
Review article

Is there a role for transversus abdominis in lumbo-pelvic stability?

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SUMMARY. There has been considerable interest in the literature regarding the function of transversus abdominis, the deepest of the abdominal muscles, and the clinical approach to training this muscle. With the development of techniques for the investigation of this muscle involving the insertion of fine-wire electromyographic electrodes under the guidance of ultrasound imaging it has been possible to test the hypotheses related to its normal function and function in people with low back pain. The purpose of this review is to provide an appraisal of the current evidence for the role of transversus abdominis in spinal stability, to develop a model of how the contribution of this muscle differs from the other abdominal muscles and to interpret these findings in terms of the consequences of changes in this function.

INTRODUCTION

The therapeutic application of exercise of the abdominal muscles has been widely used in the management of low back pain (Kendall Manniche et al. 1988; Robinson 1992). The basis for this approach has been that strong abdominal muscles could provide support for the lumbar spine (Robinson 1992). However, evaluation of the efficacy of general abdominal muscle strengthening has yielded little experimental support for this approach (Koes et al. 1991). Recently the focus has turned to transversus abdominis (TrA), the deepest of the abdominal muscles (Miller & Medeiros 1987; Richardson et al. 1992; Jull & Richardson 1994; Richardson & Jull 1995; O'Sullivan et al. 1997; Richardson et al. 1998), with the assumption that this component of the abdominal muscle group provides a specific contribution to spinal stability and that its function is impaired in the presence of low back pain.

The contribution of the superficial abdominal muscles (i.e. rectus abdominis [RA], obliquus externus abdominis [OE] and to some extent obliquus internus abdominis [OI] to spinal stability is related to their ability to produce flexion, lateral flexion and rotation moments and thus, control external forces that cause the spine to extend, laterally flex or rotate (Bergmark 1989). In addition, co-contraction of the

trunk flexors and extensors has been found to increase the stability of the spine (Bergmark 1989; Gardner-Morse & Stokes 1998). Correspondingly, activation of the superficial abdominal muscles has been found to be higher than predicted during specific tasks (Zetterberg et al. 1987).

In contrast, the role of TrA in lumbo-pelvic support is less intuitive. TrA arises from the iliac crest, lower six ribs and the lateral raphe of the thoracolumbar fascia and passes medially to the linea alba (Fig. 1) (Askar 1977; Bogduk & MacIntosh 1984; Williams et al. 1989). Due to this horizontal fibre orientation, contraction of TrA results in a reduction of abdominal circumference with a resultant increase in tension in the thora-columbar fascia and an increase in intra-abdominal pressure (if displacement of the abdominal contents is prevented). TrA has only a limited ability to produce trunk motion (McGill 1996). Due to the mechanical effect of TrA contraction it can control the abdominal contents (Keith 1923; Goldman et al. 1987; DeTroyer et al. 1990) and contributes to respiration by increasing expiratory air flow rate (Agostoni & Campbell 1970), decreasing end expiratory lung volume (Henke et al. 1988) and by defending the length of the diaphragm (De Troyer 1983).

Evidence for a contribution of TrA to spinal stability can come from two sources. Firstly, from evaluation of the ability of TrA to contribute to aspects of spinal control, or secondly, by indirect evidence from investigation of how TrA is used by the central nervous system (CNS) during specific

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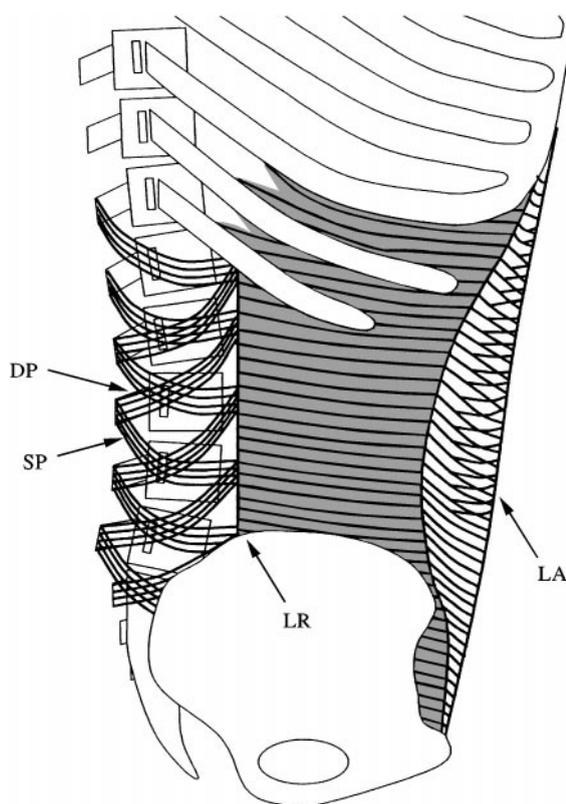


