and pain behaviours

2.1.4. Physical examination findings

Posture and movement analysis

- *Standing*: patient constantly moved—shifting weight from side to side. There was no consistency with this behaviour. She presented with poor control of standing balance.
- *Forward bending and return*: full range of motion (ROM)

- *Backwards bending*: full ROM
- *Single leg standing*: gross generalised shaking and loss of control on left leg
- *Gait*: inconsistent gait pattern—ataxic in nature
- *Squat*: unable to perform a squat due to loss of control of left leg
- *Sitting posture*: during interview and examination the patient constantly moved, changing position, bracing and unloading spine with arms. There was no consistent pattern with this behaviour.
- *Sit to stand*: use of hands and breath holding

Specific movement tests (O'Sullivan, 2005)

- Unable to normalise movement behaviours in sitting, standing, single leg standing, squat
- No change in pain with attempts to change movement behaviours
- No clear relationship between pain and movement behaviours

Specific muscle testing (O'Sullivan, 2005)

- Weakness in her left leg—strength was inconsistent depending on position tested

ASLR—prone/supine (Mens et al., 1999)

- Gross weakness and loss of control, not influenced by pelvic compression

Neurological screening examination (Hall and Elvey, 1999)

- Absence of neurological findings (normal neural provocation testing, reflexes, sensation and manual muscle tests)

Passive physiological motion segment testing (Maitland, 1986)

- No spinal movement impairment

SIJ provocation tests (Laslett et al., 2003)

- All highly pain sensitive

Lumbar spine palpation (Maitland, 1986)

- Hyperalgesia across lumbosacral, sacroiliac, buttock and pubic symphysis regions (left bias)

2.1.5. *Key features of physical examination findings*

- Presence of abnormal pain behaviours without a clear, consistent clinical pattern to them
- Generalised gross motor disruptions of left leg
- Inconsistent motor performance
- No clear relationship between abnormal pain and movement behaviours—pain was not altered with attempts to normalise movement behaviours
- Widespread pain and hypersensitivity
- No clear consistent pain pattern to suggest an organic basis to disorder

2.1.6. *Diagnosis*

- Non-specific PGP

2.1.7. *Classification*

- Central nervous system driven pain disorder with central pain sensitisation and abnormal pain and movement behaviours (Fig. 2). Presence of abnormal pain behaviours without a clear, consistent clinical pattern to them
- Psycho-social pain drivers:
  - High levels of disability, functional impairment and inability to work
  - Passive coping strategies for pain management—abnormal illness behaviour, relief with rest, avoidance of provoking activities, medication
  - High levels of stress and depression

Case 1: Centrally mediated pelvic girdle pain

Nature of the disorder :

- Widespread pain +/- referral
- Pain constant, severe and debilitating
- All activity and movement provoke pain
- Absence of consistent mechanical pattern of provocation
- Minimal relieving factors (medication only)
- Pain at rest
- Disrupted sleep
- +ve sacroiliac joint pain provocation tests
- Active straight leg raise test – inability to lift leg but not relieved with pelvic compression
- Widespread changes in motor system
- High levels of disability
- Widespread allodynia

Result :
Centrally mediated pelvic girdle pain

Management :

- Medical : Central nervous system modulation
- Psychological : Pain management coping strategies
- Physical : Maintain functional capacity

Fig. 2. The nature and management of centrally mediated pelvic girdle pain.

2.1.8. Stage

- Chronic, stable.

2.1.9. Management

The classification of this disorder is based on the high levels of widespread constant pain, generalised hyperalgesia, the non-mechanical nature of the disorder, the absence of a clear organic basis to pain, widespread disruption to the motor system and abnormal pain behaviours, the lack of a clear relationship between the abnormal movement behaviour and pain and resistance to conservative treatments. All these factors support that the pain is centrally mediated (Fig. 2).

These disorders are very complex and highly resistant to change. The management approach for this disorder must be multidisciplinary (Fig. 2):

- Cognitive (psychologist intervention)
- A focus on normalising beliefs and cognitive functioning
- Educate regarding vicious pain cycle (Fig. 3)
- Developing active coping strategies
- Pacing strategies
- Medical pain management: central nervous system inhibitory medication
- Rehabilitation: normalising movement behaviours and restoration of function, no pain focus, graduated functional whole body exercise programs, group exercise

2.1.10. Outcome

In spite of ongoing multi-disciplinary management, 5 years later this patient lives with ongoing chronic PGP. The cognitive components to the intervention provided her with active coping strategies that enabled her to reduce her disability levels, change her beliefs and maintain moderate levels of functional capacity.

2.1.11. Commentary

This case highlights the danger of considering PGP disorders purely from a biomechanical perspective. This patient did not respond to the multiple conservative and invasive interventions directed at her pelvis, based on the premise that her pelvis was 'unstable'. This in turn promoted fear, passive dependence on health care, passive coping strategies, disability, reinforcing abnormal pain behaviours and providing fuel for a centrally mediated pain disorder to develop (Fig. 3). This patient has all the hall-marks of centrally mediated pain—widespread, severe, constant pain, allodynia, gross and widespread motor disturbances, high levels of disability with peripherally directed interventions exacerbating the disorder. This case highlights the importance of the early classification of PGP disorders and directing management at the mechanism/s that underlie the pain disorder. It highlights the danger of focussing on the signs and symptoms of a disorder (i.e. ASLR test) without consideration for the complex central mechanisms that can drive pain. A one-dimensional view for the classification and management of PGP disorders (in this case assuming the pelvis was 'unstable') may in fact amplify pain.

2.2. Case 2: Reduced force closure

2.2.1. Subjective examination findings

36-year-old female; married; two children (2 and 4 years old)

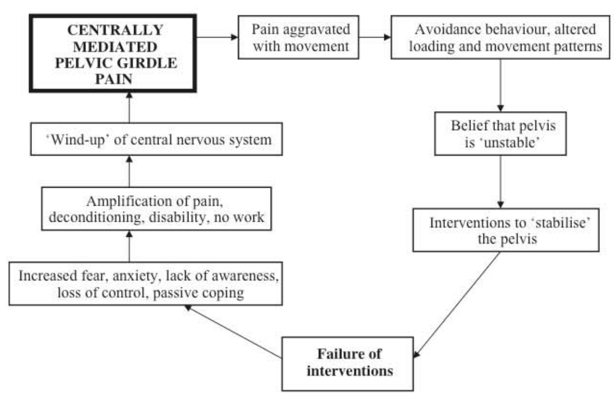

Fig. 3. The vicious cycle of pain for centrally mediated pelvic girdle pain.

Work: physiotherapist (unable to work because of pain)

Home: household activities; picking up and carrying 2-year-old child

History: gradual onset of PGP during second pregnancy. Pain increased following child birth and had not abated. Pain remained at a high level and disabling, and attempts to rehabilitate had failed. Multiple interventions and advice left her confused and disabled. Initial treatment after her child was born was pelvic manipulation which aggravated her pain. The second physiotherapist she saw advised that her pelvis was unstable and that she needed to dynamically stabilise it. She was instructed to perform transverse abdominal wall exercises and was given a series of exercise progressions that involved graduated limb loading in supine. She reported no relief from this treatment. She was then referred to a PGP clinic where she was instructed that she had a hypertonic pelvic floor and she needed to learn to relax it. She was instructed to do relaxation and breathing exercises and gradually increased her cardiovascular fitness. However this resulted in a significant increase in her pain. She took analgesic medication and non-steroidal anti-inflammatories regularly. She reported that she had developed stress incontinence after training her pelvic floor to relax.

Family history: nil

Pain: localised SIJ pain on the right with some gluteal referral. Pain was intermittent in nature.

Aggravating postures: sitting, standing (loading right leg)

Aggravating activities: walking (>10 min), lifting and carrying child; previous treatment stabilising exercises: fit-ball, limb loading, stretching exercises for the hip

Easing postures/activities: relief during unloading of right leg and non-weight bearing, rest eases pain

Coping strategies: rest, avoiding provoking activities

Beliefs:

1. Back pain likely to become persistent (5/10)
2. Activity aggravates back pain (10/10)
3. Activities that aggravate back pain are likely to be damaging (7/10)
4. No idea as to the basis of the pain or what is required to manage it

Pain-intensity (VAS): 6/10 (day intake examination); 5/10 (average pain week); 5/10 pain (average for 3 months)

Disability scale score: Revised-Oswestry (Fairbank et al., 1980): 38%

Fear avoidance: Tampa Scale of Kinesiophobia (French et al., 2007): 38/68

Psycho-social risk factors ('yellow' flags):

1. Stress levels (4/10)—pain and disability results in stress
2. Depression (7/10)—gets down because of pain disorder

Medical imaging: X-rays and CT-imaging—no abnormalities detected

Blood tests: −ve

2.2.2. Key subjective features

- Localised SIJ pain
- Loading pain disorder
- No awareness of pain disorder—conflicting advice regarding management and underlying pain mechanism
- Passive coping strategies
- High levels of pain, disability and movement-based fear
- Absence of pathoanatomical disorder on radiology

2.2.3. Plan for physical examination

- Identify symptomatic structure
- Investigate provoking postures and activities to determine whether control or movement impairments are linked to pain disorder
- Investigate motor control of lumbar spine and pelvis—especially regarding right limb loading
- Investigate whether enhancing control over painful structure/s reduces pain in provocative postures and activities
- Determine if beliefs regarding movement-based fear are real or perceived

Physical examination findings

2.2.4. Posture and movement analysis

- *Standing*: sway posture standing (Fig. 4a) (pelvis anterior to thorax) with avoidance of loading right leg. Reduction in tone in the transverse abdominal wall, lumbar multifidus and right gluteal muscles
- *Forward bending*: full ROM (no pain)
- *Return from forward bending*: poor control of posterior pelvic rotation via hips
- *Backwards bending*: full ROM (no pain)
- *Side bending (R/L)*: full ROM
- *Single leg standing*: right—increased sway of pelvis anterior to thorax and trendelenberg pattern of right hip (with pain)
- *Sitting posture*: slumped sitting with weight shift to left buttock
- *Sit to stand*: tendency to laterally shift load to left leg
- *Single leg sit to stand on right leg*: inability to transfer load on right leg

Fig. 4. (a) Subject in Case 2 with a classification of reduced force closure exhibits a passive sway standing posture as her normal standing posture. This posture is associated with inhibition of the local force closure muscles (transverse abdominal wall, lumbar multifidus, gluteal muscles, pelvic floor). (b) Corrected standing posture facilitates automatic postural activation of local force closure muscles. Assumption of this posture immediately reduced her SIJ pain.

- *Lifting*: avoidance of loading right leg/flexed lumbar spine
- *Gait*: trendelenberg pattern on right

Specific movement tests (O'Sullivan, 2005)

- Correcting sway standing posture (Fig. 4b): neutral lumbar lordosis, aligned relaxed thorax over pelvis (no sway) with equal loading reduced sacroiliac pain.
- Standing on right leg with the same postural correction as standing resulted in gluteal activation and reduced pain—the addition of manual compression to ilium further reduced pain—rapid fatigue of the right leg muscles was reported.
- Sitting with lumbopelvic posture with equal loading on buttocks reduced pain—the addition of manual ilium compression further reduced pain
- Poor capacity to isolate anterior pelvic rotation independent of thorax

Specific muscle testing (O'Sullivan, 2005)

- Attempts to elevate pelvic floor were associated with bracing of the abdominal wall, breath holding and depression of the pelvic floor
- Attempts to activate the lower transverse abdominal wall (transverse fibres of internal oblique and lower transversus abdominis) in side lying and supine were associated with bracing and breath holding
- Inability to initiate isometric contraction of right gluteal muscles
- Marked weakness of right gluteal muscle on testing

ASLR—prone/supine (Mens et al., 1999)

- Marked 'heaviness' when elevating right leg with breath holding and bracing of the abdominal wall
- Manual pelvic compression across ilium normalised the test

Neurological screening examination (Hall and Elvey, 1999)

- Absence of neurological findings (normal neural provocation testing, reflexes, sensation and manual muscle tests)

SIJ provocation tests (Laslett et al., 2003)

- All tests positive—except she experienced relief with ilium compression

Passive physiological motion segment testing (Maitland, 1986)

- No spinal movement impairment

Lumbar spine palpation (Maitland, 1986)

- Tenderness inferior sulcus of SIJ
- Trigger points and tenderness over gluteal and piriformis muscles

2.2.5. Key features of physical examination findings

- Full ROM of lumbar spine (active and passive)
- Avoidance of loading right lower limb
- Loading pain when weight bearing on right side and was associated with a lack of activation of postural stabilising muscles (right gluteal, transverse abdominal wall, lumbar multifidus, left quadratus lumborum)
- Facilitating optimal loading reduced pelvic pain
- +ve ASLR—normalised with compression
- Inability to isolate activation of local pelvic muscles

- Provocation of pain linked to deficits of control of the pelvic stabilising muscles
- High levels of disability
- Loss of conditioning

2.2.6. Diagnosis

- Non-specific PGP (post partum PGP)

2.2.7. Classification: mal-adaptive movement disorder

- Peripheral driver: reduced force closure of right SIJ and associated structures (Fig. 5)
- Cognitive drivers: lack of awareness of pain disorder, anxiety, depression, passive coping, inability to function, hyper-vigilance

2.2.8. Stage

- Chronic, stable.

