Spinal Stabilisation
3. Stabilisation Mechanisms of the Lumbar Spine

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Key Words

Lumbar support, muscle, fascia, biomechanics.

Summary

This paper reviews the active stabilising mechanisms of the lumbar spine. Intra-abdominal pressure is produced by contraction of the abdominal muscles when the glottis is closed. The posterior ligamentous system has been shown to produce 25% of the moment of the erector spinae (ES), and the ES will themselves produce an important passive elastic tension. In the thoracolumbar fascia (TLF) mechanism, the horizontal pull of transversus abdominis is changed into a vertical force *via* the angled deep and superficial fibres of the TLF. The hydraulic amplifier effect is produced as the ES contract within the fascial envelope formed from the middle layer of the TLF. This mechanism increases the stress generated by the ES by 30%. Multifidus is especially important to active stabilisation as it has segmentally arranged fibres whose lines of force may be resolved into a large vertical and small horizontal component. The ES lines of action show it to be more suitable as a prime mover than a stabiliser, and it is the endurance of this muscle rather than its strength which is important to stabilisation. Of the abdominal muscles, transversus abdominis and internal oblique act as stabilisers, while the lateral fibres of external oblique and the rectus abdominis act as prime movers.

Introduction

The human spine devoid of its musculature is inherently unstable. A fresh cadaveric spine without muscle can only sustain a load of 4-5 lb before it buckles (Panjabi *et al,* 1989). Add to this the fact that, when standing upright, the centre of gravity of the upper body lies at sternal level (Norkin and Levangie, 1992). This combination of flexibility and weight creates a set of mechanical circumstances which have been compared to balancing a weight of approximately 75 lb at the end of a 14-inch flexible rod (Farfan, 1988).

When lifting, the situation is intensified. The spine may be viewed as a cantilever pivoted on the hip (fig 1). The weight of the trunk combined with the weight of an object lifted forms the resistance, balanced by an effort created by the hip and back extensors. Using this model a number of authors have calculated that the force imposed on the lower lumbar spine greatly exceeds the failure load of the lumbar vertebral

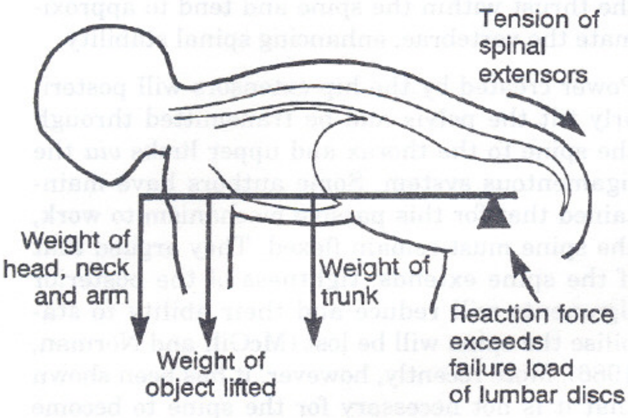


Fig 1: Cantilever model of the spine in lifting. Acting as a cantilever, the spine is pivoted at the hip. The weight of the body and the object lifted combined form the resistance, balanced by force from the spinal extensors and the hip extensors. The reaction force created in this model exceeds the failure load of the lumbar discs

discs unless an additional support mechanism is present (Bradford and Spurling, 1945; Bartelink, 1957; Morris *et al*, 1961).

A number of mechanisms have been suggested to relieve some of the compression stress on the lumbar discs and help stabilise the spine. This paper provides an overview of these mechanisms.