Fig. 1—Anatomy of transversus abdominis. The attachments of transversus abdominis to the lumbar vertebrae via middle and anterior layers of the thoracolumbar fascia are not shown. To demonstrate the bilaminar fascial attachment of the posterior layer of the thoracolumbar fascia it is shown connecting only to the spinous processes. LR – lateral raphe, LA – linea alba, SP – superficial lamina of the posterior layer of the thoracolumbar fascia, DP – deep lamina of the posterior layer of the thoracolumbar fascia.

tasks. While few attempts to investigate the mechanical effectiveness of TrA have been reported (Snijders et al. 1995), there is accumulating evidence from motor control research. Through a series of studies aimed at challenging the hypothesized contribution of TrA to lumbo-pelvic stability it has been possible to provide evidence for its control and to develop a model of its specific contribution to stability. This model has been used to predict the consequence of disruption to this system in low back pain. The purpose of this review is to critically appraise this evidence.

EVIDENCE FROM RECRUITMENT OF TRANSVERSUS ABDOMINIS

The development of techniques enabling measurement of TrA electromyographic (EMG) activity using finewire electrodes inserted under the guidance of ultrasound imaging has allowed the direct investigation of the recruitment of this muscle (Goldman et al.

1987; De Troyer et al. 1990; Cresswell et al. 1992). While many studies of TrA activity have evaluated the respiratory function of this muscle (Strohl et al. 1981; Goldman et al. 1987; De Troyer et al. 1990; Abe et al. 1996), the first investigations of TrA as a possible contributor to spinal control were performed by Cresswell et al. (1992). These studies were stimulated by the observation that high intra-abdominal pressure was present during isometric trunk extension, yet little activity of RA, OE or OI could be detected with surface EMG electrodes (Cresswell & Thorstensson 1989). TrA was postulated to be responsible for this pressure increase since it can generate pressure without opposing the trunk extensor moment (Bartelink 1957; Morris et al. 1961; Cresswell et al. 1992).

In their initial series of experiments, Cresswell and colleagues investigated the activity of the abdominal and erector spinae (ES) muscles during the performance of trunk movements (Cresswell et al. 1992). When subjects performed isometric trunk flexion in side lying, all of the abdominal muscles were active, including TrA. However, a similar magnitude of TrA EMG was recorded during trunk extension in combination with the ES. In addition, TrA was recruited continuously during flexion and extension of the trunk in standing whereas the other abdominal muscles and ES were phasically active to initiate and decelerate the trunk movement (Cresswell et al. 1992). This unexpected continuous (but varying) activity of TrA and its close relationship to intra-abdominal pressure lead the authors to conclude that TrA may contribute to a general mechanism for trunk stabilization rather than the production of torque or control of orientation of the spine. Similar observations of activity of TrA in both flexion and extension were recorded when movement was performed dynamically against resistance (Cresswell 1993) and with lifting and lowering (Cresswell & Thorstensson 1993). The activation of OI shared some similar features to that of TrA but was not as strongly related to intra-abdominal pressure and was more variable between movement directions.

In a second series of experiments, Cresswell and colleagues (1994) investigated the recruitment of the trunk muscles in response to an externally generated perturbation of the spine by adding a weight to a harness over the shoulders (Fig. 2A). When subjects were unexpectedly forced into trunk flexion, TrA was active prior to ES with a latency of 24 ms (Fig. 2B). Since TrA is unable to produce trunk torque these results provide further support to a possible contribution of this muscle to spinal stability. When subjects added the load themselves and could predict the timing and magnitude of the perturbation, TrA was active 175 ± 24 ms prior to the loading (Fig. 2B). This finding provides the first insight into the possible activation of TrA in advance of a predictable