Other important factors contributing to disorder

- Passive coping strategies for pain management—relief with rest, avoidance of provoking activities, medication
- Lack of awareness of the basis (i.e. mechanism) of the pain disorder

Case 2: Reduced force closure	**Case 3: Excessive force closure**
Nature of the disorder: • Localised pain +/- referral • Pain provoked by sustained or repeated loading → sitting / standing / walking • No spinal movement impairment or pain • *Pain provoked by long lever exercises, stretching +/- manipulation* • *Pain relieved by increased pelvic compression / sacroiliac belt / local muscle activation / optimizing alignment* • +ve sacroiliac joint provocation tests • *+ve ASLR test (supine +/- prone) → normalized by pelvic compression* • *Passive postures with poor lumbopelvic position sense* • *Inability to isolate local pelvic muscle synergies (pelvic floor, lower internal oblique, transverses abdominis, +/- lumbar multifidus, psoas major, gluteal muscles)* • *Avoidance of painful activity* • Disability	**Nature of the disorder**: • Localised pain +/- referral • Pain provoked by sustained or repeated loading → sitting / standing/ walking • No spinal movement impairment or pain • *Pain provoked by increased pelvic compression / sacroiliac belt / muscle activation* • *Pain relieved with relaxation / stretching / massage* • +ve sacroiliac joint provocation tests • *-ve ASLR test* • *Erect active postures* • *High levels of muscle tone and tension of pelvic floor, abdominal wall, adductors, gluteal muscles* • *Muscle guarding and tension (↑intra-abdominal pressure) with inability to relax pelvic muscles* • Disability
Result: Peripheral pain sensitization *due to a loss of local compression within pelvic joints resulting in repeated strain in sacroiliac joints and surrounding structures*	**Result**: Peripheral pain sensitization *due to excessive and sustained compression of sacroiliac joints and surrounding pain sensitive structures (increased pelvic compression)*
→ **Reduced force closure** classification	→ **Excessive force closure** classification
Cognitive drivers: • Anxiety related to chronic disabling pain • *Fear of activity (non-pathological)* • *Lack of control and awareness of disorder* • *Belief that activity is provocative (non-pathological)*	**Cognitive drivers**: • Associated underlying anxiety • *Active coping, poor pacing,* • *Hyper-vigilence*
Result: Central amplification of pain due to cognitive components of disorder	**Result**: Central amplification of pain due to cognitive components of disorder
Management: *Enhancing local force closure via motor learning* in conjunction with appropriate cognitive intervention leads to resolution/control of the disorder	**Management:** *Reducing excessive motor activity and facilitating relaxation* using both motor learning and appropriate cognitive intervention leads to resolution/control of the disorder

Fig. 5. The nature and management associated with mal-adaptive motor control disorders of the pelvis with; Case 2: Reduced force closure classification and Case 3: Excessive force closure classification. Normal text represent common features of the disorders while *italics* text highlights differences between the disorders (ASLR = active straight leg raise).

- Belief that activity is provocative (correct)—reinforcing disability
- Avoidance behaviours relating to right leg loading
- Deconditioning, high disability levels

2.2.9. Management: cognitive

- Provide an awareness of pain mechanism—educate regarding vicious cycle (Fig. 6)
- Make patient aware of loss of pelvic motor control and how her postural control and avoidance behaviours have reinforced her pain disorder
- Enhance functional capacity in order to develop active coping strategies with pain control

2.2.10. Management: motor learning

- Train ability to elevate pelvic floor muscles and isolate activation of transverse abdominal wall without global abdominal wall activation and breath holding (O'Sullivan and Beales, 2007b)
- Train control of pelvis independent to the thorax (in supine, sitting, and standing)
- Train lumbopelvic sitting and aligned standing postures with equal limb loading (O'Sullivan et al., 2002)
- Train loading of right leg with optimal alignment of the thorax relative to the pelvis and pain control
- Train lifting techniques with equal weight bearing and lumbopelvic control
- Graduated cardiovascular fitness program—progress from exercise bike to walking
- Increase conditioning of lumbopelvic region with whole body exercise and right leg loading exercises—lunges, squats and hand weights
- Graduated functional restoration with movement and pain control—specific to patient's provocative activities
- Graduated return to work

2.2.2. Outcome

Twelve months later this patient had returned to work as a physiotherapist with very little pain and had returned to playing handball and other sporting activities. Her bladder control also normalised.

2.2.3. Commentary

These examination findings support the presence of a loading pain disorder of the right SIJ and surrounding structures, associated with a loss of local motor control resulting in a loss of adequate force closure (impaired load transfer) of the SIJ complex. This results in excessive strain being placed through the pain sensitive supporting ligamentous structures of the SIJ, with resultant maintenance of pain during loading (Fig. 6). This loss of control is reinforced by the faulty postural and movement behaviours she had developed. Her avoidance behaviours have developed from an inability to optimally load the right leg without pain.

Management logically focuses on a cognitive based motor control intervention directed at the functional activation of the key force closure muscles of the SIJ to enhance the dynamic stability to the joint. Achieving pain control during loading allows for the restoration of normal movement and coping behaviours, reduced avoidance behaviours, conditioning and the resumption of work and sporting activities. This in turn promotes the resolution of the disorder.

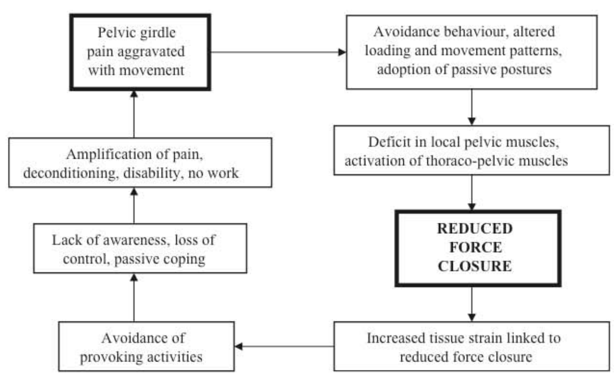

Fig. 6. The vicious cycle of pain for pelvic girdle pain with a classification of reduced force closure.

2.9. Case 3: Excessive force closure

2.9.1. Subjective examination findings

38-year-old female; single

Work: Pilates instructor full time (12 hours per day—6 days per week)

History: Onset of PGP 2 years earlier following heavy Pilates session which focussed on pelvic stabilisation exercises and hip stretching. The disorder progressively deteriorated over time in spite of various treatments. These treatments involved—stabilising exercise training (focussed on the pelvic floor, transverse abdominal wall, lumbar multifidus and gluteal muscles, stretching, muscle energy techniques for the SIJs, trigger point work and massage to the piriformis and quadratus lumborum). In spite of significant treatment the disorder worsened. She had been advised by a physiotherapist and chiropractor that her SIJs were 'unstable' and regularly become 'displaced', and as the stabilising exercise program has not worked, she required prolotherapy (sclerosing injections to the SIJ ligaments). However following the sclerosing injections, there was no change in her pain. She was finding it increasingly difficult to work and was highly anxious regarding her 'unstable pelvis', had high levels of pain, and was disabled. She wore a SIJ belt even though it was provocative. Following advice she was considering SIJ fusion surgery. She also reported developing bladder control problems.

Family history: Nil

Pain: localised to SIJs with spread to buttocks (right > left), also internal pelvic pain across perineum

Aggravating postures: sitting, standing

Aggravating activities: walking, bending, lifting, working, pain worse at end of working day and after exercise (power walking and swimming) and Pilates classes, no symptom relief during weight bearing

Easing postures/activities: rest and relaxation, heat, massage, non-steroidal anti-inflammatories

Coping strategies: Pelvic stabilisation—isometric muscle contractions of the pelvic floor, transverse abdominal wall, lumbar multifidus and gluteal muscles, although these strategies did not reduce the pain. She was reliant on passive treatments 2–3 times per week involving massage of the pelvic muscles. On questioning she very rarely rested and relaxed. After work (12 hours without a break) she would go power walking or swimming where she would focus on gluteal and pelvic floor contractions. She reported that she was constantly focussed on her pain and contracting her pelvic muscles.

Beliefs:

1. Her pelvis was unstable and weak and regularly 'goes out'
2. The more stable her pelvis is the better she should be
3. The more exercise she does the better she should be
4. Holding erect postures and contracting pelvic muscles is beneficial
5. PGP likely to become persistent (10/10)

Pain-intensity (VAS): 6/10 (day intake examination); 6/10 (average pain week); 6/10 pain (average for 3 months)

Disability scale score: revised-Oswestry (Fairbank et al., 1980): 32%

Fear avoidance: low score

Psycho-social risk factors ('yellow' flags):

1. Stress levels (8/10)—highly stressed and anxious person
2. Depression (5/10)—gets down because of pain disorder

Medical imaging: X-rays and CT-imaging—no abnormalities detected; bone scan—mild signs of inflammation of the SIJs (right > left)

Blood tests: −ve

2.9.2. Key subjective features

- Pain localised to SIJs
- Loading provokes pain
- Unloading and relaxation relieves pain
- Belief that pelvis is 'unstable' reinforced by treatment providers
- Patient constantly activates pelvic stabilising muscles although this does not relieve pain
- Coping strategies—exercise, muscle contraction, passive treatments (with resultant poor control over pain disorder)
- Lack of pacing, long work hours, lack of relaxation and rest
- Signs of inflammation of SIJ on bone scan (right > left)
- High levels of stress and anxiety and focus on pain
- Absence of any signs suggesting serious underlying pathology

2.9.3. Plan for physical examination

- Identify painful structure/s
- Investigate patient's movement behaviours
- Investigate provoking postures and activities to determine whether impairments of motor control or excessive motor activity are linked to the pain disorder
- Investigate whether enhancing control over pelvis reduces or increases pain in provocative postures and activities
- Determine whether her current coping strategies are beneficial

- Determine if beliefs regarding 'unstable pelvis' and 'weakness' are valid

2.9.4. Physical examination findings
Posture and movement analysis

- *Standing*: erect thoracolumbar posture; high tone in the abdominal wall, back and gluteal muscles, apical breathing pattern
- *Forward bending*: hands flat on the floor with no increase in pain
- *Backwards bending*: hyperextension of the spine without pain
- *Side bending (R/L)*: full ROM
- *Single leg standing*: erect standing with gluteal activation
- *Sitting posture*: erect active sitting (Fig. 7a) with forward incline, extended thoracolumbar spine, apical breathing pattern
- *Sit to stand*: initiated with hip flexion and thoracolumbar spine maintained in extension
- *Squat*: full movement with ease
- *Gait*: rigid erect thoracolumbar spine (minimal rotation) with accentuated hip extension

Specific movement tests (O'Sullivan, 2005)

- Relaxation of sitting posture via thorax (Fig. 7b) and abdominal wall reduced pelvic pain
- Relaxation of gluteal, back and abdominal wall muscles with reduced lumbar lordosis and increased thoracic flexion in standing reduced pelvic pain

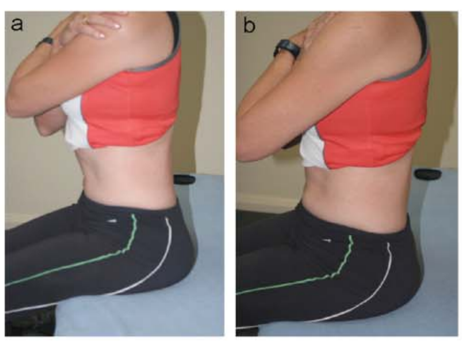

Fig. 7. (a) Subject in Case 3 adopts an erect active sitting posture with high levels of activation in the superficial abdominal wall and the thoracolumbar erector spinae, as well as an apical breathing pattern. (b) Relaxed sitting results in relaxation of the abdominal wall, back and pelvic floor muscles with an associated reduction in pelvic girdle pain.

Specific muscle testing (O'Sullivan, 2005)

- Ability to co-activate the pelvic floor, lower transverse abdominal wall (transverse fibres of internal oblique and lower transversus abdominis) and lumbar multifidus at L5/S1 in side lying and supine without breath holding
- High levels of strength of hip flexors and extensors
- Difficulty relaxing gluteals, lumbar multifidus and lower abdominal wall
- Rapid, apical breathing in all postures including supine
- Difficulty belly breathing in supine
- High levels of flexibility of trunk and hip muscles
- Internal pelvic floor examination (by womens health physiotherapist) confirmed the ability to contract and elevate the pelvic floor, but difficulty relaxing it. Strength grade 5+ Oxford scale, very strong contraction on Peritron.

ASLR—prone/supine (Mens et al., 1999)

- −ve
- Ability to lift leg with ease
- Increase in pain with addition of manual pelvic compression and local stabilising muscle activation

Neurological screening examination (Hall and Elvey, 1999)

- Absence of neurological findings (normal neural provocation testing, reflexes, sensation and manual muscle tests)

SIJ provocation tests (Laslett et al., 2003)

- All tests positive—except she experienced relief with lateral distraction of the ilium

Passive physiological motion segment testing (Maitland, 1986)

- Normal for spine and pelvis

Lumbar spine palpation (Maitland, 1986)

- Tenderness of right inferior sulcus of SIJ
- Trigger points and tenderness over gluteal and piriformis muscles

2.9.5. Key features of physical examination findings

- Full ROM spinal mobility (active and passive)
- High tone in pelvic stabilising muscles with erect rigid spinal postures with pain
- Relaxation of spino-pelvic postures and local pelvic muscles reduced pain

- Ability to activate local stabilising muscles but difficulty relaxing them
- +ve SIJ provocation tests
- −ve ASLR in prone and supine with increased pain on addition of manual compression and local muscle activation
- Abnormal movement behaviours—erect and rigid movement
- Current beliefs that pelvis is 'unstable' were not confirmed by examination
- Current coping strategies were provocative of pain
- High levels of anxiety

2.9.6. *Diagnosis*

- Non-specific PGP

2.9.7. *Classification: mal-adaptive movement disorder*

- Peripheral drivers: excessive force closure of SIJ and associated myofascial pain (Fig. 5)
- Cognitive drivers: faulty beliefs, anxiety, lack of pacing, inability to relax, hyper-vigilance

2.9.8. *Stage*

- Chronic/stable

Other important factors contributing to disorder

- Belief that pelvis is unstable and that more muscle activity is better
- Lack of accurate awareness of basis (i.e. mechanism) of the pain disorder
- Coping strategy (increasing muscle activation) is provocative
- Lack of pacing, rest, relaxation and unloading of pelvic structures
- Ironically, treatments that gave relief were those that induce relaxation of pelvic muscles—massage, trigger point work and heat (in contrast to her beliefs)

Management: cognitive

- Educate regarding vicious cycle (Fig. 8)
- Provide an awareness of pain mechanism—the fact that increasing pelvic compression increases pain and reducing it decreases pain.
- Change beliefs—pelvis is stable, muscles are strong and the inability to relax the pelvic muscles abnormally loads the pelvic structures which increases pain
- Importance of pacing, learning to relax postures, not consciously activating the pelvic and trunk muscles, use breathing control to relax and reduce anxiety levels—in order to reduce peripheral and central pain drive
- Seek psychological/medical help with regards to reducing anxiety levels
- Implement strategies to reduce work hours/introduce breaks into working day/reduce manual 'demonstrations' in Pilates classes and focus more on instruction
- Importance of relaxing during exercise

Management: motor learning

- Teach relaxation strategies—breathing control, relaxation
- Instruct on relaxation of spinal postures in sitting and standing
- Teach strategies to relax and move normally with movement—such as rolling, sit to stand, bending, walking

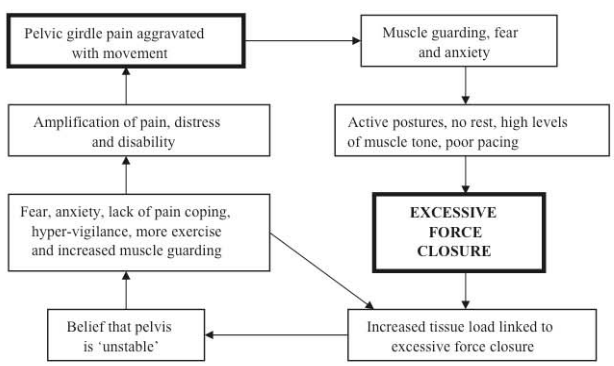

Fig. 8. The vicious pain cycle of pelvic girdle pain with a classification of excessive force closure.

