The effect of lumbar posture on spinal loading and the function of the erector spinae: implications for exercise and vocational rehabilitation

Grant A Mawston *PhD*

Mark G Boocock *PhD*

Health and Rehabilitation Research Institute, Department of Physiotherapy, AUT University, Auckland, New Zealand

ABSTRACT

Lumbar posture is considered to play an important role in low back injury and is of importance during the rehabilitation of clients employed in manual handling occupations. This clinical commentary discusses the implications of lumbar posture on the biomechanical loads placed on the active and passive tissues of the spine, and the contribution the erector spinae play during tasks involving lifting and lowering. There is evidence that lumbar posture can significantly alter the functional role of the erector spinae when lifting and lowering and has implications for the loads that the spine must contend with. This review provides insight into the issues relating to lumbar posture that need to be considered when educating and prescribing exercises for the prevention and management of those individuals involved in manual handling activities.

Mawston GA, Boocock MG (2012) The effect of lumbar posture on spinal loading and the function of the erector spinae: implications for exercise and vocational rehabilitation. New Zealand Journal of Physiotherapy 40(3): 135-140.

Key words: Lumbar spine, posture, erector spinae, spinal loading

INTRODUCTION

Low back pain is one of the most common musculoskeletal disorders treated by physiotherapists. The incidence of low back pain is particularly high in vocations involving manual handling activities, such as lifting and lowering (Magnusson et al 1990, Marras et al 1993). In the past, a number of studies have focused on the benefits of lifting techniques (stoop versus squat) to reduce compressive loading on the lumbar spine. However, the benefits of one technique over another have proved inconclusive (van Dieen et al 1999). More recently, lumbar posture when performing manual handling tasks has been identified as an important factor for the risk of back injury. For example, epidemiological evidence would suggest there is a higher incidence of low back injury associated with those manual handling occupations where workers adopt extreme trunk flexion (Hoogendoorn et al 2000, Punnett et al 1991).

From a biomechanical perspective, lumbar posture during lifting and lowering is important because as the lumbar spine flexes it undergoes a change in configuration that influences the role played by the passive tissues of the spine and the active contribution of the erector spinae. For example, high levels of lumbar flexion have been associated with increased ligamentous and lumbar disc loading, and elevated anterior shear forces (Adams and Dolan 1996, Arjmand et al 2011, McGill 1997, Potvin et al 1991). The lumbar posture adopted during lifting and lowering also influences the morphology, geometry and muscle activation levels of the erector spinae. A change in lumbar curvature can alter fascicle obliquity, lever arm distance, and the length-tension relationships of the erector spinae (McGill et al 2000, Raschke and Chaffin 1996, Singh et al 2011, Tveit et al 1994). These factors influence the ability of erector spinae to resist moments and exert forces (McGill et al 2000, Tveit et al 1994).

From a clinical perspective, understanding the influence lumbar posture has on passive (e.g. discs and ligaments) and active (the erector spinae) subsystems of the spine during lifting and lowering has important implications for postural education and exercise prescription when dealing with clients who are actively involved in manual handling tasks.

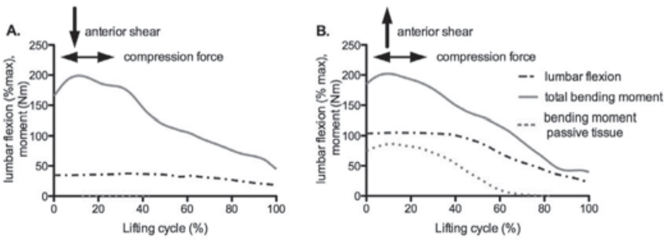
Hence, the aim of this clinical commentary is to discuss some of the biomechanical principles associated with lumbar posture, spinal loading, and erector spinae muscle activity and highlight the implications for the education and the rehabilitation of those involved in manual handling activities.

The effects of lumbar flexion on spinal loading and the risk of injury

The extent to which the lumbar spine is flexed when lifting and lowering is important as it determines the bending moments and anterior shear forces acting on the passive tissues of the spine (Adams and Dolan 1991, Dolan et al 1994a, Potvin et al 1991). Cadaver studies and *in vivo* experiments have found that the bending moment resisted by spinal ligaments and discs (passive tissues) increases exponentially when the spine is flexed beyond 80% of maximal *in vivo* flexion (Adams and Dolan 1991, Dolan et al 1994b).