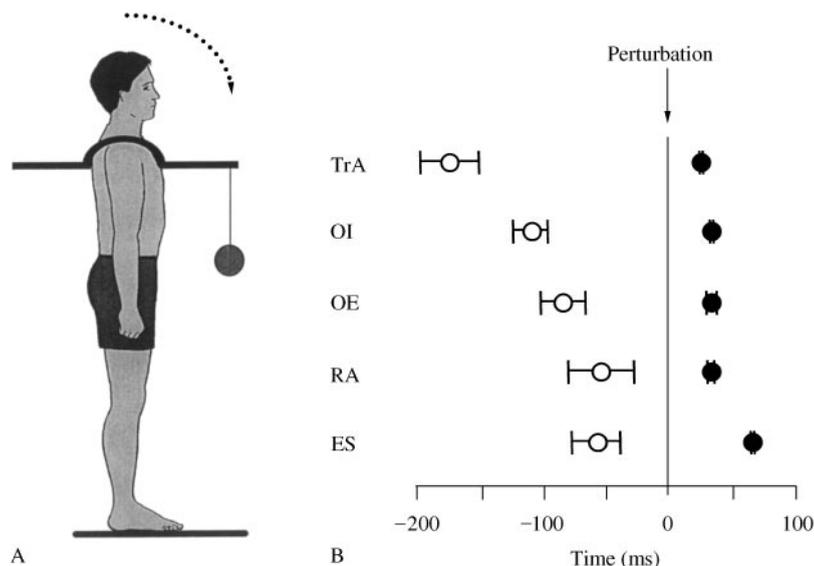


Fig. 2—Recruitment of the abdominal (transversus abdominis [TrA], obliquus internus abdominis [OI], obliquus extrenus abdominis [OE], rectus abdominis [RA]) and erector spinae (ES) muscles with addition of an unexpected (filled circles) and expected (unfilled circles) ventral load. (A) Experimental set-up with harness placed over the shoulders and load added ventrally to produce trunk flexion. (B) Mean onset (SD) of each muscle relative to the onset of the perturbation. Note the consistent activation of TrA prior to the other trunk muscles and the activation of all trunk muscles prior to loading in the 'expected' loading condition. (Adapted from Cresswell et al. [1994]).

perturbation. The complicating factor with the model used by Cresswell et al. (1994) was that the subjects were conscious of the outcome of the loading and could make voluntary adjustments. Other methods were necessary to investigate the preparatory strategies of spinal control in a more controlled manner.

EVIDENCE FROM PREDICTABLE PERTURBATIONS

By investigating the recruitment of TrA in a task that provides a predictable perturbation to the spine that is not consciously perceived, it was possible to investigate the contribution of TrA to stability and its control by the CNS in more detail. This was achieved by the investigation of spinal control associated with limb movement. When a limb is moved the configuration of the body is altered and reactive forces are imposed on the body that are equal in magnitude but opposite in direction to those producing the movement (Bouisset & Zattara 1981). Thus, when a shoulder is flexed, reactive forces act backwards and downwards on the centre of mass causing the spine to flex (Bouisset & Zattara 1987; Friedli et al. 1988; Hodges et al. 1999) and the centre of mass is displaced anteriorly by the forward displacement of the arm. It has been known since the 1960s that the CNS prepares for the predictable challenge to posture by altering the activation of muscles of the leg prior to the muscle initiating the limb movement (Belen'kii et al. 1967; Bouisset & Zattara 1987; Friedli et al.

1988; Hodges et al. 1999). In addition, several studies had identified early activation of superficial trunk muscles (RA and ES) prior to upper limb movement in specific directions (Friedli et al. 1988; Zattara & Bouisset 1988; Aruin & Latash 1995).

In an initial series of studies, the activation of the abdominal and ES muscles was investigated with the performance of rapid unilateral arm (Hodges & Richardson 1997b) and leg (Hodges & Richardson 1997a) movements (Fig. 3A, B). TrA was consistently the first muscle activated. Since the onset of activation of TrA preceded that of the muscle responsible for limb movement it must be pre-programmed by the CNS and is consistent with a contribution to the preparation of the spine for the perturbation resulting from the reactive forces on the spine. These results confirmed that the CNS controls spinal stability in anticipation of a predictable disturbance.

Further insight into the contribution of TrA to lumbo-pelvic stability came from the effect of limb movement direction on trunk muscle activation. When limb movement is performed in different directions the direction of force acting on the spine varies.