Intra-abdominal Pressure Mechanism

The theoretical basis for the intra-abdominal pressure (IAP) mechanism is that pressure within the abdomen acting against the pelvis and diaphragm provides an additional extensor moment to the spine (fig 2). IAP involves a synchronous contraction of the abdominal muscles, the diaphragm and the muscles of the pelvic floor. The obliquely placed muscles are the most important in this respect as they will produce

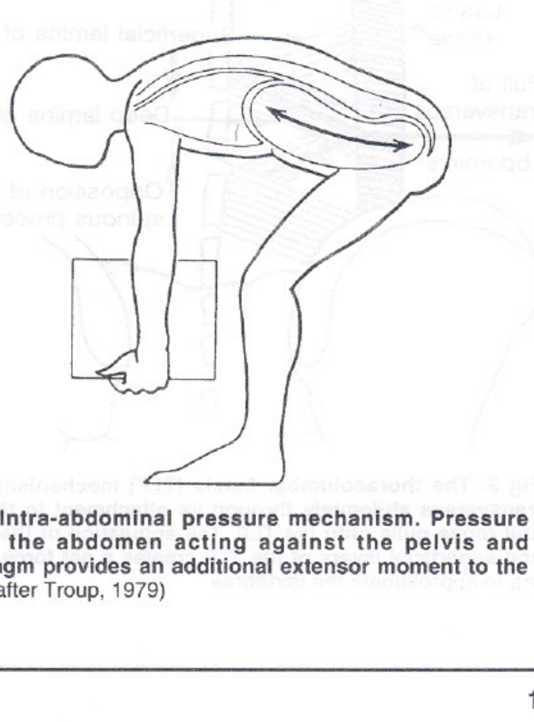


Fig 2: Intra-abdominal pressure mechanism. Pressure within the abdomen acting against the pelvis and diaphragm provides an additional extensor moment to the spine (after Troup, 1979)

the largest torques. Contraction of the transversus abdominis, and to a lesser degree the internal and external obliques, will cause an increased IAP when the glottis is closed. These muscles will pull on the rectus sheath and so compress the viscera. Compression of the abdominal contents forces them upwards on to the diaphragm and separates the pelvis from the thoracic cage. The IAP will be greater if the breath is held following a deep inspiration, as the diaphragm is lower, and the comparative size of the abdominal cavity is reduced. IAP is raised when the muscles contract reflexly to defend the abdominal viscera from a direct blow, and to protect the spine from excessive indirect loads. The muscles act involuntarily to fix the rib cage and to compress the abdominal contents.

By making the trunk into a more solid cylinder, axial compression and shear loads are reduced and transmitted over a wider area through the IAP mechanism (Twomey and Taylor, 1987). IAP is greater when heavy lifts are performed, and when the lift is rapid (Davis and Troup, 1964).

IAP is related to strength of the abdominal, pelvic floor, and diaphragm muscles. Strong athletes can produce very large IAP values (Harman *et al,* 1988). However, strengthening the abdominal muscles with sit-up type movements does not permanently increase IAP (Hemborg *et al,* 1983). Exercises of this type do not usually mimic the co-ordination between the abdominal muscles which is inherent in the IAP mechanism (Oliver and Middleditch, 1991). In a study looking at the effect of abdominal muscle training on IAP, Hemborg *et al* (1985) used an isometric trunk curl and twist. Muscle strengthening was clearly demonstrated by an increased recruitment of motor units in the oblique abdominal muscles. However, EMG activity of these muscles when lifting was shown to decrease, implying that subjects did not make functional use of their increased ability to recruit more motor units.

At the onset of a lift, IAP resists trunk flexion and reduces spinal compression. The gluteals and hamstrings rotate the pelvis backwards and flatten the lordosis. These muscles are better suited than the erector spinae to initiate the lift. A 150 lb athlete would need to develop a moment of 10,000 in/lb to lift a 450 lb weight. However, it has been calculated that while the hip extensors are able to generate a moment of 15,000 in/lb, the erector spinae can generate a maximum moment of only 3,000 in/lb, 20% of that required to perform the lift (Farfan, 1988).