Figure 1 illustrates this concept and shows that the bending moment on the passive tissues of the spine is high when a person adopts a fully flexed posture (approaching 100% lumbar flexion) at the start of a lift (Figure 1B) compared to someone who adopts a lordotic posture (Figure 1A – approximately 40% flexion). Note that the overall bending moment is similar for both lifters. Equations developed by Adams and Dolan (1991) for estimating the bending moment resisted by the passive tissues of the spine at different lumbar flexion angles indicates that there is virtually no bending moment resisted by the spinal discs and ligaments when the lumbar spine is flexed to 40% (Figure 1A). In contrast, at approximately 100% lumbar flexion the total bending moment resisted by the passive tissues rises to approximately 80 Nm (Figure 1B). Interestingly, the recruitment of passive tissues of the lumbar spine during flexion does not tend to result in a change in spinal compression forces (van Dieen et al 1999). Furthermore, even though the subject in Figure 1B approaches maximal lumbar flexion, the forces that the discs and ligaments must contend with only reach approximately 40% of their elastic limit (Adams and Dolan 1991). However, at the end range of lumbar flexion recruitment of the interspinous ligament complex imposes considerable anterior shear force on the lumbar spine, which has the potential to damage the spine at much lower forces than the spine can withstand in compression (McGill 1997, Potvin et al 1991).

Figure 1. Lumbar flexion (% maximum), total bending moment, and bending moment resisted by the passive tissues of the spine when lifting. Subject A adopts 40% maximum lumbar flexion while subject B adopts near maximum flexion. ↑ indicates increased anterior shear force, ←→ indicates no difference in compression forces between the two postures.



The potential for highly flexed postures to damage the lumbar spine becomes more evident when repetitively lifting and/or lowering. Studies that have simulated repeated loading at end range of lumbar flexion have found an attenuation of the erector spinae reflex response to aid spinal stabilisation and an increase in spinal ligament and intervertebral disc creep (Adams and Dolan 1996, Solomonow 2012, Solomonow et al 1999). Furthermore, when lumbar spine cadaver segments are loaded to simulate a moderate weight being lowered in 45 degrees lumbar flexion, this has been shown to result in spinal tissue damage at an average of 263 repetitive cycles (lumbar flexion-extension), compared to 3257 and 8253 cycles for a spine flexed at 22 and 0 degrees, respectively (Gallagher et al 2005).

The influence of lumbar posture on erector spinae geometry

The major trunk muscles responsible for resisting and controlling the bending moment and anterior shear forces acting on the lumbar spine when lifting and lowering are the erector spinae (Macintosh and Bogduk 1986, McGill et al 1988). In the past, it was assumed that the erector spinae were a single muscle group with similar morphology throughout. However, detailed anatomical studies have differentiated the erector spinae into two distinct subdivisions: 1) the upper erector spinae; and 2) the lumbar erector spinae. Each division has differing geometry in relation to the lumbar spine, which changes with increased lumbar flexion.

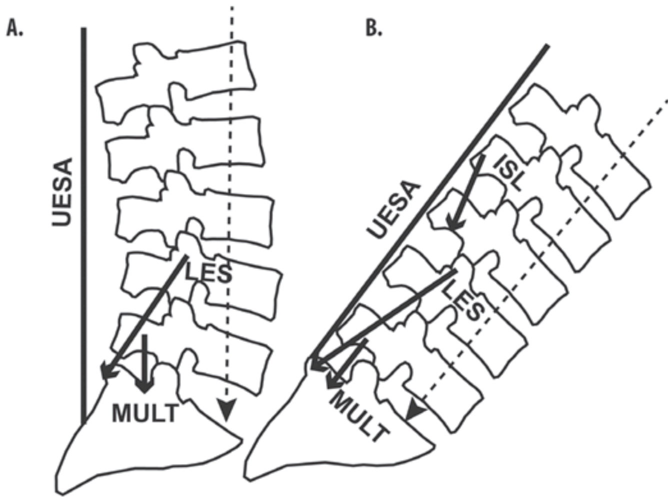
The upper erector spinae consist of the thoracic fibres of iliocostalis lumborum and longissimus thoracis. Thoracic fibres of longissimus and iliocostalis lumborum arise from thoracic spine (Macintosh and Bogduk 1987) and span the entire lumbar spine forming the erector spinae aponeurosis which moves freely over the lumbar erector spinae (Macintosh and Bogduk 1994), connecting to the sacrum and posterior superior iliac spine (Macintosh and Bogduk 1987). In a lordotic posture the upper erector spinae have the greatest moment arm of all the lumbar extensors (Daggfeldt and Thorstensson 2003), which allows them to generate a large extensor moment that resists bending forces produced by forward inclination of the trunk (Macintosh and Bogduk 1987).