The initial study identified the activation of the trunk muscles (except TrA) varied between directions of movement (Fig. 3C) (Hodges & Richardson 1997b). ES was active significantly earlier with shoulder flexion than in shoulder abduction and extension and a converse relationship was identified for the flexing abdominal muscles (Friedli et al. 1984; Aruin & Latash 1995; Hodges & Richardson 1997a; b). It appeared that the CNS

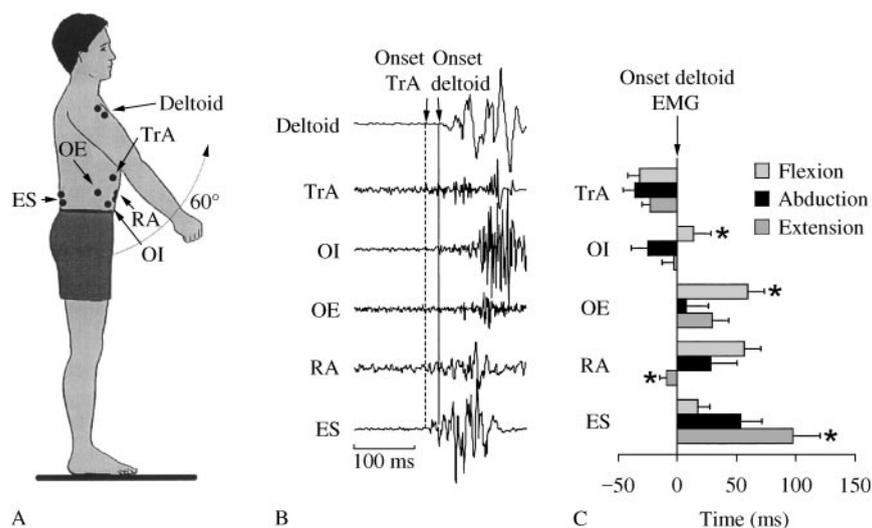


Fig. 3—Recruitment of the abdominal (transversus abdominis [TrA], obliquus internus abdominis [OI], obliquus externus abdominis [OE], rectus abdominis [RA]) and erector spinae (ES) muscles with rapid shoulder flexion. (A) Experimental set-up indicating the location of the electromyography electrodes. (B) Electromyography (EMG) data of a representative subject from a single trial of shoulder flexion. Note the onset of TrA EMG prior to that of deltoid. (C) Mean (SEM) times of EMG onset of each trunk muscle relative to that of deltoid for movement of the upper limb in each direction. Note the variation in limb movement direction for all muscles except TrA. (Adapted from Hodges & Richardson [1997b]).

recruited the superficial muscles earlier when their action opposed the direction of forces acting on the spine. In contrast, TrA was active in a consistent manner, irrespective of the force direction.

It was necessary to confirm the proposed relationship between the trunk muscle recruitment and the kinematics of the perturbation to the trunk. A study was undertaken that involved measurement of the motion of the trunk with concurrent measurement of trunk muscle EMG during performance of rapid bilateral shoulder movement (Hodges et al. 1999). Infra-red markers were placed over specific landmarks on the spine, pelvis, thigh and arm that allowed measurement of angular displacement between segments (Fig. 4A). As predicted, the results indicated that shoulder flexion was associated with flexion motion between trunk segments (Friedli et al. 1984; Bouisset & Zattara 1987). The converse reactive motion occurred for shoulder extension. However, a small but consistent motion of the spine occurred in the opposite direction to the perturbation that commenced prior to limb movement (Fig. 4B). This motion was consistent with the pattern of activation of the superficial trunk muscles, and provides evidence that the CNS deals with the perturbation to spinal stability that results from limb movement by initiation of preparatory motion of the spine to 'dampen' the forces rather than simply making the trunk rigid. The timing and magnitude of TrA activity did not vary between movement directions and is thus inconsistent with this function. An additional finding that was consistent with the initial experiment of Cresswell et al. (1992) was that TrA

responded in a relatively tonic manner in the majority of subjects.

The findings of these studies contributed to the evidence that was beginning to accumulate that suggested a possible specific and independent contribution of TrA to spinal stability. Yet before it was possible to consider the function that TrA may contribute to stability it was important to determine whether the activation of TrA was associated with a mechanical output.

EVIDENCE FROM MECHANICAL OUTPUT

The mechanical output of TrA can be evaluated by measurement of intra-abdominal pressure or tension in the thoracolumbar fascia. While measurement of fascial tension is technically difficult, it is possible to measure intra-abdominal pressure by placement of a pressure transducer in the gastric ventricle. Cresswell and colleagues (1992; 1994) identified a close relationship between intra-abdominal pressure and TrA activity. In addition, intra-abdominal pressure was measured during the performance of rapid shoulder movement. The results indicated that intra-abdominal pressure increased following the activation of TrA and was early enough to precede the onset of limb movement and could contribute mechanically to the preparatory process occurring prior to limb movement (Hodges et al. 1997a; Hodges et al. 1999).