A number of important criticisms have been made against the IAP mechanism as the only stabilising process for the spine (Bogduk and Twomey, 1987). Firstly, to stabilise the spine fully when lifting heavy weights the IAP would have to exceed the systolic pressure within the aorta, effectively cutting off the blood flow to the viscera and lower limbs. At the onset of a lift, there is an initial rapid rise in IAP. This peak is known as the snatch pressure and may last for less than half a second. For the remainder of the lift, the pressure reduces. It has been calculated that to lift a 100 kg weight, a peak IAP of 250 mm Hg would be required (Hemborg *et al,* 1985). Secondly the required muscle force to create a sufficiently high IAP is greater than the hoop pressure possible from the abdominal muscles (Gracovetsky *et al,* 1985). Thirdly, if rectus abdominis contracts to increase IAP it will produce a flexion moment. This will counteract the antiflexion effect of IAP created as the diaphragm and pelvic floor spread apart.

In addition to its antiflexion effect, the role of IAP in controlling axial rotation in lifting has also been considered (Bogduk and Twomey, 1991). Most mathematical models describe lifting in the sagittal plane only. However, functionally lifting is a multi-plane activity, requiring stability to rotation as well as flexion-extension. If the internal and external obliques contract to control rotation, IAP may increase as a secondary effect.

The Posterior Ligamentous System

The interspinous and superspinous ligaments, zygapophyseal joint capsules and thoracolumbar fascia (TLF) together provide a passive support mechanism for the spine, sufficient to balance between 24%–55% of imposed flexion stress (Adams *et al,* 1980). When the lumbar spine is flexed the posterior ligaments will stretch, and during extension the anterior ligaments are stretched.

The collagen fibres within the anterior and posterior longitudinal ligaments and the ligamentum flavum are aligned haphazardly in the unstretched position. When the ligaments are stretched, however, the collagen fibres become aligned and the ligament becomes stiffer (Kirby *et al,* 1989; Hukins *et al,* 1990a). At rest the ligaments are pre-stressed by 10-13% (Hukins *et al,* 1990b) and retract when cut. The longitudinal ligaments therefore maintain a compressive force along the axis of the spine causing the spine to act as a pre-stressed beam (Aspden, 1992). The ligaments display viscoelastic properties meaning that they will stiffen when loaded rapidly. Rapid loading will therefore increase the thrust within the spine and tend to approximate the vertebrae, enhancing spinal stability.

Power created by the hip extensors will posteriorly tilt the pelvis and be transmitted through the spine to the thorax and upper limbs *via* the ligamentous system. Some authors have maintained that for this passive mechanism to work, the spine must remain flexed. They argued that if the spine extends, tightness of the posterior ligaments will reduce and their ability to stabilise the spine will be lost (McGill and Norman, 1986). More recently, however, it has been shown that it is not necessary for the spine to become kyphotic to stretch the tissues enough to provide tension (Gracovetsky *et al,* 1990).

The posterior ligamentous system alone can produce a maximum moment of only about 50 Nm (Bogduk and Twomey, 1991), less than 25% of that of the contracting erector spinae. This is not enough to support a substantial weight in a fully flexed position where the erector spinae are relaxed. However, in their relaxed position, the erector spinae will produce a passive elastic tension equal to their maximum contraction (200 Nm). The passive effect of the combined posterior musculo-ligamentous system provides a substantial stabilising mechanism in full flexion (Bogduk and Twomey, 1991).

Thoracolumbar Fascia Mechanism

In addition to a passive role, the thoracolumbar fascia (TLF) has two further roles which involve muscle contraction. The transversus abdominis, through its attachment to the lateral raphe, will pull on the TLF. The deep laminae of the TLF are angled upwards, while the superficial laminae are angled downwards, but both attach to the lateral raphe (fig 3). As the transversus abdo-