The local subgroup of the erector spinae are those muscles whose fascicles originate and insert on the vertebrae of the lumbar spine and pelvis (Bergmark 1989). This group primarily includes the poly segmental muscles – the lumbar components of longissimus and iliocostalis, and multifidus (Bogduk and Twomey 1987), and are often termed the lumbar erector spinae. The lumbar fibres of iliocostalis lumborum and longissimus thoracis are more angulated relative to the vertebral column than the multifidus or the upper erector spinae, with a substantial increase in obliquity towards the L4-L5 region (Macintosh and Bogduk 1991). Therefore, when contracted bilaterally during a symmetrical activity, such as lifting in a lordotic posture, the lumbar fibres of iliocostalis lumborum and longissimus thoracis have the potential to produce large posterior translation and resist anterior shear forces acting on the lumbar spine (Macintosh and Bogduk 1991). The lumbar fibres of iliocostalis lumborum and longissimus have a closer proximity to the spine and, therefore, have less ability to resist bending moments on the spine than the upper erector spinae (Callaghan and McGill 1995). Due to their fascicle obliquity, they are also less able to resist anterior sagittal rotation than multifidus (Macintosh and Bogduk 1991).

Another key muscle of the local erector spinae is multifidus. Multifidus consists of multiple, overlapping layers of fibres (Bojadsen et al 2000). Each fascicle arises from a common tendon attached to the spinous process of individual lumbar vertebrae with fascicles attaching to the mamillary process of the inferior vertebrae, the iliac crest and the sacrum (Macintosh and Bogduk 1986). This fascicle arrangement and segmental innervation gives multifidus the potential to control motion of individual vertebra of the lumbar spine (Bogduk et al 1982). Fascicles of multifidus arise from a common tendon and form a vertical force vector that acts at approximately 90 degrees to the spinous process (Figure 2A). The vector lies behind the axis of sagittal rotation giving multifidus a mechanical advantage when it comes to producing an anti-flexion (extension) moment (Macintosh and Bogduk 1986).

The transition from a lordotic lumbar posture to a fully flexed lumbar spine alters the geometry of the upper erector spinae and lumbar erector spinae, potentially reducing their ability to generate extensor torque and resist anterior shear (Figure 2). Tveit et al (1994), using magnetic resonance imaging, found that at the end range of lumbar flexion the lever arm of the upper erector spinae aponeurosis is reduced by between 10% and 20% throughout the lumbar spine when compared to a lordotic posture. Therefore, it was argued that the reduction in lever arm length would require more muscle force to counteract a given bending moment. Data reported by Macintosh et al (1993) would suggest that the lever arm length of the lumbar erector spinae is also reduced in flexion, but to a lesser extent than the upper erector spinae. However, spinal flexion significantly alters the obliquity of lumbar erector spinae fascicles, which become more closely aligned to the spinal vertebrae resulting in a decrease in the ability to resist anterior shear forces (Macintosh et al 1993, McGill et al 2000, Singh et al 2011). Lumbar flexion has less of an effect on the fascicles of multifidus because of the relatively vertical orientation of the fibres (Macintosh et al 1993).

Figure 2. A schematic diagram showing the changes in the geometry of the upper erector spinae aponeurosis (UESA), lumbar erector spinae (LES) and multifidus (MULT) with a lordotic lumbar posture (A) and maximal flexion (B). In the flexed posture, the erector spinae are elongated, the UESA moves closer to the centre of the disc and the lumbar erector spinae obliquity is reduced. The recruitment of the posterior ligamentous system (including the interspinous ligament (ISL)) in flexion adds to anterior shear. The dotted arrow indicates the compressive axis.



The influence of lumbar posture on trunk extensor torque

Although increased lumbar flexion alters the geometry of the erector spinae in a way that can potentially compromise its ability to generate an extension moment and resist anterior shear, authors who have investigated back extensor torque in static lumbar postures have found increases in torque as the spine becomes more flexed. For example, Roy et al (2003) found that the extensor torque produced in 50 degrees lumbar flexion was twice that produced in a neutral standing (0 degrees) and four-fold that generated in a hyper-lordotic posture (-20 degrees).