The identification of an increase in intra-abdominal pressure prior to limb movement limb provided a

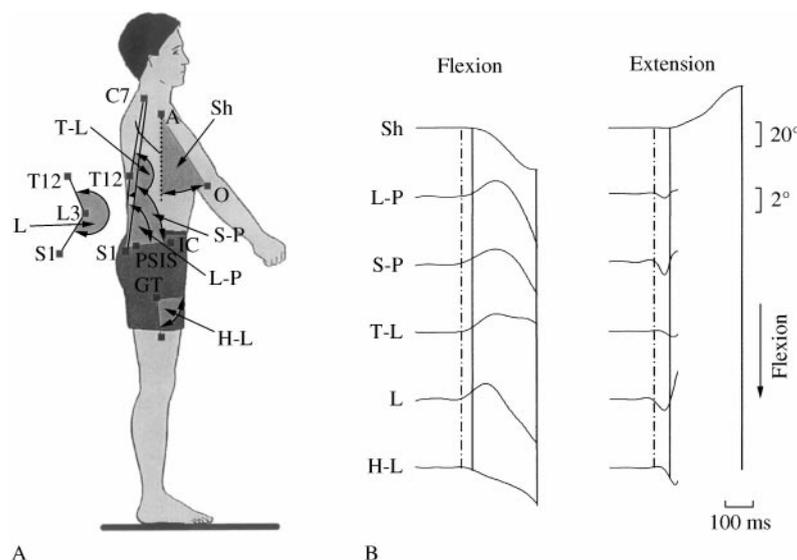


Fig. 4—Angular motion of the trunk in the sagittal plane with rapid shoulder flexion and extension. (A) Experimental set-up indicating the location of the infra-red markers and angles measured. (B) Representative raw data from a single subject with shoulder flexion and extension. The onset of shoulder movement is marked in the unbroken line and the onset of preparatory trunk motion is marked by the broken line. The missing data with shoulder extension was due to movement of the arm between the camera and markers. Note the preparatory motion occurring between trunk segments in the direction opposite to the movement provoked by the reactive forces from limb movement. A – acromion, GT – greater trochanter. IC – iliac crest, O – olecranon, PT – proximal thigh, PSIS – posterior superior iliac spine, H-L – angle between thigh (GT-PT) and lumbar spine (T12-S1), L – angle between the upper (T12-L3) and lower (L3-S1) lumbar spine, L-P – angle between the lumbar spine (T12-S1) and pelvis (PSIS-IC), Sh – angle between upper arm (A-O) and vertical, S-P – angle between the total spine (C7-S1) and pelvis (PSIS-IC). (Adapted from Hodges et al. [1999]).

further possibility to test the hypothesized contribution of TrA to spinal stability. Contraction of the diaphragm and pelvic floor muscles is essential to prevent displacement of the abdominal contents and permit TrA to develop sufficient isometric tension to increase intra-abdominal pressure and fascial tension. Thus, it was pertinent to evaluate the recruitment of the diaphragm in a postural task.

EVIDENCE FROM THE RELATIONSHIP TO THE DIAPHRAGM

The possibility that the diaphragm may perform a postural task has been considered for many years (Delhez 1968; Massion 1976). Yet studies investigating activation of the diaphragm in decerebrate animals have been unable to identify a postural function (Massion 1976). Studies of transdiaphragmatic pressure (pressure difference between the thorax and abdomen) have provided indirect evidence of diaphragm activity during lifting (Hemborg et al. 1985). The experimental paradigm used to evaluate the postural response to limb movement provided a possible method to investigate this question. For reasons outlined in the preceding section, the ability of TrA to influence spinal stability would be unlikely if activation of the diaphragm did not occur in this task. Monopolar needle and oesophageal electrodes were used to make recordings

of the costal and crural portions of the diaphragm, respectively, while subjects performed rapid unilateral shoulder flexion (Hodges et al. 1997a). The results indicated that the onset of diaphragm EMG activity (costal and crural) preceded the onset of deltoid EMG activity (Fig. 5A) and was concurrent with that of TrA. Measurement of transdiaphragmatic pressure indicated that the mechanical output of the diaphragm preceded the onset of movement (Fig. 5B). In addition the length of the diaphragm was indirectly evaluated by ultrasound measurement of the length of the region of the diaphragm in contact with the internal surface of the rib cage (zone of apposition) prior to and during the movement. The length of the zone of apposition has been shown to provide an indirect index of the length of the diaphragm (McKenzie et al. 1994). The results indicated that shortening of the diaphragm preceded the onset of shoulder movement, and provides further confirmation of the mechanical efficiency of the feedforward activation of the diaphragm (Fig. 5C). A further study investigated the diaphragm during the performance of a voluntary abdominal manoeuvre aimed at activation of TrA and found activity of the diaphragm in association with this contraction (Allison et al. 1998). While the results of this study suggest that TrA and the diaphragm are activated concurrently in certain tasks it is difficult to interpret the results since surface electrodes were used and it is impossible to be certain what proportion of the signal