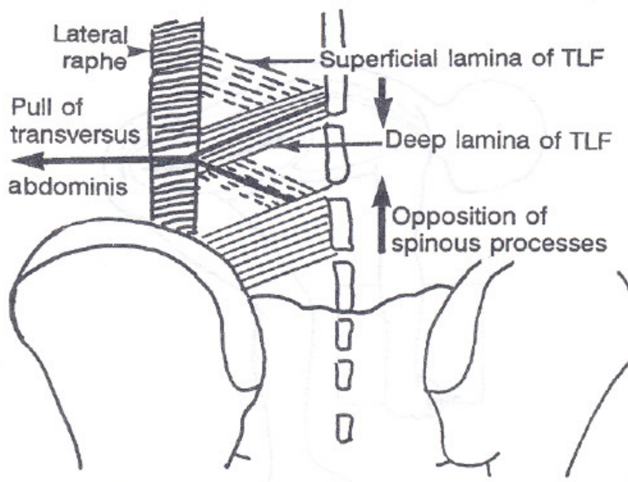


Fig 3: The thoracolumbar fascia (TLF) mechanism. The transversus abdominis through its attachment to the lateral raphe pulls onto the TLF. The angulation of the deep and superficial layers of the TLF creates a net force tending to approximate the vertebrae

minis contracts and pulls on the lateral raphe, the deep and superficial fibres of the TLF will pull laterally, but some force will be transmitted along the length of the TLF, tensing it. Originally this approximating force was calculated to be 57% of the force applied to the lateral raphe (Mackintosh and Bogduk, 1987), an increase in force termed the 'gain' of the TLF (Gracovetsky *et al,* 1985). However, more detailed anatomical investigation has revealed that the moment created by contraction of transversus abdominis on to the TLF is between 3.9 and 5.9 Nm compared to that from the back extensors of 250 to 280 Nm (Macintosh *et al,* 1987).

Hydraulic Amplifier

A mechanism by which the TLF may exert a substantially greater stabilising effect is that of the hydraulic amplifier. The posterior layer of the TLF is retinacular and envelops the erector spinae (fig 4). As the erector spinae contract, their expansion is resisted by the TLF, leading to a build-up of fascial tension.

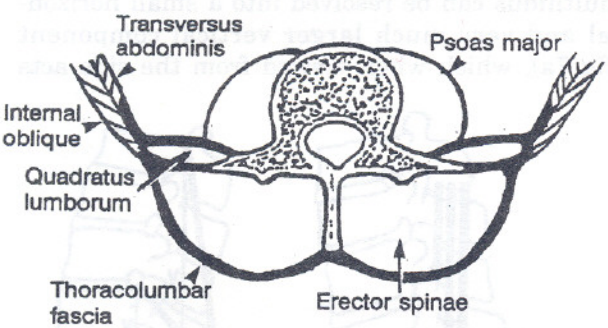


Fig 4: The hydraulic amplifier mechanism. The posterior layer of the TLF envelops the erector spinae. As these muscles contract and bulge, fascial tension builds up increasing the stress generated by the muscles by 30% (Oliver and Middleditch, 1991)

It has been suggested that tensioning the TLF through the hydraulic amplifier effect, rather than by the pull of transversus abdominis, may exert the predominant anti-flexion effect (Macintosh *et al,* 1987). Restriction of the radial expansion of the erector spinae by the TLF has been shown to increase the stress generated by these muscles by as much as 30% (Hukins *et al,* 1990a).

Arch Model of the Spine

The traditional model of the spine is of a lever subjected to external loads created by the weight of the trunk and any object lifted, and the forces created by the various muscles and ligaments surrounding the spine (fig 1). This lever model has been used to calculate forces imposed on the spine during lifting especially, and relies on external forces for its stability.

An alternative representation of the spine is that of an arch (Aspden, 1987, 1989). The ends (abutments) of the arch are provided caudally by the sacrum and cranially by a combination of bodyweight, and muscular and ligamentous forces. The principal difference between a lever and an arch is that the lever is externally supported where as the arch is intrinsically stable. Any load positioned on the convex surface of the arch will create an internal thrust line which runs straight to the arch abutments (fig 5). For the arch to remain stable, the thrust line must stay within the depth of the arch ring. The deeper within the arch the thrust line stays, the more stable the arch will be. In the case of the spine, the thrust line is positioned within the vertebral bodies.