This ability to produce considerably greater torque in a flexed lumbar posture has been attributed to increase in the length of the erector spinae (Raschke and Chaffin 1996). As the spine becomes flexed the erector spinae increase muscle fascicle length by an average of 39% of that in a neutral lumbar posture (Macintosh et al 1993). This increased length can increase extensor torque production in two ways. Firstly, an increase in erector spinae length, or stretch, has the potential to store elastic energy within the muscle and provide resistance against bending forces (McGill et al 1994). Secondly, greater torque in a flexed posture may be explained by the length-tension relationship. Raschke and Chaffin (1996) investigated the association between erector spinae length and tension (torque production) using modelling techniques. They found that the length-tension relationship of the erector spinae increases linearly up to 45 degrees of trunk flexion. This suggests that optimal torque production could occur in spinal postures approaching 80% of maximum flexion, independent of passive tissue recruitment.

The length-tension relationship of the erector spinae seems to be supported by studies that have investigated the effect of lumbar posture on the ratio of extensor torque production to levels of erector spinae muscle activation (neuromuscular efficiency ratio) (Roy et al 2003, Tan et al 1993). Evidence has shown that the neuromuscular efficiency ratio increases with increased lumbar flexion at both maximal and submaximal effort (Roy et al 2003, Tan et al 1993). These findings suggest that as the lumbar spine becomes more flexed the length-tension relationship for the erector spinae optimises and less muscle activation is required for a given torque (Granata and Rogers 2007, Roy et al 2003, Tan et al 1993).

The influence of lumbar posture on erector spinae muscle activation and lumbar spine kinematics during dynamic lifting and lowering

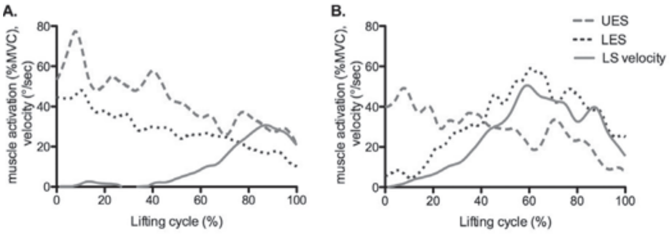
Lifting

An important aspect of transitioning clients into manual handling activities is understanding the relationships between levels of erector spinae muscle activation and lumbar kinematics. These relationships provide an indication of the magnitude of erector spinae recruitment and the types of muscle action (isometric, concentric, and/or eccentric) occurring during lifting and lowering. The lumbar posture (lordotic versus flexed) adopted at the initiation of a lift has a significant bearing on the type and intensity of muscle activity.

Figure 3A shows an example of a person initiating a lift with a lordotic posture (40% of maximal flexion) and the rate of change in lumbosacral angle (angular velocity) and the extent of erector spinae muscle activation. When lifting with a lordotic posture, the upper erector spinae and lumbar erector spinae show similar activation patterns. At the initiation of the lift both the upper erector spinae and lumbar erector spinae activation peak and there is minimal change in lumbar curvature (Figure 3A). This would suggest that the primary action of the erector spinae during the initial stages of a lift is isometric. The advantage of having a relatively stationary lumbar spine during the early stages of lifting is that erector spinae torque production is greater at low levels of lumbar spine velocity (McGill and Norman 1986, Raschke and Chaffin 1996). A relatively static lumbar posture is followed by the dynamic (concentric) phase where the lumbar spine extends rapidly and activation levels of both the upper erector spinae and lumbar erector spinae decrease (Figure 3A). A reduction in activation levels towards the termination of the lift would be expected because as a person lifts their centre of mass and the mass of the load progressively move closer to the to the base of the spine (Keyserling 2000).

When using a flexed lifting posture the upper erector spinae and lumbar erector spinae display quite different activation patterns. Figure 3B shows an example of a person initiating

Figure 3. Upper erector spinae (UES) and lumbar erector spinae (LES) muscle activation expressed as a percentage of maximum voluntary contraction (MVC), and angular velocity of the lumbar spine (LS) during a lift. The subject in Figure 3A uses a lifting technique with minimum of lumbar flexion and in Figure 3B with near maximum lumbar flexion. The lumbar erector spinae of the subject who initiates the lift in fully flexed posture (3B) exhibit the "flexion-relaxation phenomenon", followed by an increase in activation as the angular velocity of the lumbar spine increases.