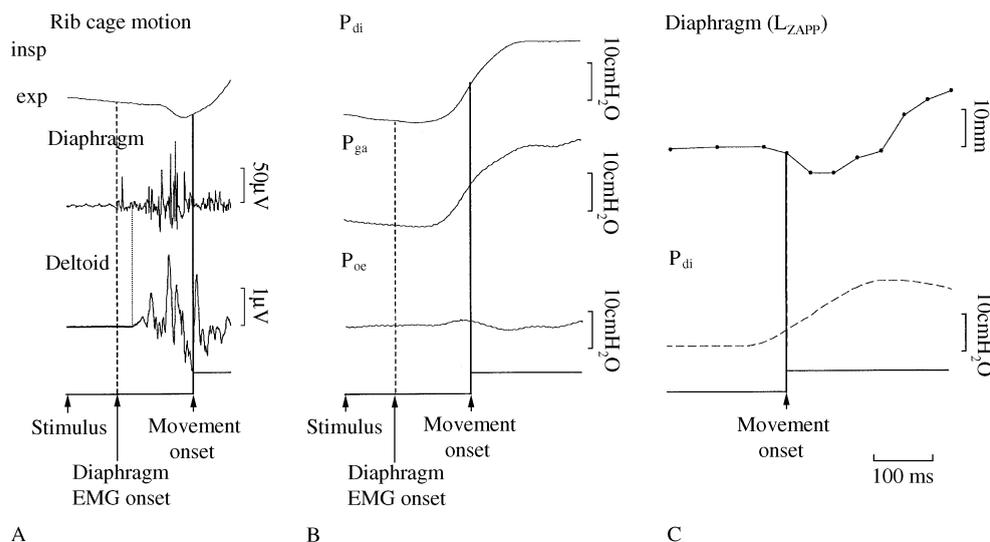


Fig. 5—Recruitment of the diaphragm with rapid shoulder flexion. (A) Representative electromyographic (EMG) activity of the costal diaphragm and deltoid and rib cage motion for a trial performed during expiration. Note the onset of diaphragm EMG prior to that of deltoid. (B) Representative transdiaphragmatic (P_{di}), gastric (P_{ga}) and oesophageal (P_{oe}) pressures for the same trial as panel A. Note the onset of pressure increase prior to limb movement which indicates that the activity of the diaphragm (and TrA) is associated with a mechanical response. (C) Representative data of changes in length of the zone of apposition (L_{ZAPP}) with shoulder flexion. Note the decrease in diaphragm length that precedes the onset of movement. (Adapted from Hodges et al. [1997a]).

arose from the intercostal muscles underlying the electrode.

The confirmation that the diaphragm contributes to the feedforward postural response provided additional support to the contribution of TrA to spinal stability. Yet further questions arise, such as how the CNS may coordinate the respiratory and postural functions of TrA and the diaphragm. When rapid movement of the upper limb is performed at random throughout the respiratory cycle, there is no difference between the onset of EMG of the diaphragm (Hodges et al. 1997a) and TrA (Hodges et al. 1997b) between movements performed during inspiration and expiration with normal quiet respiration. However, if the respiratory demand is increased by provision of an inspiratory load or forced expiration (which results in expiratory activation of TrA [DeTroyer et al. 1990]) it has been shown that the onset of TrA EMG activity occurs earlier in expiration than inspiration (Hodges et al. 1997b). Similarly, the onset of TrA activation occurs later when a sub-maximal expulsive manoeuvre is performed prior to the limb movement. These findings suggest that the CNS coordinates the respiratory and postural function of TrA and interprets the status of stability in order to plan the recruitment of TrA on the basis of pre-existing pressure in the abdomen. Yet rapid limb movement provides only a brief challenge to stability and presents as a minor disturbance to respiration. How the CNS deals with a longer duration postural demand is more complicated and is an area of ongoing investigation. A recent study provided evidence that individual TrA motor units may be recruited differently in respiratory and

postural tasks (Puckree et al. 1998). This finding provides preliminary evidence for independent control of these two tasks and requires further investigation.