- Maintain cardiovascular fitness but with relaxed spinal postures and increased trunk rotation
- Reduce exercise levels to four times per week
- Prescribed rest each day
- Cease stabilising exercises
- Relaxation yoga

2.9.9. Outcome

Twelve months later this patient had changed jobs, reduced her activity levels to a normal level, stopped contracting her pelvic muscles, normalised her movement behaviours and had very little pain or disability. Her bladder control had also normalised.

2.9.10. Commentary

This disorder was driven by the belief that the pelvis was 'unstable' reinforced by her physiotherapists and her own belief system. The management and coping strategies that the patient has been taught to develop (conscious activation of pelvic stabilising muscles) and the belief that her pelvis is unstable are highly provocative for these disorders, reinforcing hypervigilance and abnormally high levels of dynamic compression across her sensitised pelvic joints (Fig. 8). Her long work hours, the active nature of her work, the lack of rest, high levels of exercise, high levels of anxiety and focus on pain further increase the muscle tone resulting in increased central and peripheral drive of pain. All these factors contributed to maintaining a vicious pain cycle (Fig. 8).

Management must address both cognitive and motor control factors that drive pain. Providing a new belief system and different coping strategies is critical for this patient. Learning to relax, move normally, cease stabilisation exercises and passive treatments, change the focus away from pain towards relaxation and appropriate pacing is critical. This highlights how faulty belief systems and abnormal motor control strategies reinforced by physiotherapists and adopted by patient's can be potentially detrimental to a patients disorder.

3. Summary

These three distinct cases act as clinical examples highlighting the importance of classification and specifically directed management of PGP disorders. Working within a biopsychosocial framework is critical for the management of these disorders. Management strategies that target both the physical and cognitive impairments associated with these disorders has the potential to positively impact on long-term PGP disorders.

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Appendix 3: Altered motor control strategies in subjects with sacroiliac joint pain during the active straight-leg-raise test

Reprint of O'Sullivan, P. B., Beales, D. J., Beetham, J. A., Cripps, J., Graf, F., Lin, I. B., et al. (2002). Altered motor control strategies in subjects with sacroiliac joint pain during the active straight-leg-raise test. Spine, 27(1), E1-8, with permission from Wolters Kluwer Health.

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Altered Motor Control Strategies in Subjects With Sacroiliac Joint Pain During the Active Straight-Leg-Raise Test

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Study Design. An experimental study of respiratory function and kinematics of the diaphragm and pelvic floor in subjects with a clinical diagnosis of sacroiliac joint pain and in a comparable pain-free subject group was conducted.

Objective. To gain insight into the motor control strategies of subjects with sacroiliac joint pain and the resultant effect on breathing pattern.

Summary of Background Data. The active straight-leg-raise test has been proposed as a clinical test for the assessment of load transfer through the pelvis. Clinical observations show that patients with sacroiliac joint pain have suboptimal motor control strategies and alterations in respiratory function when performing low-load tasks such as an active straight leg raise.

Methods. In this study, 13 participants with a clinical diagnosis of sacroiliac joint pain and 13 matched control subjects in the supine resting position were tested with the active straight leg raise and the active straight leg raise with manual compression through the ilia. Respiratory patterns were recorded using spirometry, and minute ventilation was calculated. Diaphragmatic excursion and pelvic floor descent were measured using ultrasonography.

Results. The participants with sacroiliac joint pain exhibited increased minute ventilation, decreased diaphragmatic excursion, and increased pelvic floor descent, as compared with pain-free subjects. Considerable variation was observed in respiratory patterns. Enhancement of pelvis stability *via* manual compression through the ilia reversed these differences.

Conclusions. The study findings formally identified altered motor control strategies and alterations of respiratory function in subjects with sacroiliac joint pain. The changes observed appear to represent a compensatory strategy of the neuromuscular system to enhance force closure of the pelvis where stability has been compromised by injury. [Key words: diaphragm, low back pain, pelvic floor, respiration, sacroiliac joint, spirometry, ultrasonography] **Spine 2002;27:E1–E8**

The estimated prevalence of sacroiliac joint pain (SIJP) is approximately 13% to 30% in patients with a classification of nonspecific chronic low back pain.[24] This is a significant group worthy of investigation. The sacroiliac joint (SIJ) is designed for stability rather than mobility. This facilitates safe load transfer through the pelvis. It has been proposed that the stability of the pelvis depends on form and force closure.[21] *Form closure* results primarily from the bony structure of the sacrum and the joint surfaces that allow the SIJ to be resistant to shear forces.[25,26,29,30] *Force closure* refers to the additional compressive force necessary for maintaining stability of the pelvis.[25,26] Force closure is primarily a dynamic process performed by the muscular system that depends on the integrity of ligamentous and fascial structures in the region of the SIJ. Impairment of form or force closure mechanisms may be associated with pain disorders of the lumbopelvic region.[16,25,28]

It has been proposed that the functional integrity of the form and force closure mechanisms can be examined clinically by use of the active straight-leg-raise (ASLR) test.[16,18] This maneuver has been advocated as a reliable test for the quality of load transfer through the lumbopelvic region.[18] During this test, subjects are instructed to assume a relaxed supine position, and then to lift one leg 5 cm from the couch. It has been documented that this is accompanied by profound heaviness of the leg in subjects with postpartum SIJ instability.[16,18] The test then is repeated while a manual compressive force is applied through the ilia, or with a belt tightened around the pelvis. A positive test is denoted by improved ability to raise the leg.[16,18] The proposed mechanism for this improvement is the augmentation of force closure.[16,25] Recent research has shown a strong correlation between impairment of ASLR and a unilateral increase in pelvic mobility at the symphysis pubis visualized radiographically.[16] These findings support the use of ASLR as a measure of impaired load transfer through the lumbopelvic region in subjects with pelvic pain disorders.[16]

The transversus abdominis, internal oblique, diaphragm, and pelvic floor form part of the abdominal cavity's muscular boundaries. These muscles work together in a coordinated pattern to produce and control intraabdominal pressure (IAP).[11,12] These same muscles are thought to have a role in maintaining pelvic stability *via* force closure[21,25,26] and a role in respiration.[23] Alterations in motor control that involve this musculature have been reported in subjects with lumbar segmental instability, resulting in disruption to respiration.[20] Similar alterations also have been observed clinically in sub-

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Conflict of interest category: 12.

Table 1. Inclusion and Exclusion Criteria for All Subjects*

Inclusion criteria for the SIJP group
- The subject has a clinical presentation suggestive of SIJP longer than 3 months, that shows no sign of abating.
- The subject reports pain over the SIJ, with no proximal referral.[7,9,10,15,24]
- The outcome of ASLR test is positive.[16]
- At least four of five SIJ provocation tests are positive:[13,14]
  1. distraction and compression test
  2. posterior shear test (thigh-thrust test)
  3. pelvic torsion (right and left posterior rotation)
  4. sacral thrust test
  5. palpation of long dorsal sacroiliac ligament

General Exclusion Criteria for Both Groups	Specific Exclusion Criteria for the Comparison Group
Any neurologic dysfunction	Medical history that might lead to an inability to perform an ASLR.
Facial pain that could lead to an inability to use the mask	History of low back, pelvis, hip, knee, or ankle disorder in the past 6 months.
History of significant respiratory disorder	Surgery to the lumbar spine, pelvis, chest or abdomen in the past 12 months.
Pregnancy less than 6 months postpartum.	Any inflammatory disorders.
Body mass index less than 31 kg/m.	

* The inclusion criteria for the SIJP group shown in the first part of the table were all negative or absent in the comparison group. The exclusion criteria are shown in the second part of the table.
SIJ = sacroiliac joint; SIJP = sacroiliac joint pain; ASLR = active straight leg raise.

jects with SIJP during ASLR. This appears to result from the attempt of the neuromuscular systems to compensate for inadequacies in the force closure mechanism. At this writing, these strategies have not been investigated in subjects with SIJP.

The purpose of this experimental study was to gain an insight into the motor control strategies adopted by subjects with a clinical diagnosis of SIJP during ASLR and, because the diaphragm is involved, the resultant effect of these strategies on respiratory patterns. It was hypothesized that respiratory function and kinematics of the diaphragm and pelvic floor in a group of subjects with a clinical diagnosis of SIJP would differ from that of a comparison group with no pain during ASLR, and that augmentation of force closure *via* the addition of pelvic compression during ASLR would homogenize the two groups. It was expected that this would provide further validation of the ASLR test and identify compensatory motor control strategies in subjects with this diagnosis.

■ Methods

For this study, 13 participants (11 women and 2 men) with a clinical diagnosis of SIJP were recruited. An equal number of symptom-free subjects matched for gender, age, and body mass index volunteered for the study. Statistical analysis of the two groups showed no significant differences in age, gender, or anthropometric measurements. Subjects were included or excluded according to the strict criteria shown in Table 1. Demographic data for both groups are displayed in Table 2. The study was approved by the Human Research Ethics Committee of Curtin University of Technology, and written informed consent was obtained from all the participants before testing.

Table 2. Demographic Data of Subjects

	SIJP Group	Comparison Group
Age (years)	32.3 ± 11.2	31.4 ± 11.4
Duration of symptoms (months)	40.8 ± 35.7	–
Weight (kg)	64.4 ± 9.3	64.7 ± 14.4
Height (cm)	165.3 ± 8.5	169.5 ± 7.9
BMI (kg/m)	23.8 ± 4.2	22.6 ± 3.5
Subjects postpartum (n)	5	2
Subjects posttrauma (n)	13	0
Subjects with bladder dysfunction (n)	13	0

Mean ± SD.
SIJP = sacroiliac joint pain; BMI = body mass index.

Spirometry and ultrasonography were performed separately with the participant the supine lying position during the following test conditions: at rest, while performing an ASLR, and while performing an ASLR with manual pelvic compression through the ilia. Respiratory rate and tidal volume were recorded using a Stead-Wells water-sealed spirometer (60 Hz, serial number 3657, Warren E. Collins, Inc., Braintree, MA). Subsequently, minute ventilation was calculated.

Movement of the diaphragm and pelvic floor was recorded with a Toshiba Sonolayer SSA 250A real-time ultrasound unit (3.75-MHz probe, serial number 32926, Toshiba, Corp., Tochigi, Japan) in movement mode. For diaphragmatic motion, the probe was positioned in the midclavicular line below the right costal margin.[5] In-built electronic calipers were used to measure displacement of the diaphragm's leading edge over three breaths, and the mean of the three breaths was recorded in millimeters.[3]

Sonography of the pelvic floor was performed transabdominally with the sound head angled inferiorly and posteriorly to the symphysis pubis.[32] Anatomically, the bladder, urethra, and vesical neck are seen as part of the pelvic floor.[6] Given this relation, motion of the inferior bladder was interpreted as motion of the pelvic floor. A resting position of the inferior bladder was recorded as zero using in-built electronic callipers, and movement from this position was recorded in millimeter.

A test–retest repeatability study for all measures was performed on five of the participants from the comparison group to establish the reliability of the measures. Repeat measures of all variables were recorded in each of the three test conditions.

Visual analysis of spirometry data was performed, followed by statistical analysis of both sonography and spirometry data using a two-group (SIJP group and comparison group) for three-condition (resting supine position, ASLR, and ASLR with compression) analysis of variance (ANOVA). Simple contrasts were performed between all possible pairs of the three conditions. A critical alpha value of 0.05 was used to determine statistical significance. Repeatability data were analyzed using a two-way mixed intraclass correlation coefficient for single measures. The data management software package used was SPSS version 10.0 for Windows.

■ Results

Respiratory Function

Minute ventilation was significantly different between the SIJP and pain-free groups ($F[1,24] = 5.49$; $P = 0.028$) and the three testing conditions ($F[1.28,30.63] =$

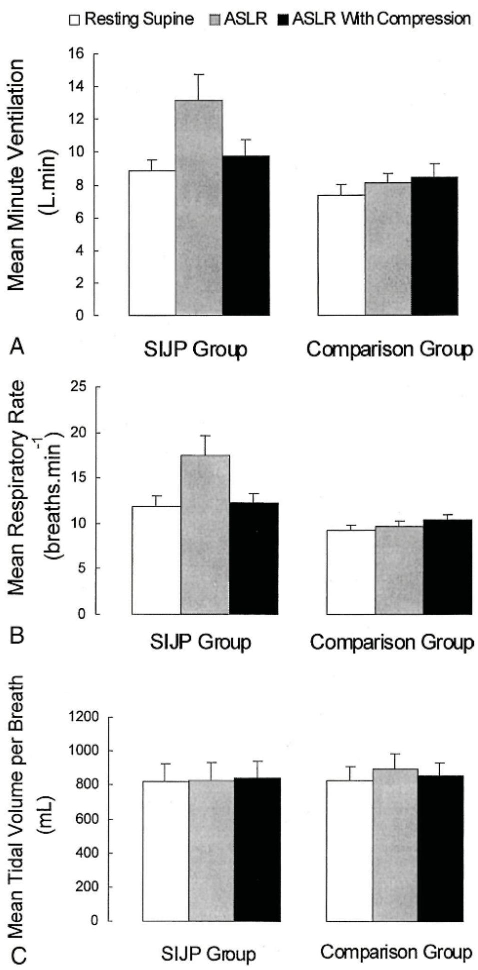

Figure 1. Means (standard error) for minute ventilation (**A**), respiratory rate (**B**), and tidal volume per breath (**C**) during the three test conditions for the sacroiliac joint pain group and the pain-free comparison group.

6.43; $P = 0.011$). An interaction was evident between the resting supine and ASLR conditions ($F[1,24] = 5.17$; $P = 0.032$). The key feature of this interaction was an increase in minute ventilation in the group with SIJP during ASLR (Figure 1A). An interaction between ASLR and ASLR with compression also was identified ($F[1.24] = 4.42$; $P = 0.046$). In the participants with SIJP, it was observed that minute ventilation decreased to a level similar to that in the comparison group (Figure 1A). There was no interaction between the resting supine condition and ASLR with compression ($F[1,24] = 0.07$, $P = 0.800$), indicating that minute ventilation during compression was the same as that during the resting supine condition. The repeatability intraclass correlation coefficient values were 0.91 for the resting supine condition, 0.92 for ASLR, and 0.74 for ASLR with compression.