a lift in maximum lumbar flexion and the changes in lumbar angular velocity and erector spinae muscle activation that occur. During the initiation of the lift, upper erector spinae activation reaches a peak. However, at the same time the lumbar erector spinae is relatively inactive (Figure 3B). The reduction in lumbar erector spinae activity at the end range of lumbar flexion has been termed the flexion-relaxation phenomenon and has been commonly reported in both static postures and during lifting and lowering (Floyd and Silver 1955, Kippers and Parker 1984, Shan et al 2012, Toussaint et al 1995). This phenomenon is thought to occur because the passive tissues of the spine are recruited at end range of lumbar flexion to support the bending moment (Delitto and Rose 1992, Dickey et al 2003, Holmes et al 1992). Throughout the remainder of the lift the activity of the upper erector spinae decreases, whereas lumbar erector spinae activation reaches a peak during the middle of the lift (de Looze et al 1993, Holmes et al 1992, Toussaint et al 1995). This peak in lumbar erector spinae activity corresponds with the point at which lumbar angular velocity is at its highest (Mawston 2010). These activation patterns observed when lifting with a flexed posture may reflect the different functional roles of the upper erector spinae and lumbar erector spinae (Mawston et al 2010). The upper erector spinae is at an increased mechanical advantage when compared to the lumbar erector spinae and is better placed to resist bending moment at the start of the lift (Toussaint et al 1995). However, the morphology of the lumbar erector spinae is better adapted to rapidly change lumbar curvature during the middle to later stages of the lift when bending moments are reduced (Mawston 2010).

Lowering

Whilst a number of studies have focused on lumbar posture during lifting, few have investigated the effects that lumbar posture has on bending moments and erector spinae muscle activation during lowering. De Looze et al (1993) found that lowering an object from an upright position mirrored the moment produced during lifting, with the moment being lowest on the initiation of lowering, and peaking near the end of the lowering cycle, where inertial effects of the decelerating trunk were maximal.

Despite showing a similar peak moment, when compared to lifting, muscle activation of the lumbar erector spinae is substantially less when lowering (de Looze et al 1993, Toussaint et al 1995). The reduced lumbar erector spinae muscle activation during lowering is best explained by the different muscle actions (eccentric and concentric) that occur during the dynamic phases of lowering. For a given force (tension), lower levels of muscle activation are observed during eccentric muscle actions (as occurs during lowering) compared to concentric muscle actions (as occurs during lifting) (de Looze et al 1993, Toussaint et al 1995). At the end stage of lowering, subjects using a flexed lumbar posture will also exhibit the same flexion-relaxation phenomenon of the lumbar erector spinae as that described for lifting in a flexed posture (de Looze et al 1993, Toussaint et al 1995). In contrast, high levels of upper erector spinae activity are evident at the end stages of lowering (Toussaint et al 1995). The different activation patterns of the upper erector spinae and lumbar erector spinae observed during lowering may indicate that in some lumbar postures the upper erector spinae has quite an independent and functionally different role to the lumbar erector spinae.

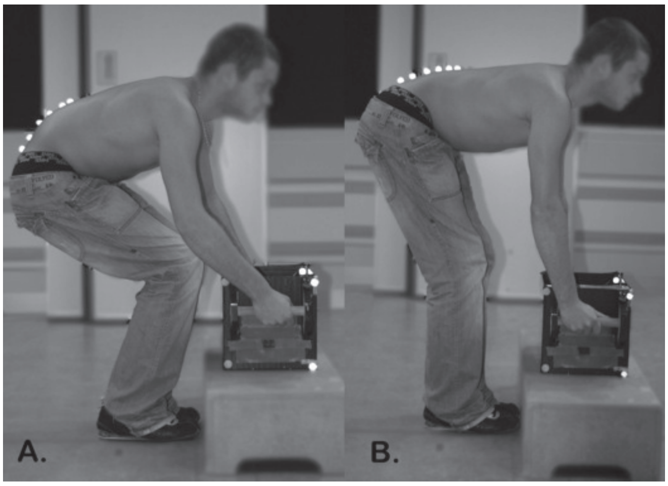
Implications for vocational retraining and exercise rehabilitation