A corresponding requirement exists for co-activation of the pelvic floor muscles with TrA. Preliminary evidence suggests that early activation of the pelvic floor muscles does occur (Hodges et al. unpublished observations 1996). However, more extensive evaluation is required. In summary, there is evidence that TrA, the diaphragm and the pelvic floor muscles are co-activated to form an enclosed abdominal cavity (Fig. 6) which further suggests that the function of this response is to control spinal stability.

EVIDENCE FROM RELATIONSHIP TO LOAD

An additional option to test the hypothesized contribution of TrA to spinal stability is to investigate how the activation of this muscle is affected by variation in force magnitude. If the activation of TrA is related to spinal stability then it should be related to force magnitude and not be active in situations where the force is negligible and unlikely to perturb the spine. The relationship between force magnitude and the response of TrA has been investigated in a variety of ways. In an initial study subjects were asked to perform movement at a variety of speeds (Hodges & Richardson 1997c). When the speed of limb movement is reduced the magnitude of acceleration and resulting reactive force is reduced. Feedforward activation of TrA was recorded with rapid movement and with movement performed at an intermediate speed. Yet no response occurred with

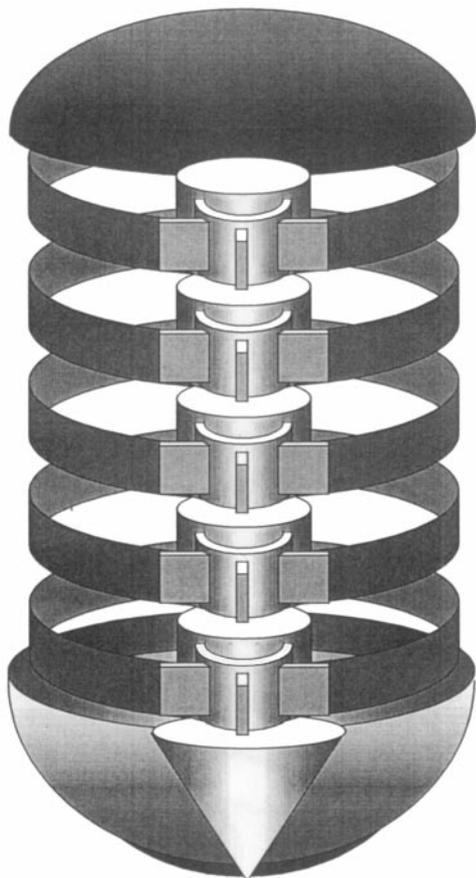


Fig. 6—Diagrammatic representation of the abdominal ‘canister’ formed by co-activation of the diaphragm, transversus abdominis and the pelvic floor. Activation of all muscles of this canister is required in order for abdominal contents to be controlled and for contraction of transversus abdominis to increase the pressure in the abdominal cavity and increase the tension in the thoracolumbar fascia.

movement performed at a slow speed. A similar experiment involved movement of progressively smaller segments of the upper limb. A response of TrA was identified with movements of the shoulder or elbow but not the wrist or thumb (Hodges & Gandevia, unpublished observations, 1996). Identical results were obtained for the diaphragm (Hodges et al. 1997a). Further evidence comes from comparison of the movement of the arm and the leg. When arm movement is performed, the onset of TrA activity precedes that of deltoid by approximately 30 milliseconds (Hodges & Richardson 1997b). In contrast, when the leg is moved (producing reactive forces of greater magnitude due to the increased mass) activation of TrA precedes that of deltoid by more than 100 milliseconds (Hodges & Richardson 1997a). An additional study provided evidence that the period between the onset of increased intra-abdominal pressure and trunk movement increased as the velocity of trunk movement is increased (Marras & Mirka 1996).

While each of these studies provides evidence of a threshold for TrA activation, additional evidence comes from comparison of the changing force magnitude during a movement and the corresponding changes in TrA activation. For instance, Cresswell and colleagues (1993) identified bursts of increased EMG magnitude of TrA during periods of high acceleration and deceleration of the trunk during both flexion and extension. This was in contrast to RA/OE and ES which were only active during acceleration when they generated the movement and during deceleration when they opposed the movement. Intra-abdominal pressure was found to respond in a two-burst pattern consistent with a relationship to TrA. The response of TrA associated with rapid shoulder flexion occurs in a similar manner with a greater magnitude burst at the initiation of the movement followed by continuous activation at a lower level (Hodges et al. 1999). In addition, when subjects perform a lifting task at different velocities the magnitude of TrA is greatest with the fastest movement speeds (Cresswell & Thorstenson 1993). These results suggest that the activation of TrA is closely related to periods of maximal stress of the spine and provides additional support to the proposed role of TrA in enhancing spinal stability.