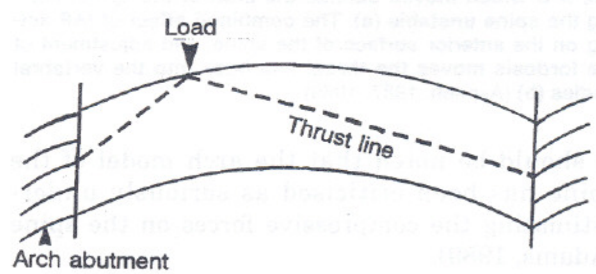


Fig 5: Arch model of the spine. A load positioned on the convex surface of an arch creates an internal thrust line. For the arch to remain stable, the thrust line must stay within the depth of the arch ring (Aspden, 1989)

As we have seen above, analysis of a lifting technique using the lever model has shown that the load imposed on the spine greatly exceeds the failure load of the lumbar discs, unless an additional support mechanism is supplied. Of these mechanisms, both IAP and TLF have been criticised as failing to produce a sufficiently high extensor moment.

Using an arch model, however, the analysis is different. A 100 kg weight lifted in a stooped position (lordosis lost) creates a thrust line which moves outside the spine (fig 6a overleaf). The arch is therefore unstable. However, introducing IAP creates an additional force vector acting on the anterior surface of the lumbar region. This will move the thrust line back into the spine and increase spinal stability (fig 6b). In addition the spinal muscles, which are intrinsic to the arch, may be used to adjust the lordosis so that the thrust line remains within the arch of the spine. Further, the stiffness of the spine (resistance to bending) is increased through the TLF and hydraulic amplifier mechanisms.

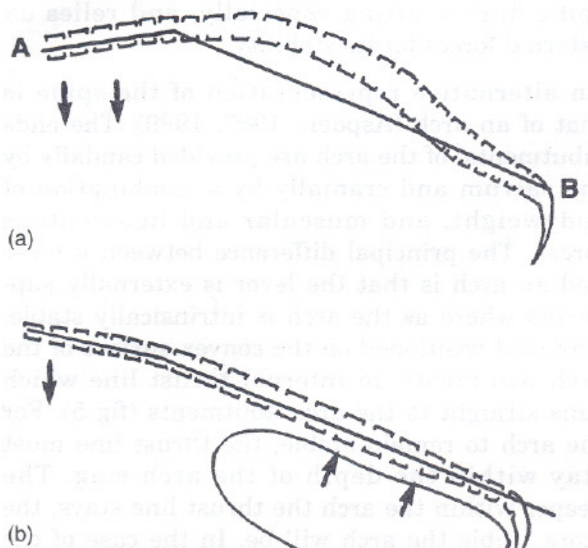


Fig 6: Arch model of the spine in relation to stability. Lifting a heavy weight in a stooped position creates a thrust line A-B which moves outside the arch of the spine, leaving the spine unstable (a). The combined effect of IAP acting on the anterior surface of the spine, and adjustment of the lordosis moves the thrust line back into the vertebral bodies (b) (Aspden, 1987, 1989)

It should be noted that the arch model of the spine has been criticised as seriously underestimating the compressive forces on the spine (Adams, 1989).

Trunk Muscle Action

It has been suggested that the mechanisms for spinal stability can be enhanced by facilitating a co-contraction of the muscles surrounding the lumbar spine, especially the oblique abdominals, transversus abdominis, erector spinae, and multifidus (Richardson *et al*, 1990).

Spinal Extensor Muscles

The spinal extensors may be broadly categorised into superficial muscles (the erector spinae) which travel the length of the lumbar spine and attach to the sacrum and pelvis, and deep muscles (multifidus, interspinales, and intertransversarii) which span between the individual lumbar segments.

The intersegmental muscles, being more deeply placed, are closer to the centre of rotation of the spine, and have a shorter lever arm than the superficial muscles. However, by being closer to the centre of rotation, the change in length of the intersegmental muscles will be less for any given change in angular position of the spine. The shorter length of the intersegmental muscles gives them a faster reaction time, creating a smoother and more efficient stabilising control system (Panjabi *et al*, 1989). The intersegmental nature of these muscles also means that they are able to 'fine tune' the spinal movements by acting on individual lumbar segments rather than the whole spine (Aspden, 1992).