A subanalysis of minute ventilation was performed to investigate the components of this measure. The respiratory rate was different between the two groups ($F[1,24] = 10.42$; $P = 0.004$) and between the three testing conditions ($F[1.25,29.95] = 5.85$; $P = 0.016$). The difference noted was a respiratory rate increase in the participants with SIJP during ASLR (Figure 1B). No difference in tidal volume was observed between groups ($F[1,24] = 0.055$; $P = 0.816$) or conditions ($F[1.74,41.85] = 0.48$; $P = 0.599$) (Figure 1C).

Respiration Patterns

In the comparison group, the spirometry tracings were observed to be similar across the three test conditions. In contrast, high variability of respiratory pattern was observed in participants with SIJP when performing ASLR. Whereas the overall trend for this group was increased respiratory rate during ASLR (Figures 2A and 2B), two participants demonstrated a decreased respiratory rate. Five participants exhibited transient breath holds during ASLR while displaying an increase in respiratory rate (Figures 2A and 2B). This was observed during either the middle or end phase of inspiration. A large variability in tidal volume was observed in the participants with SIJP. This variability occurred not only between the participants, but within the same participant on a breath-to-breath basis (Figure 2C). With the addition of compression, respiratory rate and tidal volume were normalized and breath holds were eliminated (Figures 2A–C).

Diaphragmatic Excursion

The magnitude of diaphragmatic excursion across all conditions was not significantly different between the two groups ($F[1,24] = 0.97$; $P = 0.335$), whereas a significant difference did exist between the three conditions ($F[2,48] = 22.25$; $P < 0.001$). An interaction was distinguished between the resting supine condition and ASLR ($F[1,24] = 60.93$; $P < 0.001$). The main feature of this interaction was decreased diaphragmatic excursion during ASLR in the participants with SIJP (Figure 3). In seven participants, diaphragmatic motion actually was zero. Again, with the addition of compression, diaphragmatic excursion increased, returning to a level comparable with that of the comparison group (Figure 3). This interaction also was significant ($F[1,24] = 34.85$; $P < 0.001$). An interaction also was found between the resting supine condition and ASLR with compression ($F[1,24] = 9.62$; $P = 0.005$), demonstrating that it did not return to the resting level. This resulted from an initial difference between the two groups during the resting supine condition (Figure 3). The repeatability intra-

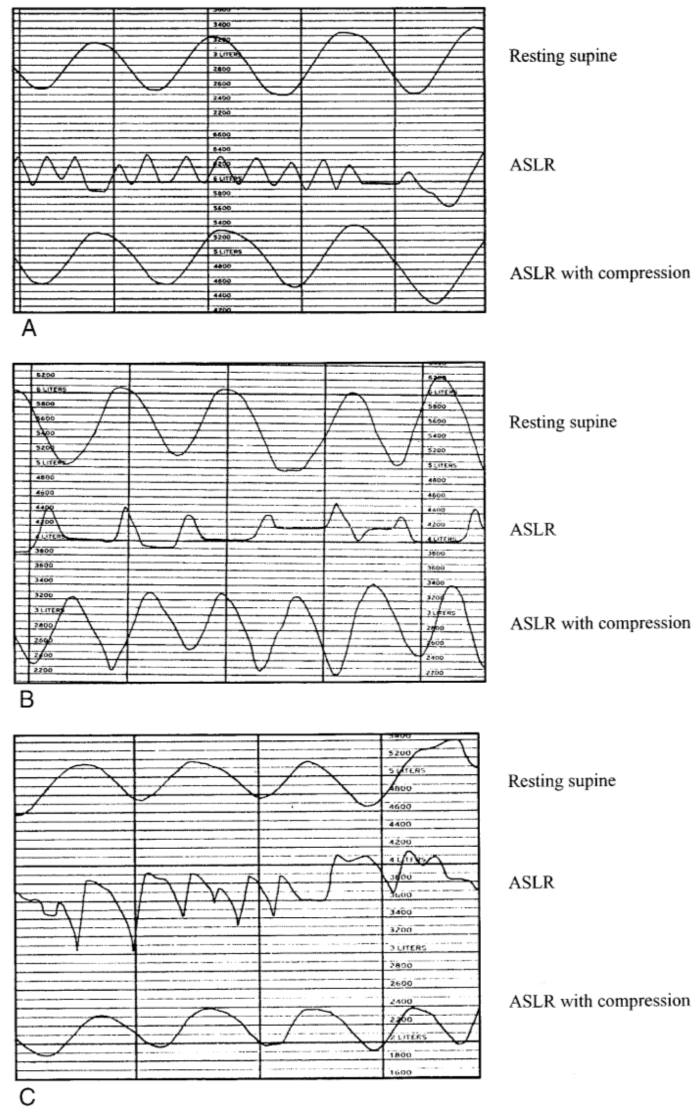

Figure 2. Spirometry traces for three subjects with sacroiliac joint pain. **A**, Increased respiratory rate, decreased tidal volume, and two transient breath holds during the active straight-leg-raise (ASLR) test. **B**, Multiple transient breath holds with increased respiratory rate and decreased tidal volume during the ASLR test. **C**, Erratic tidal volume and increased respiratory rate during the ASLR test.

class correlation coefficient values were 0.94 for the resting supine condition, 0.71 for ASLR, and 0.89 for ASLR with compression.

Pelvic Floor Descent

A significant difference was observed between the two groups ($F[1,24] = 22.95$; $P < 0.001$) and between the two conditions ($F[1,24] = 27.75$; $P < 0.001$) for pelvic floor descent. An interaction between the resting supine condition and ASLR could not be tested because there was no pelvic floor motion in the resting supine condition. However, an interaction did exist between ASLR and ASLR with compression ($F[1,24] = 26.82$; $P < 0.001$). The distinguishing feature of this interaction was

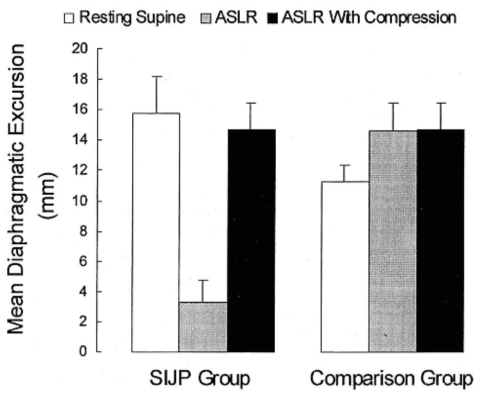

Figure 3. Means for diaphragmatic excursion during the three test conditions for the sacroiliac joint pain group and the pain-free comparison group.

the magnitude of pelvic floor descent during ASLR in the SIJP group (Figure 4). Repeatability intraclass correlation coefficient values for pelvic floor descent were 0.95 for ASLR and 0.85 for ASLR with compression.

■ Discussion

The results of this study document altered breathing patterns and kinematics of the diaphragm and pelvic floor during the ASLR test in subjects with SIJP, as compared with a pain-free comparison group. The addition of pelvic compression during ASLR homogenized the two groups.

Respiratory Responses

This study used real-time ultrasound to measure diaphragmatic motion. The small values measured during tidal breathing of the subject at rest and the absence of a fixed anatomic reference point from which to measure diaphragmatic motion have been suggested as limitations of this method.[4,5] To minimize potential error in measuring diaphragm excursion, the apex of the diaphragm where the largest excursion takes place was measured. The repeatability data for diaphragm excursion were good, implying that low variability was introduced in the measurement approach. In the current study, the measures of diaphragmatic excursion observed with the participant in the supine lying position were comparable with those of other studies using both fluoroscopy[31] and ultrasonography,[2,4] supporting the validity of the instrument and the methods used.

It was observed that the participants with SIJP displayed greater diaphragm excursion at rest than the control group, although no significant difference in minute ventilation, respiratory rate, or tidal volume was observed between the groups. A possible reason for the observed increase in diaphragm motion may have been a lower level of abdominal muscle resting tone in the SIJP participants, resulting in reduced resistance to diaphragm excursion. On the other hand, this increase may reflect an altered resting respiratory pattern in subjects with lumbopelvic pain. Electromyographic studies are required for further investigation of these findings.

During ASLR, the SIJP participants displayed a decrease in diaphragmatic motion, with a complete loss of diaphragmatic motion in seven subjects. This finding represents the presence of a bracing or splinting action of the diaphragm in conjunction with what appears to be increased production of IAP. It is interesting to note that despite the overall decrease in diaphragmatic motion, respiratory function itself actually was enhanced, as indicated by increased minute ventilation. The increase in respiratory rate accounts for the increased minute ventilation. Presumably this was achieved *via* the recruitment of other respiratory muscles, implying a change in respiratory motor control mediated by a neuromuscular mechanism involving musculature not investigated in this study.

The altered diaphragmatic function during ASLR observed in the participants with SIJP may represent the attempt of neuromuscular systems to control load transfer through the lumbopelvic region during limb loading. In this case, it appears that the respiratory function of the diaphragm was disrupted as it was recruited to generate and control IAP. In contrast, subjects in the comparison group had no observed alteration of the diaphragm or respiratory function during ASLR. This indicates that in these participants the neuromuscular system was able to coordinate the respiratory role of the diaphragm with its role as a producer and controller of IAP during physical loading. This view is consistent with the increased levels of IAP generation found in subjects with low back pain during low-level spine loading tasks in weightbearing.[8] Further research is required to investigate the action of the diaphragm and its relation to IAP generation under

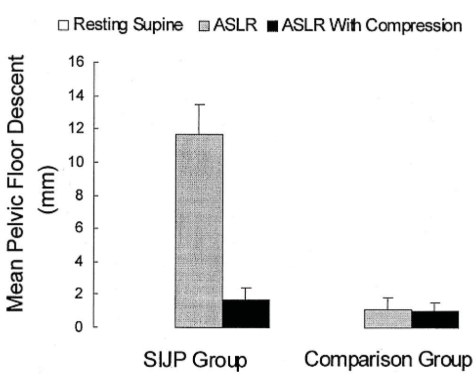

Figure 4. Means for pelvic floor descent during the three test conditions for the sacroiliac joint pain group and the pain-free comparison group. Note that there is no bar for the supine resting condition because the value is zero for both groups.

different respiratory and physical loading demands and in different pain populations, and to clarify its dual function as a respiratory- and trunk-stabilizing muscle.

Pelvic Floor Response

It has been suggested that the pelvic floor plays a role in the control of IAP.[11] It may contribute also to pelvic stability by enhancing force closure.[25,26] In the current study, all the participants with SIJP demonstrated a significant drop of the pelvic floor during ASLR, as compared with little movement in the comparison group. Aberrant movement of the pelvic floor also was reported in another group of subjects with SIJP.[1] One explanation for these findings is that the pelvic floor depression is a response to what appears to be the generation of increased IAP from diaphragmatic splinting during ASLR. Alternatively, pelvic floor descent may reflect a primary motor dysfunction of the pelvic floor muscles. The possibility of pelvic floor musculature dysfunction is supported in this study by the report of impaired bladder control (stress incontinence and urinary frequency) in all the SIJP participants. Currently, further investigation is underway to clarify the nature of these relations.

Sacroiliac Joint Pain

It is accepted that the SIJ can be a source of pain.[7,9,10,15,24] Other authors have defined an association between pelvic pain disorders and pregnancy,[17,19] with Mens et al[18] suggesting that pain may arise from impaired load transference through the pelvic girdle. This impairment can be assessed clinically using the ASLR test.[16] Positive results from the ASLR test alone may not be diagnostic for involvement of the SIJ and its supporting ligaments because other structures such as the symphysis pubis and lumbosacral spine also are stressed during the test. However, all the symptomatic participants in this study reported pain directly over the SIJ without proximal referral,[7,9,10,15,24] had positive SIJ pain provocation test results,[13,14] and positive results on the ASLR test.[16] These findings support the hypothesis that the SIJ, the supporting ligamentous structures, or both were a source of the participants' symptoms. Interestingly, the participants reported that the onset of their symptoms related to a traumatic incident occurred at a time other than the peripartum period. The nature of the trauma involved sudden high load shear forces through the pelvis such as a fall on one buttock. This mechanism is consistent with potential injury to the ligaments of the pelvis, suggesting that trauma may be another etiologic factor in the development of a clinical presentation similar to that observed in peripartum subjects.

Implications

The findings from this study raise a number of questions regarding the ASLR test. These questions relate to the specificity of the test, the implications of the reported sensation of heaviness of the leg, the findings of altered motor and respiratory patterns, and the normalization of motor control patterns after compression of the pelvis.

It could be argued that the motor and respiratory responses observed during ASLR are associated with the adoption of splinting strategies as a reaction to pain,[8] fear of loading painful structures, or both.[27] However, the primary reported problem of subjects during the ASLR test was not that of pain, but of "heaviness" and an inability to lift the leg. This tends to negate the explanation that these findings are simply a motor response to a painful stimulus. Furthermore, the addition of pelvic compression over painful tissue likely would provoke pain and therefore magnify the motor response. In fact, the opposite was the case with the normalization of motor and respiratory patterns observed and the decreased heaviness of the leg reported. The other possibility is that pelvic compression causes increased stiffness in the pelvic joints, which unloads sensitized ligamentous structures, allowing normalized motor responses during ASLR.

The authors propose that the altered motor responses observed during ASLR in subjects with SIJP is an attempt by the neuromuscular system to compensate for a lack of ability to load transfer through the lumbopelvic region resulting from an impairment of form and/or force closure in the pelvis. This proposal is supported by the finding that these observed responses are normalized with application of pelvic compression.

A loss of form closure could arise potentially from an underlying lesion in the ligamentous system of the pelvis after a traumatic injury. In this scenario, the neuromuscular system attempts to compensate for a deficit in the form closure mechanism during ASLR by recruiting the diaphragm to generate IAP, with resultant disruption of respiration. With the application of external pelvic compression, this deficit is compensated for allowing normalization of diaphragmatic and respiratory patterns.

Another possibility is that the participants in this study had underlying dysfunction of the muscles that control force closure of the pelvis, such as the deep abdominal wall and pelvic floor muscles. In this scenario, inability of the neuromuscular system to create adequate force closure of the lumbopelvic region during ASLR may result in substitution strategies such as splinting of the diaphragm and respiratory disruption. In this case, the application of manual pelvic compression compensates for the deficit in the force closure mechanism, normalizing the motor responses. This underlying muscle dysfunction could occur in response to a pain disorder, or it could reflect some underlying motor control deficit in these participants.