There seems to be strong biomechanical evidence to suggest that end range of lumbar flexion during lifting and lowering should be avoided. It could be argued that this is not just a matter of instructing patients to "bend the knees", as patients who use a bent knee technique can still flex their lumbar spine to maximum range (McGill 1997). An example of this is shown in Figure 4. When the subject is instructed to bend their knees their lumbar spine may flex and approach maximum flexion (Figure 4A), as this becomes their primary mechanism to achieve trunk inclination. In this position their passive tissues would be recruited to bear a large majority of the moment, with an associated increase in the anterior shear force (Dolan et al 1994b, Potvin et al 1991). However, when they adopt a straight knee technique, hip flexion, as opposed to lumbar flexion, can contribute more to trunk inclination (Figure 4B). The lumbar spine in Figure 4B is only flexed to approximately 70% of its maximal range, and the active system (the erector spinae) is the main contributor to resisting the bending moment. Emphasis on maintaining lumbar lordosis during the initiation of a lift will not tend to result in a hyper-lordotic lumbar spine, as even when individuals are instructed to perform a lift in a lordotic posture some degree of lumbar flexion occurs. For example, we have found in a recent study (unpublished data) that when subjects were asked to maximise their lordosis while simulating a box lift close to the ground (30 cm) with the knees flexed at 45 degrees, average lumbar flexion was 40% of their maximal flexion.

The extent of lumbar flexion during exercise rehabilitation is important. The use of machines and exercises that impose large loads towards the end range lumbar flexion should be avoided. For example, exercises, such as bilateral leg press performed incorrectly, can force the lumbar spine into end range of flexion. Lumbar flexion during this exercise can be reduced by performing a unilateral leg press whilst placing the opposite foot on the ground to control lumbo-pelvic rotation (McGill 2007).

The therapist should also take into consideration the different functional roles of the upper erector spinae and lumbar erector spinae when developing rehabilitation programmes. For example, retraining of the lumbar erector spinae should be performed in lumbar postures (avoiding maximal flexion),

Figure 4: A subject lifting a box using bent knee technique with maximal lumbar flexion (A) and with a straight knee technique with reduced lumbar flexion (B).



where lumbar erector spinae are at a mechanical advantage to enable sufficient muscle recruitment without generating high compressive forces on the spine. This mechanical advantage should take into consideration the erector spinae length-tension relationships, which would indicate that retraining in hyper-lordotic postures might not be appropriate. This is further evidenced by the high compressive forces that have been reported during exercises (e.g. prone superman) that hyper-extend the lumbar spine (McGill 2010). It is also important to include exercises that recruit the upper erector spinae, as this muscle group has a more influential role in resisting bending moments when the lumbar erector spinae become mechanically disadvantaged.

The various erector spinae muscle actions (isometric, concentric and eccentric) during lifting and lowering should also be given suitable consideration when designing back exercise programmes. It would seem that at high loads during the initiation of the lift and termination of lowering the erector spinae muscle action is relatively isometric. This highlights the importance of developing adequate motor control to restrict spinal motion during activities where bending moments and inertial forces are large. However, during mid- to late-lifting and the initial and mid-stages of lowering the bending moments are considerable lower, the erector spinae are better placed to exert a force, and muscle activity involves concentric and eccentric actions, respectively. Therefore, the inclusion of exercises that take into consideration erector spinae muscle action when extending (concentric) and flexing (eccentric) the lumbar spine at low loads in moderately flexed postures may also be of benefit when developing training programmes for those individuals involved in lifting and lowering activities.

CONCLUSION

This clinical commentary has highlighted the implications that lumbar posture has on the mechanical loads placed on the active and passive tissues of the spine, and the contribution of the erector spinae during tasks involving lifting and lowering. Whilst it is appreciated that a number of other factors (e.g. contribution of other muscles, load and environmental factors) can influence spinal loading during manual handling tasks performed in or outside the workplace, it is hoped that this review will provide clinicians with an insight into the effective implementation of educational and exercise prescription programmes for the prevention and management of low back injury.

KEY POINTS

- End range of lumbar flexion should be avoided as it recruits the passive tissues of the lumbar spine and alters erector spinae geometry. This serves to increase the bending moment on the spine and decrease the spine's ability to resist anterior shear forces.
- Exercise programmes should target the different functional roles of the upper and lumbar erector spinae during lifting and lowering, and incorporate static and dynamic muscle training appropriate for controlling lumbar posture.

ADDRESS FOR CORRESPONDENCE

Grant A Mawston, Health and Rehabilitation Research Institute, Department of Physiotherapy, AUT University, Private Bag 92006, Auckland, New Zealand. Email: grant.mawston@aut.ac.nz

REFERENCES

Adams MA and Dolan P (1991) A technique for quantifying the bending moment acting on the lumbar spine in vivo. *Journal of Biomechanics* 24: 117-126.

Adams MA and Dolan P (1996) Time-dependent changes in the lumbar spine's resistance to bending. *Clinical Biomechanics* 11: 194-200.

Arjmand N, Plamondon A, Shirazi-Adl A, Lariviére C and Parnianpour M (2011) Predictive equations to estimate spinal loads in symmetric lifting tasks. *Journal of Biomechanics* 44: 84-91.