The superficial muscles being larger in size and further from the centre of rotation are better placed to create gross sagittal rotation movements, while the intersegmental muscles are of greater importance to spinal stability (Panjabi *et al*, 1989).

Deep (Intersegmental) Muscles

Of the deeply placed intersegmental muscles, it is the multifidus which is of most interest with respect to lumbar stability. The fibres of multifidus are arranged segmentally, and each fascicle of a given vertebra has a separate innervation by the medial branch of the dorsal ramus of the vertebra below (Macintosh and Bogduk, 1986). The primary function of each fascicle of multifidus is therefore likely to be focused on an individual spinous process, and it may be able to control the lordosis at each vertebral level independently to match any imposed loading (Aspden, 1992). The line of action of the multifidus can be resolved into a small horizontal and very much larger vertical component (fig 7a), which when viewed from the side acts

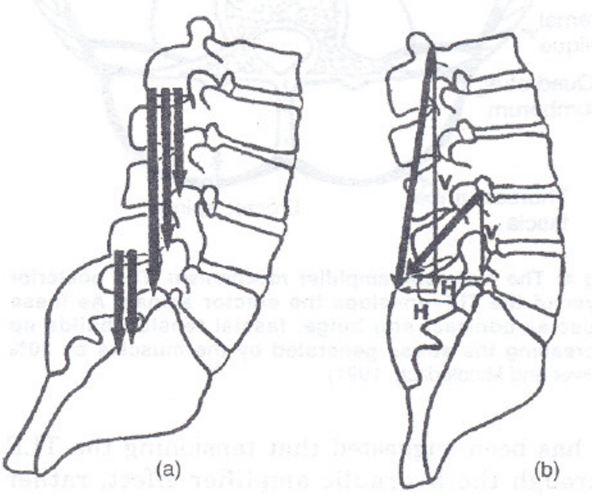
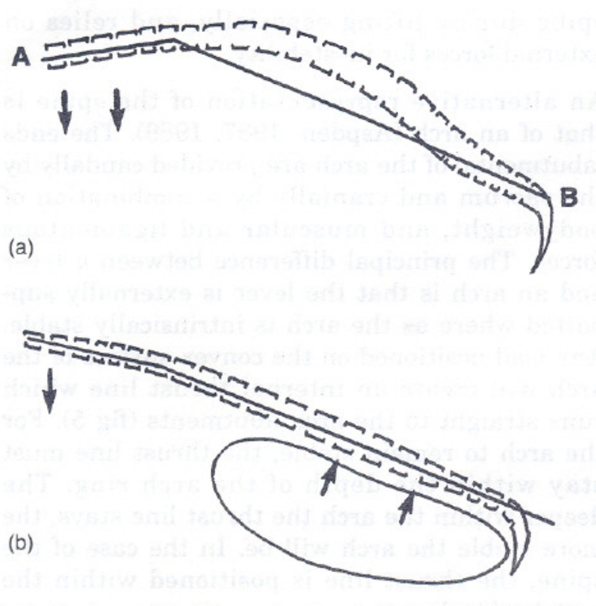


Fig 7: Line of action of lumbar muscles. Lateral view showing (a) the line of action of multifidus, with its vertical alignment, and (b) the line of the lumbar iliocostalis and lumbar longissimus, showing their more oblique orientation. Note the greater horizontal force vector (H) and smaller vertical force vector (V) of the lower fibres of these muscles (from Bogduk and Twomey, 1987)

at 90° to the spinous processes. This configuration enables multifidus to produce posterior sagittal rotation (rocking) of the lumbar vertebrae (Macintosh and Bogduk, 1986). This action is used to neutralise flexion of the spine caused as a secondary action of the oblique abdominals as they produce spinal rotation. Because the line of action of the long fascicles of multifidus lies