A final possibility is that compromise to both the form and force closure mechanisms could coexist in subjects with SIJP. To test these hypotheses, further studies are required to assess the specificity of the ASLR test for different lumbopelvic pain disorders, and to determine whether these motor patterns are associated with other functional movement tasks demanding load transfer through the lumbopelvic region.

Enhancement of pelvic stability *via* compression has been demonstrated theoretically,[25,26,28] and in subjects with peripartum pain syndrome.[16] The action of the deep abdominal muscles to enhance stiffness in the SIJ also has been demonstrated.[22] This suggests that an intervention program focused on integrating control of the deep abdominal muscles with normal pelvic floor and diaphragm function may be effective in managing subjects with SIJP, as defined in this study. Outcome studies are required to test this premise, and to determine whether the altered motor control strategies observed in this study can be normalized with a resultant resolution of symptoms and disability.

In conclusion, this study documents changes in the kinematics of diaphragm and pelvic floor muscles, with consequential alteration of respiratory function during the ASLR test in subjects with SIJP. It is hypothesized that these alterations in motor control result from an ineffective attempt by the neuromuscular system to maintain lumbopelvic stability during ASLR. The reversal of these alterations with the addition of pelvic compression supports and validates the use of this test procedure to assess load transfer in subjects with apparent impairments of lumbopelvic stability.

■ Key Points

- Altered motor control patterns have been reported in subjects with a clinical diagnosis of sacroiliac joint pain, but have not been formally investigated previously.
- Altered kinematics of the diaphragm and pelvic floor were observed in subjects with sacroiliac joint pain during the active straight-leg-raise test.
- Resultant disruption in respiratory patterns is associated with the altered kinematics of the diaphragm and pelvic floor during the active straight-leg-raise test.
- The augmentation of force closure *via* manual compression through the ilia normalizes these altered motor control strategies.

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Appendix 4: Changes in pelvic floor and diaphragm kinematics and respiratory patterns in subjects with sacroiliac joint pain following a motor learning intervention: a case series

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Original article

Changes in pelvic floor and diaphragm kinematics and respiratory patterns in subjects with sacroiliac joint pain following a motor learning intervention: A case series

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Abstract

This study was a case series design. The objectives of the study were to investigate the ability of a motor learning intervention to change aberrant pelvic floor and diaphragm kinematics and respiratory patterns observed in subjects with sacroiliac joint pain (SIJP) during the active straight leg raise (ASLR) test.

The ASLR test is a valid and reliable tool to assist in the assessment of load transference through the pelvis. Irregular respiratory patterns, decreased diaphragmatic excursion and descent of the pelvic floor have been reported in subjects with SIJP during this test. To date the ability to alter these patterns has not been determined.

Respiratory patterns, kinematics of the diaphragm and pelvic floor during the ASLR test and the ability to consciously elevate the pelvic floor in conjunction with changes in pain and disability levels were assessed in nine subjects with a clinical diagnosis of SIJP. Each subject then undertook an individualized motor learning intervention. The initial variables were then reassessed.

Results showed that abnormal kinematics of the diaphragm and pelvic floor during the ASLR improved following intervention. Respiratory patterns were also influenced in a positive manner. An inability to consciously elevate the pelvic floor pre-treatment was reversed. These changes were associated with improvement in pain and disability scores.

This study provides preliminary evidence that aberrant motor control strategies in subjects with SIJP during the ASLR can be enhanced with a motor learning intervention. Positive changes in motor control were associated with improvements in pain and disability. Randomized controlled research is required to validate these results.

Keywords: Diaphragm; Low back pain; Motor control; Pelvic floor; Respiration; Sacroiliac joint

1. Introduction

The sacroiliac joint (SIJ) and surrounding ligamentous structures are reported to be a source of symptoms in subjects with a diagnosis of non-specific chronic low back pain (Young et al., 2003). Recent research has focused on a test that investigates the ability of a subject to transfer load between the lower limb and the trunk, called the active straight leg raise (ASLR) test. The validity and reliability of this test procedure has been established in subjects with clinically diagnosed SIJ pain (SIJP) (Mens et al., 2001, 1999; O'Sullivan et al., 2002a). This test involves lying supine and raising the leg 5 cm off the supporting surface. The test is positive when accompanied by a primary sensation of profound heaviness of the leg (±pain), which is relieved with the application of compression across the ilium. This test is reported to be positive in a sub-group of subjects with SIJP (Mens et al., 1999; Pool-Goudzwaard et al., 2005). It has been proposed that the reduction in the sensation of heaviness with the application of compression across the ilia reflects enhanced force closure through the SIJ (Pool-Goudzwaard et al., 1998; O'Sullivan et al., 2002a).

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Recent research has documented motor control deficits in the presence of SIJP (O'Sullivan et al., 2002a). O'Sullivan et al. (2002a) reported in a group of SIJP subjects with a positive ASLR the presence of aberrant motor control strategies observed during the ASLR test when compared to pain-free controls. Using real time ultrasound and spirometry, the authors' demonstrated decreased diaphragmatic motion, increased descent of the pelvic floor, increased minute ventilation and respiratory rate, and altered breathing patterns in the pain subjects during the ASLR. These aberrant motor control strategies were eliminated with the addition of manual compression through the ilia applied during the ASLR.

It was hypothesized that these disruptions might represent a deficit in local motor control (pelvic floor, transverse abdominal wall) within the lumbopelvic region in these subjects. This manifested as the adoption of splinting or bracing strategies of the abdominal wall with associated disrupted patterns of respiration during the ASLR, not observed in the normal subjects (O'Sullivan et al., 2002a). Furthermore the normalization of these patterns with the application of compression supported this notion. The adoption of these splinting strategies appears to represent an underlying deficit in the motor control systems ability to provide adequate local compression, or force closure, to the SIJs during the ASLR (O'Sullivan et al., 2002a). This concept is also supported by the report that abdominal bracing is less effective than preferential activation of the transverse abdominal wall muscles for increasing the compression across the SIJs (Richardson et al., 2002).

To test the validity of this hypothesis we proposed that the application of a motor learning intervention directed to the local stabilizing muscles of the pelvis would result in the normalization of the aberrant motor control strategies displayed by these subjects, with associated reductions in pain and disability.

Previous studies have reported motor learning interventions to be effective in altering specific motor control deficits in the presence of chronic low back (O'Sullivan et al., 1997, 1998) and knee pain (Cowan et al., 2002), but to date no study has investigated these specific changes with SIJP during the ASLR test.

2. Methods

Nine subjects (8 female and 1 male) with a clinical diagnosis of SIJP and a positive ASLR test were recruited for this study. These subjects were recruited directly from a previous study by O'Sullivan et al. (2002a) providing a series of clinical case studies. Four of the 13 subjects from the original study declined to be involved in the intervention aspect of the study as they were already under different forms of management. The inclusion criteria included pain over the SIJ without proximal referral (Maigne et al., 1996; Young et al., 2003) present for a duration of at least 3 months and showing no signs of abating, no impairment of spinal range of motion, a positive ASLR test (Mens et al., 1999, 2001) and at least three out of five positive pain provocation tests which include: (1) posterior shear test (Ostgaard et al., 1994; Laslett et al., 2005); (2) sacral torsion test (Laslett et al., 2005); (3) sacral thrust test (Laslett et al., 2005); (4) distraction test (Laslett et al., 2005); and (5) tenderness on palpation of the long dorsal SIJ ligament (Vleeming et al., 2002). Potential subjects were excluded if they had a specific radiological diagnosis for their pain disorder, the presence of radicular pain, neurological deficits or disorders, hip joint pathology, an inflammatory disorder, a history of a significant respiratory disorder, were pregnant or less than 6 months post partum and/or had a body mass index of greater than 31 kg/m as previously described by O'Sullivan et al. (2002a, b). The demographic data for this group is displayed in Table 1.

The methodology used in this paper has been previously utilized and described in detail (O'Sullivan et al., 2002a). Respiratory rate, tidal volume, diaphragmatic motion and pelvic floor kinematics were measured in resting supine, during the ASLR and during the ASLR with the application of manual compression through the ilia. In addition pelvic floor kinematics were measured while subjects were instructed to consciously elevate their pelvic floor muscles as described in detail elsewhere (Thompson and O'Sullivan, 2003). A Stead–Wells water-sealed spirometer (60 Hz, serial number: 3657, Collins, USA) was used to record respiratory rate and tidal volume from which minute ventilation was calculated. Movement of the diaphragm was recorded utilizing real-time ultrasound to visualize the leading edge of the diaphragm (Cohen et al., 1994). The probe was positioned transversely and angled superiorly below the right costal margin in the midclavicular line. Pelvic floor motion was also recorded using real-time ultrasound with the probe positioned trans-abdominally and

Table 1
Demographic data of subjects

Age in years	34.9 (11.2)
Gender	8 female/1 male
Duration of symptoms in months	44.1 (41.2)
Weight (kg)	64.8 (6.5)
Height (cm)	164.3 (6.5)
BMI (kg/m^2)	24.2 (3.4)
Number of subjects post-partum	4
Number of subjects post-trauma	9
Number of subjects with a subjective complaint of bladder dysfunction	9

Data expressed as mean (standard deviation).

angled inferiorly and posteriorly (Walz and Bertermann, 1990). This allowed visualization of the bladder. Due to the anatomical relationship of the bladder to the pelvic floor (DeLancey, 1994) motion of the inferior bladder can be interpreted as motion of the pelvic floor. For both variables inbuilt electronic calipers were used to record motion. A Toshiba Sonolayer SSA-250A (serial number: 32926, Shimoishigami, Japan) real-time ultrasound unit (3.75 MHz probe) in movement mode was used for this purpose. The reliability of these methods have been previously reported (O'Sullivan et al., 2002a; Thompson and O'Sullivan, 2003; Sherburn et al., 2005; Thompson et al., 2005).

Subjects then underwent a motor learning intervention tailored to their individual clinical presentation over a 12-week period. Three treating physiotherapists were involved in the study. The specifics of this intervention are discussed below. Following the intervention the dependant variables were reassessed. Measurements were carried out in a clinical practice by one of two physiotherapists, one of whom was also involved in the intervention process. In conjunction with these physiological measures the Short Form McGill Pain Questionnaire (Melzack, 1987) including a visual analogue scale for pain severity and the Oswestry Disability Index (Fairbank et al., 1980) were employed to document changes in pain and functional status following the treatment period. The study was approved by the Human Research Ethics Committee of Curtin University of Technology and written informed consent was obtained from all participants prior to testing.

Initial data analysis involved visual inspection of the spirometry traces. Statistical analysis was then performed with SPSS Version 10.0 for Windows. Sonography and spirometry data were analysed using a 2 group (pre/post-treatment) by 3 condition (resting supine, ASLR, ASLR with compression) analysis of variance. Simple contrasts were performed between all possible pairs of the three conditions. Paired *t*-tests were performed on the pain and disability measures as well as the pelvic floor kinematics during conscious pelvic floor contraction. A critical alpha value of 0.05 was used to determine statistical significance.

3. Intervention model

The motor learning intervention model utilized in this study was adapted from work described elsewhere (O'Sullivan et al., 1997; Richardson et al., 1999; O'Sullivan, 2005b). This model is directed by the specific classification of a group of disorders where deficits in motor control appear to be a mechanism for increased strain and resultant ongoing pain (Elvey and O'Sullivan, 2005; O'Sullivan, 2005a). Within this management model the impairments of motor control that are considered to be linked to the pain disorder are identified, and correct patterns are trained within a cognitive as well as a physical framework. The aim of the intervention was to retrain the local stabilizing muscles of the pelvis in a functional and automatic manner while gaining pain control and enhancing functional capacity. The reported functional impairments for each individual specifically directed their intervention although all patients reported pain aggravation during sustained sitting and standing.

Components of the intervention paradigm are presented in Fig. 1. Each subject was initially educated that they had specific deficits in their local stabilizing muscles of the pelvis (pelvic floor, transverse fibres of the abdominal wall) that had resulted in increased strain across the pain sensitive structures of the pelvis. These deficits were identified as a potential mechanism for ongoing pain and disability. Training of each subject began in supine crook lying with a semi-full bladder utilizing transverse abdominal real-time ultrasound imaging of the pelvic floor. This was conducted as a means of providing visual feedback in order to teach each subject to achieve an elevating contraction of the pelvic floor with simultaneous co-contraction of the lower transverse abdominal wall (transverse abdominis and the transverse fibres of internal oblique) without associated breath holding and/or global bracing of the abdominal wall (Thompson et al., 2006a). Once the correct pattern of contraction had been achieved, the holding capacity of the muscles was trained for up to 30 s at a time. This stage took up to 4 weeks of training.

This new motor pattern was then progressed to upright sitting, with the pelvis in slight anterior tilt, a neutral lumbar lordosis and the thorax in a relaxed neutral position. The exact sitting position was considered critical to enable pain control and facilitate automatic activation of the local stabilizing muscles (O'Sullivan et al., 2002b; O'Sullivan et al., 2006). The holding capacity in this posture was then trained so that the posture could be maintained for long periods of time, such as sitting in a non-supported chair for up to 30 min while watching TV or reading, in order to improve the endurance of the trunk postural muscles.

Concurrently subjects were instructed in moving from sitting to standing while maintaining appropriate lumbopelvic alignment, to enable pain-free transfer of load during functional movement tasks. Subjects were then taught to alter their standing posture to align the thorax over the pelvis with a neutral lumbar lordosis, and avoid 'sway' postures known to inhibit the local stabilizing muscles of the lumbopelvic region (O'Sullivan et al., 2002b). This new posture was then trained in its holding capacity during single leg standing followed by walking. Initially subjects were instructed to walk

PHYSICAL COMPONENTS OF MOTOR LEARNING INTERVENTION

Elevating contraction of the pelvic floor with simultaneous co-contraction of the lower transverse abdominal wall (transverse abdominis and the transverse fibres of internal oblique) without associated breath holding and/or global bracing of the abdominal wall

↓

Train neutral lordosis in sitting with relaxed thoracic postures

↓

Train load transfer such as sit to stand

↓

Train aligned standing posture (avoiding sway standing) with neutral lumbar lordosis and relaxed thorax

↓

Integrate postural alignment into single leg stance and walking

↓

Train trunk loading such as bending and lifting as directed by aggravating factors reported by patient

COGNITIVE COMPONENTS OF INTERVENTION

- Enhanced understanding of the pain mechanism
- Enhanced body awareness and control
- Learning strategies to develop pain control
- Enhancement of positive coping strategies and beliefs regarding disorder
- Self management of disorder
- Enhancement of functional capacity
- Independence from passive treatment

Fig. 1. The first part of this figure presents a paradigm for clinical utility of the physical dimension of the intervention model. This is complimented by list of the cognitive components of the intervention model.

with control until they could hold the motor pattern for up to 30 min at a time.