Bergmark A (1989) Stability of the lumbar spine. A study in mechanical engineering. *Acta Orthopaedica Scandinavica. Supplementum* 230: 1-54.

Bogduk N and Twomey LT (1987) *Clinical anatomy of the lumbar spine* (First edn). New York: Churchill Livingstone.

Bogduk N, Wilson AS and Tynan W (1982) The human lumbar dorsal rami. *Journal of Anatomy* 134: 383-397.

Bojadsen TW, Silva ES, Rodrigues AJ and Amadio AC (2000) Comparative study of Mm. Multifidi in lumbar and thoracic spine. *Journal of Electromyography and Kinesiology* 10: 143-149.

Callaghan JP and McGill SM (1995) Muscle activity and low back loads under external shear and compressive loading. *Spine* 20: 992-998.

Daggfeldt K and Thorstensson A (2003) The mechanics of back-extensor torque production about the lumbar spine. *Journal of Biomechanics* 36: 815-825.

de Looze MP, Toussaint HM, van Dieen JH and Kemper HC (1993) Joint moments and muscle activity in the lower extremities and lower back in lifting and lowering tasks. *Journal of Biomechanics* 26: 1067-1076.

Delitto RS and Rose SJ (1992) An electromyographic analysis of two techniques for squat lifting and lowering. *Physical Therapy* 72: 438-448.

Dickey JP, McNorton S and Potvin JR (2003) Repeated spinal flexion modulates the flexion-relaxation phenomenon. *Clinical Biomechanics* 18: 783-789.

Dolan P, Earley M and Adams MA (1994a) Bending and compressive stresses acting on the lumbar spine during lifting activities. *Journal of Biomechanics* 27: 1237-1248.

Dolan P, Mannion AF and Adams MA (1994b) Passive tissues help the back muscles to generate extensor moments during lifting. *Journal of Biomechanics* 27: 1077-1085.

Floyd WF and Silver PH (1955) The function of the erectores spinae muscles in certain movements and postures in man. *Journal of Physiology* 129: 184-203.

Gallagher S, Marras WS, Litsky AS and Burr D (2005) Torso flexion loads and the fatigue failure of human lumbosacral motion segments. *Spine* 30: 2265-2273.

Granata KP and Rogers E (2007) Torso flexion modulates stiffness and reflex response. *Journal of Electromyography and Kinesiology* 17: 384-392.

Holmes JA, Damaser MS and Lehman SL (1992) Erector spinae activation and movement dynamics about the lumbar spine in lordotic and kyphotic squat-lifting. *Spine* 17: 327-334.

Hoogendoorn WE, Bongers PM, de Vet HC, Douwes M, Koes BW, Miedema MC, Ariens GA and Bouter LM (2000) Flexion and rotation of the trunk and lifting at work are risk factors for low back pain: results of a prospective cohort study. *Spine* 25: 3087-3092.

Keyserling WM (2000) Workplace risk factors and occupational musculoskeletal disorders, Part 1: A review of biomechanical and psychophysical research on risk factors associated with low-back pain. *American Industrial Hygiene Association Journal* 61: 39-50.

Kippers V and Parker AW (1984) Posture related to myoelectric silence of erectores spinae during trunk flexion. *Spine* 9: 740-745.

Macintosh JE and Bogduk N (1986) The biomechanics of the lumbar multifidus. *Clinical Biomechanics* 1: 205-213.

Macintosh JE and Bogduk N (1987) The morphology of the lumbar erector spinae. *Spine* 12: 658-668.

Macintosh JE and Bogduk N (1991) The attachments of the lumbar erector spinae. *Spine* 16: 783-792.

Macintosh JE and Bogduk N (1994) The anatomy and function of the lumbar back muscles. In Boyling JD, Palastanga N, Jull GA, Lee DG (Eds) Grieve's Modern Manual Therapy Edn). New York: Churchill Livingstone, pp 189-209.

Macintosh JE, Bogduk N and Pearcy MJ (1993) The effects of flexion on the geometry and actions of the lumbar erector spinae. *Spine* 18: 884-893.

Magnusson M, Granqvist M, Jonson R, Lindell V, Lundberg U, Wallin L and Hansson T (1990) The loads on the lumbar spine during work at an assembly line. The risks for fatigue injuries of vertebral bodies. *Spine* 15: 774-779.