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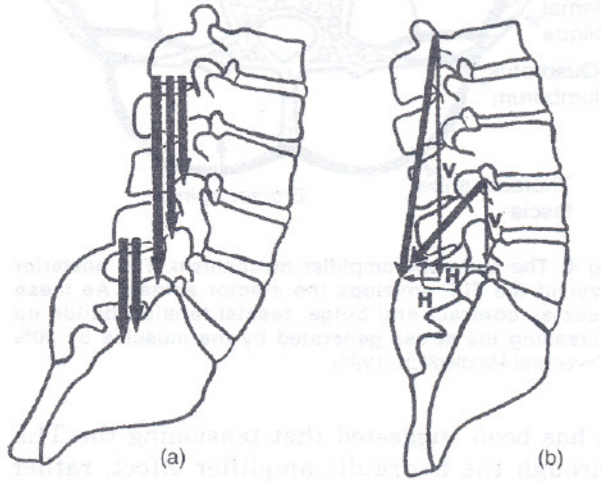

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Marked asymmetry of the multifidus has been shown using real-time ultrasound imaging (Hides *et al*, 1994). Cross-sectional area (CSA) of the multifidus was markedly reduced on the ipsilateral side to symptoms, the site corresponding to the level of lumbar lesion as assessed by manual therapy palpation. In addition, the muscle showed a rounder shape suggesting muscle spasm. The suggested mechanism for the CSA reduction was by inhibition through perceived pain *via* a long loop reflex. The level of vertebral pathology may have been targeted to protect the damaged tissues from movement. The muscle wasting was rapid (less than 14 days in 20 of the total 26 patients studied) which the authors suggested could illustrate a metabolic effect of circulation reduction due to muscle spasm.

In addition to changes in muscle bulk, alteration in fibre type has been shown in the multifidus with low back pain (LBP) patients (Biedermann *et al,* 1991). Patients who tended to decrease their physical and social activities as a result of LBP showed a reduced ratio of slow twitch to fast twitch muscle fibres in the multifidus. This could possibly be an adaptive response by the muscle to changes in functional demand placed upon it. In addition, there may have been a shift in the recruitment patterns of the motor units of the paraspinal muscles as a result of injury, with the fast twitch motor units being recruited before the slow twitch units.

The interspinales muscles act synergistically with multifidus to produce posterior sagittal rotation. However, the intertransversarii lie so close to the axes of both sagittal rotation and lateral flexion, that they are unlikely to contribute significantly to these movements. Their importance seems more likely to be proprioception rather than active movement (see part two of this article series).

Superficial Muscles

The lumbar erector spinae consists of two muscles, the iliocostalis and the longissimus. Each of these muscles has two components, arising from both the thoracic and lumbar spine. Functionally, therefore, the erector spinae can be considered in four distinct groups, lumbar longissimus, lumbar iliocostalis, thoracic longissimus and thoracic iliocostalis (Macintosh and Bogduk, 1987).

The force produced by the lumbar longissimus can be resolved into a large vertical vector and a smaller horizontal vector (fig 7b). However, the fascicle attachments are closer to the axis of sagittal rotation than those of multifidus and so their effect on posterior sagittal rotation is less. The horizontal vectors of lumbar longissimus are directed backward and so the muscle is able to draw the vertebrae backwards into posterior translation and restore the anterior translation which occurs with lumbar flexion. The upper lumbar fascicles are better equipped to facilitate posterior sagittal rotation while the lower levels are better suited to resist anterior translation.

The lumbar iliocostalis has a similar action to that of the lumbar longissimus. In addition, the muscle will co-operate with multifidus as a neutraliser of flexion caused by the abdominals as these muscles rotate the trunk.

The thoracic longissimus has an indirect effect on the lumbar spine through the aponeurosis of the erector spinae to increase the lumbar lordosis. It will also laterally flex the thoracic spine and thereby indirectly laterally flex the lumbar spine.