Other functional movement tasks were then identified and retrained based on pain provoking activities reported by each of the subjects. It is important to note that each subject reported pain control when they were able to adopt the new postures while maintaining their motor pattern.

Each subject was seen weekly over a period of 12 weeks and instructed to carry out a home exercise programme on a daily basis. Three subjects wore SIJ belts during the first 3 weeks of the training period until they had achieved functional activation of their local stabilizing muscles at which time they reported that they no longer required the belt. No other co-interventions were carried out during the study period.

4. Results

The individual pre-treatment data for respiratory rate, tidal volume, diaphragmatic motion and pelvic floor kinematics for these subjects was extracted from our previous study (O'Sullivan et al., 2002a) and reprocessed as a new group to provide the pre-intervention baseline for this case intervention series.

4.1. ASLR tasks

4.1.1. Pelvic floor kinematics

As there was no pelvic floor motion in resting supine this condition was not included for analyses. A significant difference was found between pre- and post-treatment ($F = 12.142$, $P = 0.008$) and between the remaining two conditions ($F = 48.700$, $P < 0.001$). There was an interaction between ASLR and ASLR with manual pelvic compression ($F = 12.374$, $P = 0.008$). The distinguishing feature of this interaction was the decrease in pelvic floor descent during the ASLR following the intervention (Fig. 2). No subject had any descent of the pelvic floor during the ASLR with compression post-treatment.

4.1.2. Diaphragmatic excursion

A significant difference between pre- and post-treatment ($F = 6.105$, $P = 0.039$) was found for diaphragm excursion and between the three conditions ($F = 11.915$, $P = 0.006$). An interaction was distinguished between resting supine and the ASLR ($F = 25.928$, $P = 0.001$), and between ASLR and ASLR with manual pelvic compression ($F = 19.837$, $P = 0.002$). The main feature of this interaction was increased diaphragmatic excursion during the ASLR post-intervention (Fig. 3).

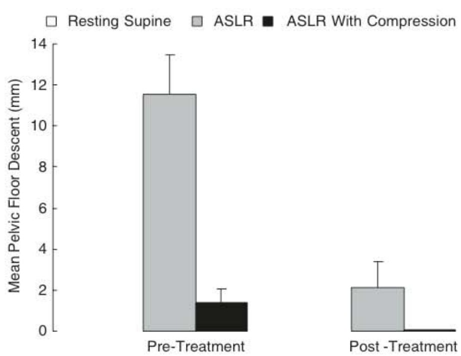

Fig. 2. Mean (standard error of the mean) measurements for pelvic floor descent pre- and post-treatment. Note there is no bar for resting supine as there was no pelvic floor movement during this test condition. The graph depicts decreased descent of the pelvic floor during the ASLR post-treatment. Note there is no error bar for pelvic floor descent post-treatment during the ASLR with compression as all subjects had no descent during this task.

4.1.3. Respiratory function

Changes in minute ventilation did not reach a statistically significant difference pre- and post-treatment ($F = 4.966$, $P = 0.056$) nor between the conditions ($F = 4.008$, $P = 0.069$). However, a trend towards reduced minute ventilation during the ASLR post-intervention was observed (Fig. 4A).

Subanalysis of the components of minute ventilation was also undertaken. Respiratory rate was reduced in post-intervention compared to pre-intervention ($F = 8.563$, $P = 0.019$), however a significant difference was not identified between the three test conditions ($F = 1.267$, $P = 0.339$). No significant interaction was found between resting supine and the ASLR ($F = 2.465$, $P = 0.155$) or between the ASLR and ASLR with compression ($F = 2.861$, $P = 0.129$). Fig. 4b therefore denotes a trend towards decrease respiratory rate during the ASLR after the intervention. No difference in tidal volume was observed pre- and post-treatment ($F = 1.900$, $P = 0.205$) or between conditions ($F = 0.286$, $P = 0.760$).

The respiratory traces across all subjects were variable. In spite of a lack of statistically significant difference, visual inspection of the respiratory traces highlighted interesting changes between the pre- to post-intervention period. Three cases are depicted in Fig. 5 as examples. (Note: pre-treatment traces were previously reported in O'Sullivan et al. (2002a).) The notable feature of these traces is the marked improvement of the respiratory traces during the ASLR following intervention. The increase in respiratory rate and decrease in

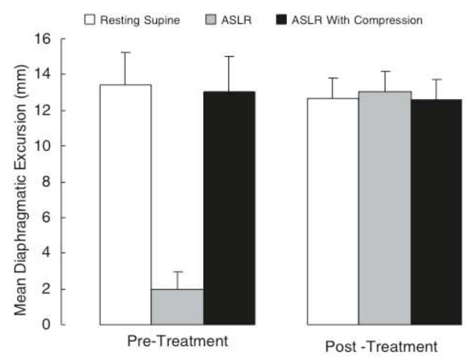

Fig. 3. Mean (standard error of the mean) measurements for diaphragmatic excursion pre- and post-treatment, denoting increased diaphragmatic motion during the ASLR following the intervention period.

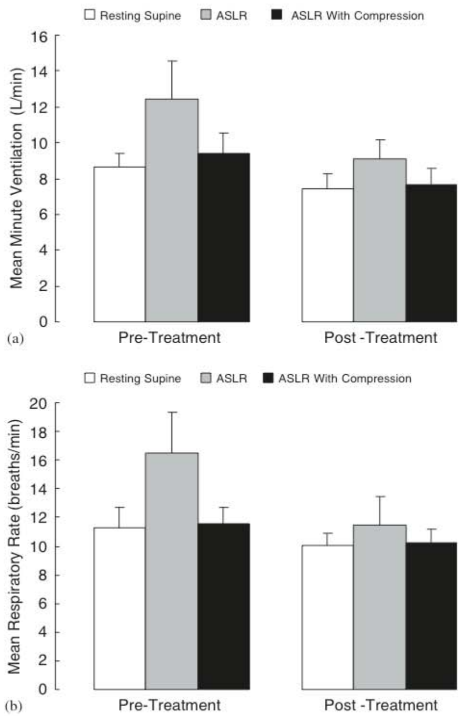

Fig. 4. Mean (standard error of the mean) values for: (a) minute ventilation, and (b) respiratory rate, during the three test conditions before and after treatment. Both denote trends for improvement during the ASLR post-treatment.

tidal volume during the ASLR observed in Fig. 5a before the intervention match that of the resting supine condition post-intervention. Similarly the multiple breath holds displayed during the ASLR pre-intervention in Fig. 5b, denoted by the flat line in the respiratory trace, are not observed after the intervention. The erratic pattern seen in Fig. 5c during the ASLR, while not equivalent to resting supine post-intervention, has improved.

4.2. Conscious pelvic floor elevation task

Pelvic floor kinematics during conscious contraction of the pelvic floor before and after intervention was only available for eight of the nine subjects due to lost data. Prior to the intervention all subjects exhibited descent of the bladder with this task. The average magnitude of this descent was 11.5 mm ($SE = 2.09$). After the intervention all subjects demonstrated elevation during conscious pelvic floor contraction with an average magnitude of 6.12 mm ($SE = 0.97$). This change was significantly different ($P<0.001$). It was recorded in the treatment notes that all subjects reported improved bladder function following the intervention although this was not formally measured.

4.3. Pain and disability scores

Significant differences were found between pre- to post-treatment for the Short Form McGill Pain Questionnaire ($P<0.001$), the VAS for usual pain ($P = 0.001$) and the Oswestry Low Back Pain Questionnaire ($P = 0.003$), denoting reductions in pain and disability associated with the intervention (Fig. 6). In addition it was recorded in the treatment notes that all subjects reported reduced heaviness during the ASLR test following the intervention although this was not formally measured.

5. Discussion

This study provides preliminary evidence that a specific motor learning intervention for subjects with SIJP can positively change pelvic floor and diaphragm kinematics and patterns of respiration observed during the ASLR. These changes were associated with concurrent reductions in pain and disability in a group of chronically disabled pelvic pain subjects. However as this study is a case series and did not have a control group or blinded independent investigators, the findings should be viewed with caution. Randomized controlled research is required to validate these results.

While it is well recognized that movement and motor control impairments commonly co-exist with lumbopelvic pain disorders (O'Sullivan et al., 2002a; Hungerford et al., 2003; Pool-Goudzwaard et al., 2005), the mere presence of these impairments does not establish cause and effect. Movement and motor control impairments are known to occur secondary to the presence of pain (Hodges and Moseley, 2003; van Dieen et al., 2003) as well as pathological and psychological processes (Frymoyer et al., 1985; Hall and Elvey, 1999; Hodges and Moseley, 2003; Marras, 2004; O'Sullivan, 2005a). Attempts to simply 'normalize' movement or motor control impairments in many of these disorders without consideration for their underlying mechanism may be inappropriate and ineffective.

There is however growing evidence that some disorders do exist where movement and motor control impairments appear to result in abnormal tissue loading and pain, leaving them amenable to specific physical therapy intervention (O'Sullivan et al., 1997; Hides et al., 2001; Cowan et al., 2002; Stuge et al., 2004b). Furthermore there is evidence that patterns of abnormal

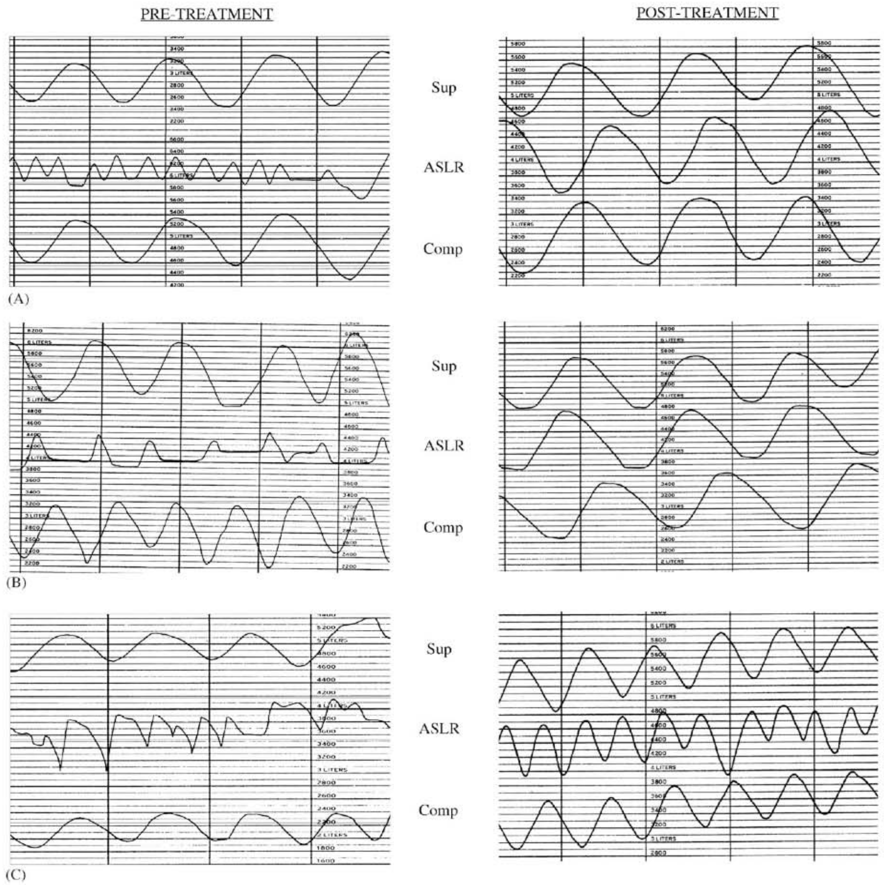

Fig. 5. Respiratory patterns of three subjects before and after treatment. Traces for Subjects A and B during the ASLR post-treatment match that of the resting supine condition. Subject C demonstrates an improved, though not fully resolved, respiratory pattern during the ASLR post-treatment. Pre-treatment traces previously published in O'Sullivan et al (2002a) (Sup = resting supine, ALSR = active straight leg raise, Comp = ASLR with manual pelvic compression).

motor behaviour can be altered with specific exercise or motor learning interventions, leading to improvements in pain and disability in specific pain populations (O'Sullivan et al., 1998; Cowan et al., 2002). Clearly a priority for clinicians is the ability to identify specific patient groups for whom motor learning interventions are appropriate and effective.

The subjects in this current study represent a subgroup with non-specific chronic pelvic pain as they had no radiological diagnosis specific for their disorder. Selection was based on specific clinical inclusion criteria. There is growing evidence to support that this cluster of signs and symptoms are associated with pain disorders of the SIJ and its supporting structures (Mens et al., 2001; Young et al., 2003; Stuge et al., 2004a; Laslett et al., 2005; Pool-Goudzwaard et al., 2005).

In our previous paper we proposed that the altered pelvic floor and diaphragm kinematics and patterns of respiration in subjects with SIJP during an ASLR that were normalized with manual pelvic compression (O'Sullivan et al., 2002a) may reflect loss of force closure within the pelvis, secondary to a deficit in the

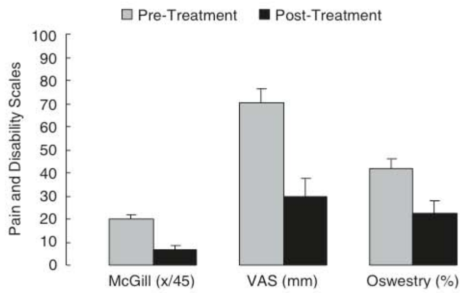

Fig. 6. Mean (standard error of the mean) scores pre- and post-treatment for the Short Form McGill Pain Questionnaire, the Visual Analogue Scale for usual pain and the Oswestry Low Back Pain Questionnaire. Significant improvements were found for all three of these variables.

local muscles such as the pelvic floor and transverse abdominal wall. Biomechanical studies show that the pelvic floor and transverse abdominal wall have the capacity to locally compress or stabilize the SIJs (Snijders et al., 1993a, b; Richardson et al., 2002; Pool-Goudzwaard et al., 2004; van Wingerden et al., 2004). Growing evidence suggests that dysfunction of these muscles is present in subjects with SIJP (Avery et al., 2000; O'Sullivan et al., 2002a; Hungerford et al., 2003; Pool-Goudzwaard et al., 2005). The improvement of the altered motor control patterns in the current study, following a motor learning intervention targeting these local force closure muscles, lends support for this hypothesis. Further to this the clinical reports of the reduction of the 'heaviness' associated with the ASLR may be suggestive of an enhanced motor control strategy for load transfer across the pelvis during the ASLR.