Marras WS, Lavender SA, Leurgans SE, Rajulu SL, Allread WG, Fathallah FA and Ferguson SA (1993) The role of dynamic three-dimensional trunk motion in occupationally-related low back disorders. The effects of workplace factors, trunk position, and trunk motion characteristics on risk of injury. *Spine* 18: 617-628.

Mawston G (2010) *Neuromuscular and postural responses to sudden loading and high frequency lifting: effects of posture and fatigue*. PhD Thesis. AUT University, pp 236.

Mawston GA, McNair PJ and Boocock MG (2010) Lumbar spine kinematics and trunk muscle activation in stoop and squat lifters during repetitive lifting and lowering to fatigue. Proceedings of the ISEK 2010: The XVIII congress of International Society of Electrophysiology and Kinesiology, Aalborg, Denmark,

McGill S (1997) The biomechanics of low back injury: implications on current practice in industry and the clinic. *Journal of Biomechanics* 30: 465-475.

McGill S (2007) *Low back disorders: evidence-based prevention and rehabilitation.* (Second edn). Champaign, IL.: Human Kinetics.

McGill S (2010) Core training: Evidence translating to better performance and injury prevention. *Strength and Conditioning Journal* 32: 33-46.

McGill S, Hughson RL and Parks K (2000) Changes in lumbar lordosis modify the role of the extensor muscles. *Clinical Biomechanics* 15: 777-780.

McGill S and Norman RW (1986) Partitioning of the L4-L5 dynamic moment into disc, ligamentous, and muscular components during lifting. *Spine* 11: 666-678.

McGill S, Patt N and Norman RW (1988) Measurement of the trunk musculature of active males using CT scan radiography: implications for force and moment generating capacity about the L4/L5 joint. *Journal of Biomechanics* 21: 329-341.

McGill S, Seguin J and Bennett G (1994) Passive stiffness of the lumbar torso in flexion, extension, lateral bending, and axial rotation. Effect of belt wearing and breath holding. *Spine* 19: 696-704.

Potvin JR, McGill SM and Norman RW (1991) Trunk muscle and lumbar ligament contributions to dynamic lifts with varying degrees of trunk flexion. *Spine* 16: 1099-1107.

Punnett L, Fine LJ, Keyserling WM, Herrin GD and Chaffin DB (1991) Back disorders and nonneutral trunk postures of automobile assembly workers. *Scandinavian Journal of Work, Environment and Health* 17: 337-346.

Raschke U and Chaffin DB (1996) Support for a linear length-tension relation of the torso extensor muscles: an investigation of the length and velocity EMG-force relationships. *Journal of Biomechanics* 29: 1597-1604.

Roy AL, Keller TS and Colloca CJ (2003) Posture-dependent trunk extensor EMG activity during maximum isometrics exertions in normal male and female subjects. *Journal of Electromyography and Kinesiology* 13: 469-476.

Shan X, Zhang Y, Zhang T, Chen Z and Wei Y (2012) Flexion relaxation of erector spinae response to spinal shrinkage. *Journal of Electromyography and Kinesiology* 22: 370-375.

Singh DKA, Bailey M and Lee RYW (2011) Ageing modifies the fibre angle and biomechanical function of the lumbar extensor muscles. *Clinical Biomechanics* 26: 543-547.

Solomonow M (2012) Neuromuscular manifestations of viscoelastic tissue degradation following high and low risk repetitive lumbar flexion. *Journal of Electromyography and Kinesiology* 22: 155-175.

Solomonow M, Zhou BH, Baratta RV, Lu Y and Harris M (1999) Biomechanics of increased exposure to lumbar injury caused by cyclic loading: Part 1. Loss of reflexive muscular stabilization. *Spine* 24: 2426-2434.

Tan JC, Parnianpour M, Nordin M, Hofer H and Willems B (1993) Isometric maximal and submaximal trunk extension at different flexed positions in standing. Triaxial torque output and EMG. *Spine* 18: 2480-2490.

Toussaint HM, de Winter AF, de Haas Y, de Looze MP, Van Dieen JH and Kingma I (1995) Flexion relaxation during lifting: implications for torque production by muscle activity and tissue strain at the lumbo-sacral joint. *Journal of Biomechanics* 28: 199-210.

Tveit P, Daggfeldt K, Hetland S and Thorstensson A (1994) Erector spinae lever arm length variations with changes in spinal curvature. *Spine* 19: 199-204.

van Dieen JH, Hoozemans MJ and Toussaint HM (1999) Stoop or squat: a review of biomechanical studies on lifting technique. *Clinical Biomechanics* 14: 685-696.