The thoracic iliocostalis attaches not to the lumbar vertebrae but to the iliac crest. On contraction these fascicles will increase the lordosis and through their additional leverage from the ribs they will indirectly laterally flex the lumbar spine. During contralateral rotation the ribs will separate, stretching the thoracic iliocostalis which can therefore act as a limiting factor to this movement. On contraction, the thoracic iliocostalis will derotate the rib cage and lumbar spine from a position of contralateral rotation.

Rather than the strength of the erector spinae it is their endurance which may be important to LBP rehabilitation. Endurance has been used as a predictor for susceptibility to LBP (Beiring-Sorensen, 1984). In addition, subjects with a history of LBP have been shown to have reduced endurance of the back extensors but similar strength (Jorgensen and Nicolaisen, 1987). With increasing fatigue, subjects with LBP show a reduction in precision and control of trunk movements. Loss of torque from the trunk muscles in these subjects is relatively less than the loss of control and precision (Parnianpour *et al,* 1988), indicating that a rehabilitation programme should include restoration of endurance for the spinal extensors. Separation (selective recruitment) of the torque producing superficial muscles from the stabilising deep muscles is also seen as important for rehabilitation of active lumbar stabilisation (Ng and Richardson, 1994).

Abdominal Muscles

The rectus abdominis and lateral fibres of external oblique may be considered as the prime movers of trunk flexion, while the internal oblique and transversus abdominis are the major stabilisers, as they are the only two abdominal muscles which pass from the anterior trunk to the lumbar spine (Miller and Medeiros, 1987). In terms of spinal stabilisation, rather than the strength of these muscles, it is the speed with which they contract in reaction to a force tending to displace the lumbar spine which is important (Saal and Saal, 1989).

The rectus abdominis will flex the trunk by approximating the pelvis and ribcage. EMG investigation has shown the supraumbilical portion to be emphasised by trunk flexion, while activity in the infra-umbilical portion is greater in positions where a posterior pelvic tilt is held (Lipetz and Gutin, 1970; Guimaraes *et al,* 1991).

By assessing EMG activity of the trunk muscles it has been shown that the muscles do not simply work as prime movers of the spine, but show antagonistic activity during various movements. The oblique abdominals are more active than predicted, to help to stabilise the trunk (Zetterberg *et al,* 1987). During maximum trunk extension, activity of the abdominal muscles varied from 32% to 68% of the activity in longissimus. In resisted lateral flexion, as would be expected, the ipsilateral muscles showed maximum activity, but the contralateral muscles were also active at about 10% to 20% of these maximum values (Zetterberg *et al,* 1987).

During maximum voluntary isometric trunk extension, transversus abdominis is the only one of the abdominal muscles to show marked activity. The co-ordinated patterns seen between the abdominal muscles has been shown to be task specific, with transversus abdominis being the muscle most consistently related to changes in IAP (Cresswell *et al,* 1992).

Differences between the properties of the abdominal muscles have led to them being categorised as movement synergists and stability synergists (Richardson, 1992). Transversus abdominis, internal oblique and external oblique have been classified as stability synergists while rectus abdominis has been classified as a movement synergist. The stability synergists tend to be more deeply placed, and have a predominance of type I muscle fibres. The movement synergist has a greater number of type II fibres, and is preferentially recruited during rapid performance of trunk exercise. More detail of movement synergists and stability synergists in relation to the muscle imbalance process is given in part four of this article series.

Conclusion

The spine devoid of its musculature is unable to support large loads (Panjabi *et al,* 1989). Although the precise mechanisms of spinal stability are subject to debate, the importance of active mechanisms relying on muscle contraction is increasingly recognised. It seems logical that co-ordinated action of the lumbar and abdominal muscles is essential for stability of the lumbar spine. Therefore, it is proposed that any rehabilitation programme designed to enhance lumbar stabilisation must aim at rehearsing and improving the motor skills inherent in active lumbar stabilisation, rather than simply increasing strength of the trunk musculature.

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