Recent research has documented that depression of the pelvic floor is associated with generation of high levels of intra-abdominal pressure and global activation of the pelvic floor, abdominal wall and chest wall muscles (Thompson et al., 2006a). These bracing strategies have been shown less able to locally stabilize the SIJs (Richardson et al., 2002) and have been reported to be associated with reduced muscle activity of the pelvic floor during pelvic floor muscle contraction in women with bladder control disorders (Thompson et al., 2006b). Recent research has also documented a relationship between pelvic pain and bladder control disorders with increased pelvic floor muscle activation (Pool-Goudzwaard et al., 2005). Further research into the functioning of the pelvic floor muscles in conjunction with the other muscles of the abdomino-pelvic cavity is required to further identify patterns of altered motor control in subgroups with SIJP. In contrast a lifting contraction of the pelvic floor (as was trained in this study), is associated with high levels of activation of the pelvic floor and transverse abdominal with minimal activation of the external oblique, rectus abdominis and chest wall muscles, minimal increase in intra-abdominal pressure and allows relaxed respiration (Sapsford et al., 2001; Thompson et al., 2006a). This local stabilizing strategy has been shown to enhance the stability of the SIJs (Richardson et al., 2002) and is also considered important for the control of continence (Bo et al., 1988; Thompson et al., 2006a). In light of this research, the findings of the current study support that a more local stabilizing strategy was adopted in the subjects following the training period, compared to a straining pattern prior to the intervention. This trained strategy closely reflects a normal motor control pattern associated with the ASLR under the pelvic compression condition, and that previously documented in a pain-free population during ASLR (O'Sullivan et al., 2002a). It was also interesting to note the subjective reports that bladder control symptoms reduced in subjects following the intervention period. This may be suggestive of a positive change in the motor control strategies associated with the control of intra-abdominal pressure and activation of the pelvic floor muscles associated with the control of continence. Further research is warranted to further investigate these issues.

Stuge and co-workers have recently reported long-term benefits from a specific stabilizing exercise programme directed to the lumbopelvic region in subjects with post partum pelvic pain (Stuge et al., 2004a, b). Interestingly these authors reported that the normalization of the ASLR test was associated with increased functional mobility and reductions in pain in this group of subjects. These findings suggest that the change in the ASLR was predictive of outcome in these subjects. In contrast Mens et al. (2000) reported that global training of the trunk muscles did not result in reduction of pain and disability in subjects with pelvic pain.

It should be noted that improvement of the motor patterns associated with the ASLR in this study did not fully resolve the pain disorder, but rather was associated with reductions in pain and disability. Furthermore the intervention had both a functional and cognitive component to it, with subjects being taught to utilize their local stabilizing muscles so as to enhance their functional capacity with pain control. These findings may support that other physical, neurophysiological and cognitive factors may also be associated with these pain disorders. Such factors may include underlying disruption to the pelvic ligaments resulting in ongoing compromise to the form closure mechanism of the pelvis, central nervous system adaptation resulting in ongoing tissue sensitization due to a chronic pain state and cognitive factors such as anxiety, fear avoidance behaviour and poor coping strategies.

Although it cannot be ruled out that the improvements observed were as a result of a change in the subjects' natural history, this is unlikely given that the subjects had reported chronic disabling pelvic pain for an average of 44 months with no sign of abating prior to the intervention. Furthermore there is a possibility that the changes observed were due to a placebo effect secondary to the expectation of improvement with treatment. Certainly further research is indicated to repeat this study using a randomized-controlled clinical trial design with long-term follow-up and greater subject numbers. Furthermore, repeating this study with concurrent measures of IAP and muscle activity would also provide further insight into the exact motor control strategies that were utilized in these subjects before and after the intervention period.

In conclusion this study provides preliminary case-based evidence that altered kinematics of the pelvic floor and diaphragm, as well as disrupted respiratory patterns, observed in subjects with SIJP can be shifted towards those patterns observed in pain-free individuals with a motor learning intervention. Furthermore the improvement of these motor patterns was associated with functional improvements and decreased symptoms. These findings may provide some insight into the relationship between motor control strategies and the ASLR test in subjects with SIJP, however further research is required to validate this.

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Appendix 5: Methodological Issues

Premise of the methodological section

Each individual study (Chapter 4 to 8) has an integrated methods section, fully detailing the methodology particular to those studies. This appendix discusses broader methodological issues faced in the design and implementation of the project as a whole. Specifically these are:

A. Calibration of intra-abdominal pressure (IAP) and intra-thoracic pressure (ITP) catheter
B. Sterilisation of the pressure catheter
C. Rationale for IAP and ITP processing method
D. Rationale for electromyography (EMG) processing method
E. Measurement of pelvic floor (PF) movement
F. Subject recruitment
G. Test procedure

A. Calibration of intra-abdominal pressure and intra-thoracic pressure catheter

The equipment used in this thesis to monitor IAP and ITP pressure fluctuations consisted of a custom-made silicone nasogastric catheter (Dentsleeve International Ltd, Mississauga, Canada) which had sterile saline solution passed through tiny lumen in the catheter at high pressure. Changes in the flow rate of the saline through the lumen that occur in response to changes in pressure were monitored with custom-built pressure transducer equipment.

Calibration of this system required the use of a known, reproducible pressure. For this purpose a column of water was used. Pressure at a known depth was calculated with the following formula:

$$P_2 = P_1 + \rho g h$$

where:

P_1 = pressure at the surface
= 1.01×10^5 Pa

ρ = density of water
= 1×10^3 kg.m^{-3}

g = acceleration due to gravity
= 9.8 m.s^{-2}

h = depth of water

Calibration data were collected with a custom LabVIEW v6.1 data collection program. Data were collected at seven depth increments in a column of water. Three seconds of data were collected at each depth and averaged to give a single value for that depth. Data from both channels were collected simultaneously. With the catheter in a vertical position there is a difference in the sensing positions of 10cm, meaning the depths over which each channel were measured were slightly different. Measures were repeated three times at each depth for each channel. This data is represented graphically in Figure A1.

The data were investigated to ensure a linear output from the pressure transducers in relation to changes in depth. The scatter plot graphs (Figure A1) show this to be the case, and this is reinforced by the goodness of fit values for each line of best fit (Table A1). Thus a linear equation could be utilised for calibration purposes.

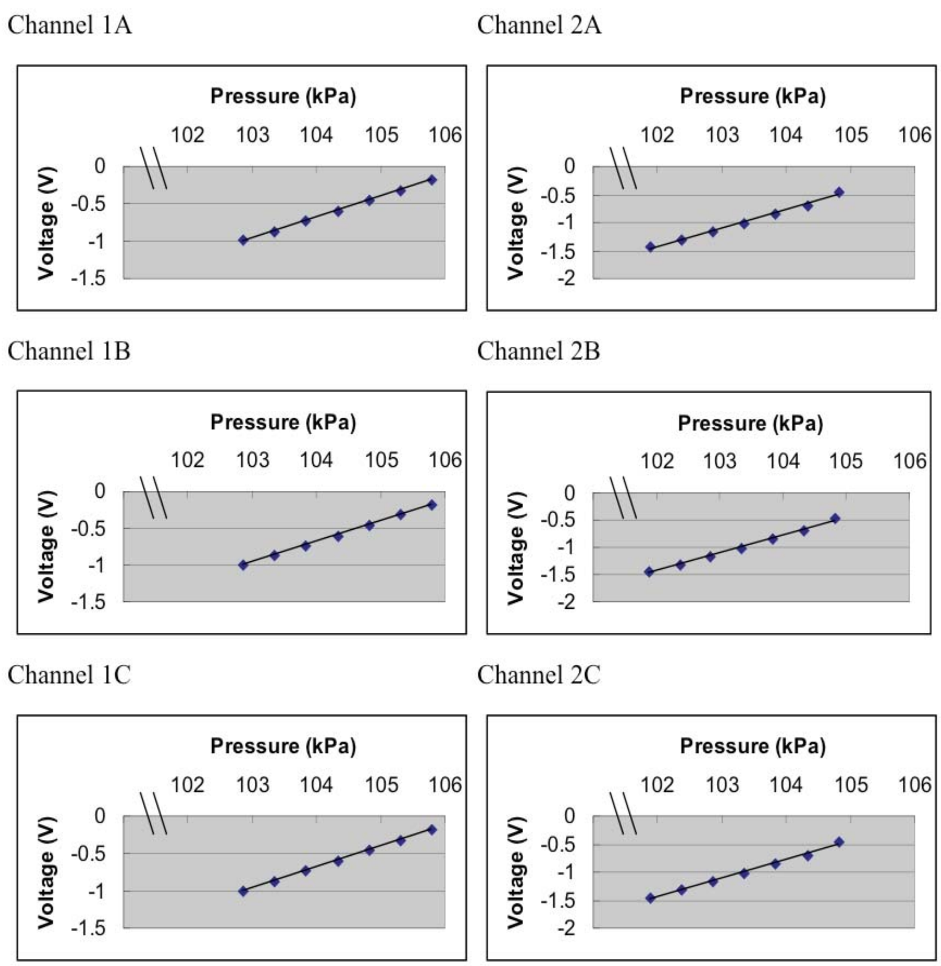

Figure A1: Scatter plots of data collected for the two pressure channels from known depths in a column of water for the purpose of calibration. Line of best fit included on each graph.

Given that a linear equation could be used, the 'forecast' function in Microsoft Excel 2000 was used in conjunction with the raw data to calculate pressure values for 0V and 1V respectively. These numbers were then subtracted from one another to leave the pressure change, in Pascal's, for a change of 1V in the raw data. These values have been included in Table A1. The calibration values of the three trials were averaged for use in data processing during the separate studies in this thesis.

Table A1: Linear equation (y = a + bx) values, goodness of fit (r^2) and calibration values for calibration data.

Channel	Trial	a	b	r^2	Calibration (Pa)
1	A	- 29.501	0.0003	0.9994	3606.959
1	B	-29.529	0.0003	0.9995	3604.163
1	C	-29.638	0.0003	0.9996	3591.16
2	A	-35.1	0.0003	0.9914	3004.637
2	B	-35.074	0.0003	0.9928	3011.064
2	C	-34.933	0.0003	0.9946	3029.161

It was also necessary to ascertain if changes in the pressure input into the flow resistor would affect the output from the pressure transducer. The input pressure would naturally change over time as the fluid drained from the saline bag. Also there could be minor changes in inflation of the cuff between trials. Thus the pressure system was calibrated at half of the standard input pressure (ie 20kPa) that was used during the original calibration trials. The outcome of this calibration series was that the slope of the line of best fit remained at 0.0003. The goodness of fit was between 0.9997 and 0.9999. These results mean that the input pressure did not alter the calibration constants for each channel. Thus constant recalibration of the pressure system was not required.

B. Sterilisation of the pressure catheter

The custom-made silicone nasogastric catheters (Dentsleeve International Ltd, Mississauga, Canada) used in this thesis were reusable. The following procedure for cleaning and sterilisation was used, which adheres to the manufactures recommendations.

CLEANING

1) Body fluids should not be allowed to dry in or on the assembly
2) Directly after use the catheter shall be immersed in a bowl of warm, mild detergent solution. It shall be wiped several times.
3) A 20 ml syringe will be used to flush all channels with the detergent solution.

RINSING

1) The catheter shall be rinsed in clean water.
2) The catheter will then be cover in a towel.
3) Each channel will be flushed with water and then air.

STERILISATION

1) The catheter shall be autoclaved to ensure adequate sterilisation
2) The catheter will be steam autoclaved at 134 degrees for 5 minutes at 30 psi/206 kpa
3) A total cycle of 30 minutes will be used to allow for warm up and cool down.

C. Rationale for intra-abdominal pressure and intra-thoracic pressure processing method

Much of the research investigating IAP and ITP looks at measures such as peak pressure and average pressure. Visual inspection of the pressure traces (Figure C1) indicated that these types of values would be inadequate to describe the observed pressure changes. A process was required which would distinguish changes in pressure related to respiration from changes in pressure related to the physical task of an ASLR.

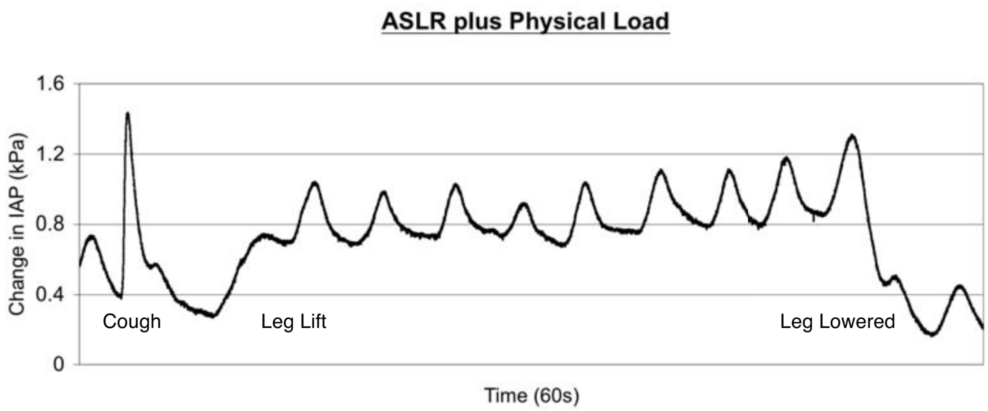

Figure C1: This trace for intra-abdominal pressure (IAP) during an active straight leg raise (ASLR) with additional physical load highlights the inadequacies that would occur in using either peak or average pressure values during this task.

A respiratory fluctuation value was utilised to indicate pressure changes in relation to breathing (Figure C2). This was calculated for one specific breath cycle (start of inspiration to end of expiration) by:

$$P_{RF} = P_{max} - P_{min}$$

where:

P_{RF} = respiratory fluctuation of pressure over one breath cycle

P_{max} = maximum pressure value over the breath cycle

P_{min} = minimum pressure value over the breath cycle

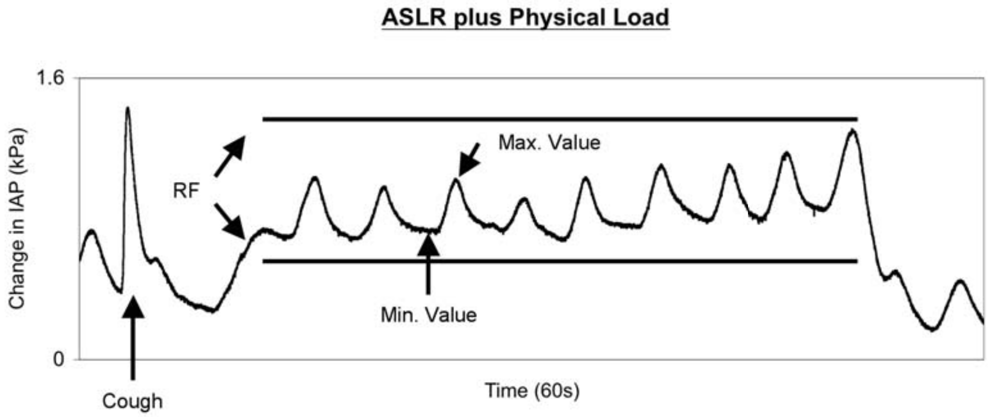

Figure C2: The respiratory fluctuation (RF) component of an intra-abdominal pressure (IAP) trace. This is calculated by subtracting the minimum pressure value of a single breath cycle (Min. Value) from the maximum of the same breath cycle (Max. Value).

A baseline shift of pressure was used to indicate pressure changes related to physical load (Figure C3). Specifically this was lifting the leg during a task involving the ASLR. This was calculated by:

$$P_{BS} = (P_{B1min} + P_{B2min} + P_{B3min}) / 3) - P_{RS\ min}$$

where:

P_{BS} = baseline shift of pressure

P_{B1min} = minimum pressure value over first breath cycle

P_{B2min} = minimum pressure value over second breath cycle

P_{B3min} = minimum pressure value over third breath cycle

$P_{RS\ min}$ = average minimum pressure value over three resting supine breath cycles

This was slightly modified when performing an ASLR with inspiratory resistance (see Chapter 7: Study 4), where values from inspiratory resistance in supine were substituted for resting supine breathing values indicated in this formula.

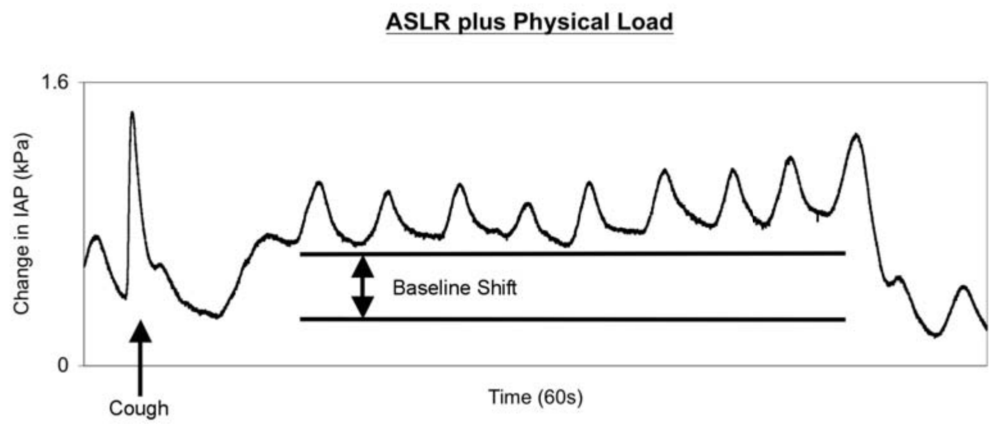

Figure C3: The baseline shift component of an intra-abdominal pressure (IAP) trace. This was calculated by subtracting the average minimum pressure value of a three breath cycle during resting supine from the average minimum pressure value of a three breath cycle during the active straight leg raise (ASLR) inclusive task.

D. Rationale for the electromyography processing method

A consideration for this project was to differentiate respiratory muscle activation from muscle activation related to the physical load of lifting a leg during ASLR tasks. Respiratory activation would be denoted by phasic activity over a breath cycle. Activation in response to lifting the leg would be tonic in nature. Hence 500ms of muscle activity from both the inspiratory and expiratory phases of a breath cycle were taken for processing purposes (Figure D1).

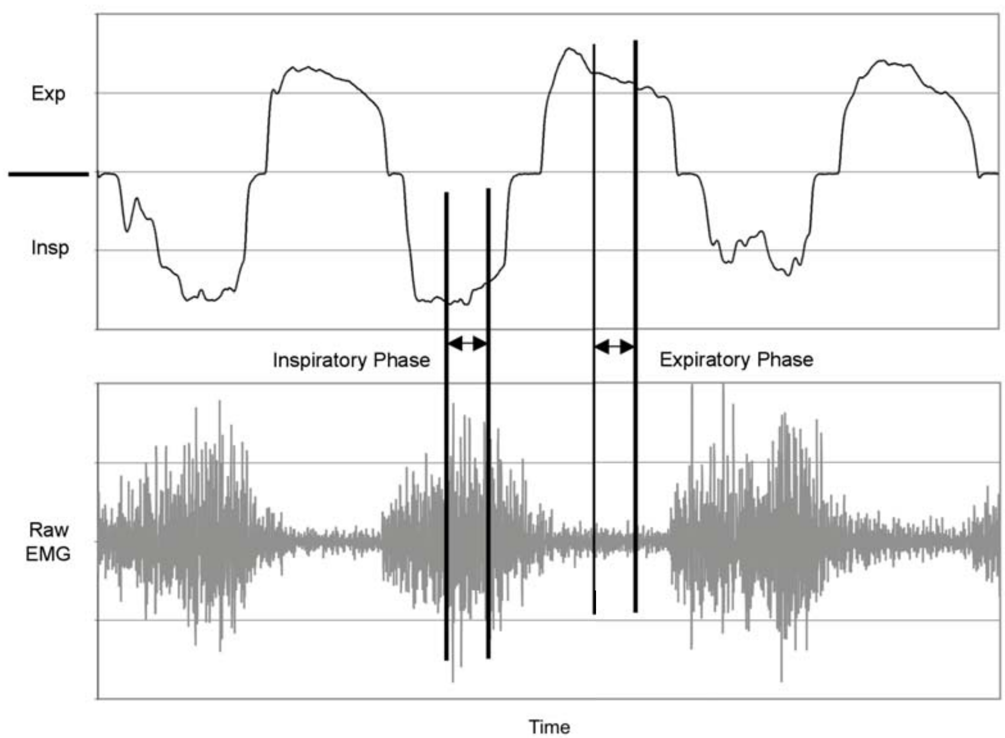

Figure D1: Graphical representation of the electromyography (EMG) processing procedure. Samples of EMG, 500ms in duration, during inspiration (Insp) and expiration (Exp) allowed the examination of phasic versus tonic muscle activation.

E. Measurement of pelvic floor movement

Our previous investigation of PF movement with real time ultrasound utilised the inbuilt electronic calipers of the ultrasound unit to quantify this variable. That method was deemed unsatisfactory in terms of practicality and would not allow accurate synchronisation of data collection for all variables. A digital measuring technique was adopted to solve these problems.

Output from the real time ultrasound unit was recorded to digital videotape at the time of data collection. It was then converted to digital video file format:

File type- WMV
Bit Rate- 512.0Kbps
Display- 320 x 240
Frame Rate- 30 frames/s

The PF video was synchronised to the other variables via a cough, which produced downward movement of the bladder and concurrent EMG activity. Then specific frames were cut from the digital video. Movement of the pelvic floor in relation to performing an ASLR utilised a frame cut just prior to lifting the leg and another frame taken as soon as the PF position had stabilised after lifting the leg (Figure E1). Respiratory related movement of the PF utilised two frames at each limit of motion during a breath cycle.

The images were transported to photo editing software where the base of the bladder was marked with a horizontal line (Figure E1). The two images were then overlaid and the transparency of the uppermost image adjusted to 50% such that the lines placed on both pictures were simultaneously visible (Figure E2). The measuring function of the software was used to measure the number of pixels between the two lines. Measurements were also made of the scale from the real time ultrasound unit on the side of the still image, allowing conversion from pixels to millimeters.

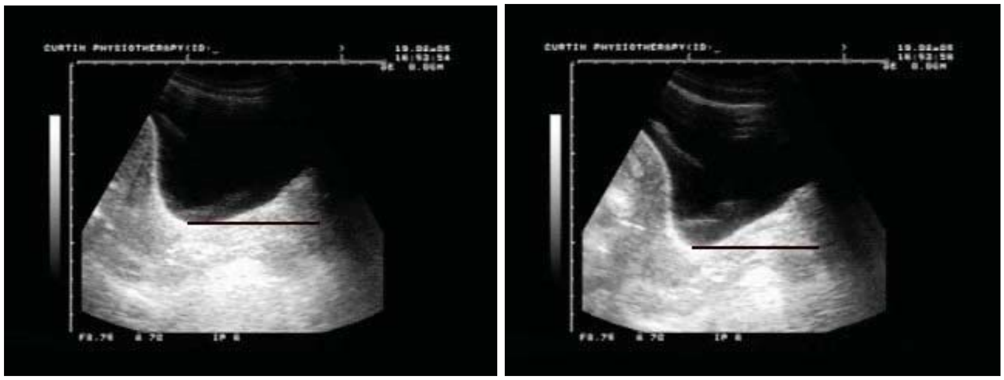

Figure E1: Video frames pre-active straight leg raise (ASLR) and post-ASLR, with markings for the base of the bladder. (Note: finer lines were used in processing, thicker line here just for visual acuity at this scale)

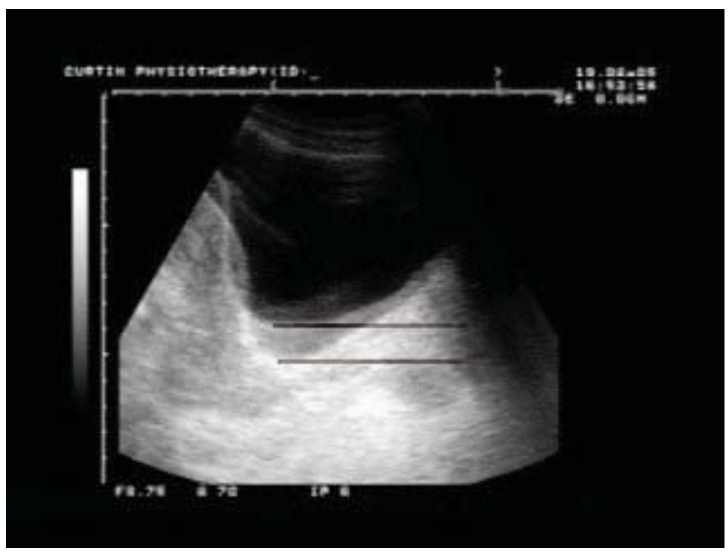

Figure E2: Pre-active straight leg raise (ASLR) and post-ASLR video frames overlaid for measurement purposes.

To assess the reliability of this measurement procedure a pilot study was performed on real time ultrasound footage collected from 10 subjects. Movement of the PF during an ASLR with additional load around the ankle was measured from the same video on two separate occasions. The intra-class correlation coefficient between measures was 0.997, with a 95% confidence interval of 0.988 - 0.999, indicating excellent consistence between measurement occasions.

F. Subject recruitment

Specific inclusion and exclusion criteria for pain free and chronic pelvic girdle pain (PGP) subjects are presented in the separate studies. Pain free subjects were recruited from amongst colleagues and their acquaitances. A short questionnaire was used to determine their eligibility according to the exclusion criteria.

Pain subjects were recruited from referral by health practitioners supplied with the selection criteria, and by advertisement in local newspapers. Potential subjects were screened via telephone interview with regard to the exclusion criteria. If they were not excluded, they were informed of the test procedures at this time, particulary with regard to the invasive nature of measuring IAP and ITP. If they were willing to proceed, they were physically examined by the primary investigator against the inclusion criteria as documented within the body of this thesis (see Table 4.2). Consecutive potential subjects were physically evaluated according to these criteria until 12 suitable subjects were found.

The results of the pain provocation tests and palpation of the sacroiliac joints for each subject are shown in Table F1. An ASLR on the affected side of the body was considered positive if; (i) the score was at least two out of five on the ASLR subjective scoring scale where 0=Not Difficult, 1=Minimally Difficult, 2=Somewhat Difficult, 3=Fairly Difficult, 4=Very Difficult and 5=Unable To Perform (Mens, Vleeming, Snijders, Koes, & Stam, 2002), and (ii) this score reduced when the ASLR was repeated with pelvic compression (see Table 4.3 for results).

Table F1: Results of the sacroiliac joint pain provocation tests, including palpation, for all subjects with chronic pelvic girdle pain. Positive results mean that the test reproduced the subject's primary pain in the area of the sacroiliac joint. (PPPP = posterior pelvic pain provocation test, Thrust = sacral thrust test, Torsion = pelvic torsion test, P = positive, N = negative)

Subject	PPPP	Thrust	Torsion	Distraction	Palpation
1	P	P	P	N	P
2	P	P	P	N	P
3	P	P	P	P	P
4	P	P	P	P	P
5	P	P	P	N	P
6	P	P	P	P	P
7	P	P	N	P	P
8	P	P	N	P	P
9	P	P	P	P	P
10	P	P	N	N	P
11	P	P	N	P	P
12	N	P	N	P	P

G. Test procedure

The separate studies described in this thesis were performed on one group of subjects during a single testing session.

Other than where noted in the specific studies, for the pain free subjects this procedure was:

1. EMG sub-maximal normalisation contractions
2. Resting supine
3. Right ASLR
4. Left ASLR
5. Repeat 3 and 4
6. Right ASLR with pelvic compression
7. Left ASLR with pelvic compression
8. Right ASLR with inspiratory resistance
9. Repeat 8
10. Left ASLR with additional physical resistance
11. Repeat 10.

Other than where noted in the specific studies, for the chronic PGP subjects this procedure was:

1. EMG sub-maximal normalisation contractions
2. Resting supine
3. ASLR on affected side of the body
4. ASLR on non-affected side of the body
5. Repeat 3 and 4
6. ASLR on affected side of the body with pelvic compression
7. ASLR on non-affected side of the body with pelvic compression
8. ASLR on affected side of the body with inspiratory resistance
9. Repeat 8
10. ASLR on non-affected side of the body with inspiratory resistance
11. Repeat 10.

The testing procedure was standardised in this fashion so that any effect of fatigue would be the same for all subjects.

References for Appendix 5

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