Tonic low-level activation of TrA has been reported in standing subjects (DeTroyer et al. 1990; Hodges et al. 1997b). Several authors have postulated that continuous activity of specific muscles at a low percentage of maximum could be beneficial to spinal stability by raising muscle stiffness (Gardner-Morse et al. 1995; Cholewicki et al. 1997) and thus, maintain a constantly changeable level of stiffness to the joints (Johansson et al. 1991). However, it has been argued that the tonic activity of TrA in standing is related to the control of the abdominal contents (Keith 1923; DeTroyer et al. 1990) and thus, the length of the diaphragm. In support of this proposal, the activity of TrA has been shown to be related to the gravitational load on the abdomen. When a subject lies supine activity in the abdominal muscles is absent but can be increased by tilting the support surface up to 45 degrees (DeTroyer 1983). In addition, the activity of TrA in relaxed standing can be ceased voluntarily (DeTroyer et al. 1990; Hodges et al. 1997b). Therefore, whether the tonic activity in standing is related to ongoing maintenance of spinal stability has not been confirmed and requires additional investigation.

DEVELOPMENT OF A MODEL OF THE CONTRIBUTION OF TrA TO SPINAL STABILITY

From the preceding discussion it is apparent that substantial motor control evidence exists for a contribution of TrA to spinal stability. However, it

is important to consider the specific components of lumbo-pelvic stability that are controlled by TrA and the superficial muscles. The contribution of the superficial trunk muscles (RA, OE, OI, ES) to spinal stability is more straightforward than TrA and is associated with the control of trunk orientation or posture (Fig. 7A). For instance, when dynamic trunk movement was performed against resistance in side lying, activation of RA, OE, OI occurred at the end of trunk extension to decelerate the trunk, the converse relationship occurred for ES (Cresswell 1993). Similarly, activation of the superficial muscles was linked with the production of preparatory trunk motion prior to movement in the limb movement paradigm (Hodges et al. 1999). While this preparatory activity is consistent with the control of trunk orientation or posture it was also consistent with the control of the centre of mass (Aruin & Latash 1995; Hodges et al. 1999). Thus the activation of the superficial trunk muscles must be controlled by the CNS in a manner that combines the challenges of controlling orientation and the centre of mass concurrently.

From the studies of Cresswell and colleagues (1992; 1993) and Hodges and colleagues (1999; 1997b) it can be seen that the activation of TrA is not related to the direction of trunk movement (Cresswell et al. 1992), the direction of the acceleration or deceleration of the trunk (Cresswell & Thorstensson 1993), the direction of perturbing forces acting on the spine (Hodges & Richardson 1997b; Hodges et al. 1998) or the direction of displacement of the centre of mass (Hodges et al. 1999).

Thus, TrA must contribute to an aspect of spinal stability other than the control of spinal orientation. The likely candidate is inter-segmental control (Fig. 7B). The muscle fibres of TrA have multiple attachments to the lumbar vertebrae via the layers of the thoracolumbar fascia and can also influence the lumbar segments via the development of intra-abdominal pressure. Due to the inherent instability of the lumbar spine, particularly around the neutral zone (Panjabi 1992b), the control of this feature is of paramount importance. While muscles such as lumbar multifidus provide up to two thirds of the control of inter-segmental motion in certain directions (Wilke et al. 1995), there are limitations in the control provided by this muscle. For instance multifidus can contribute little to the control of lumbar rotation (Wilke et al. 1995) and the shearing forces generated at the L5 level by maximal contraction of this muscle are counterproductive (Bogduk et al. 1992).

The mechanisms through which TrA may contribute to inter-segmental stability are complex and involve either fascial tensioning (Tesh et al. 1987), generation of intra-abdominal pressure (Grillner et al. 1978; Tesh et al. 1987; Cresswell et al. 1992) or a combination of both (Hodges & Richardson 1997b). As such it is likely that TrA can only influence segmental stability in a general, non-direction specific manner. In the limb movement and trunk loading studies presented earlier the response of TrA was consistent with a role in increasing the stiffness of the lumbar intervertebral joints to potentially simplify the control of orienta-

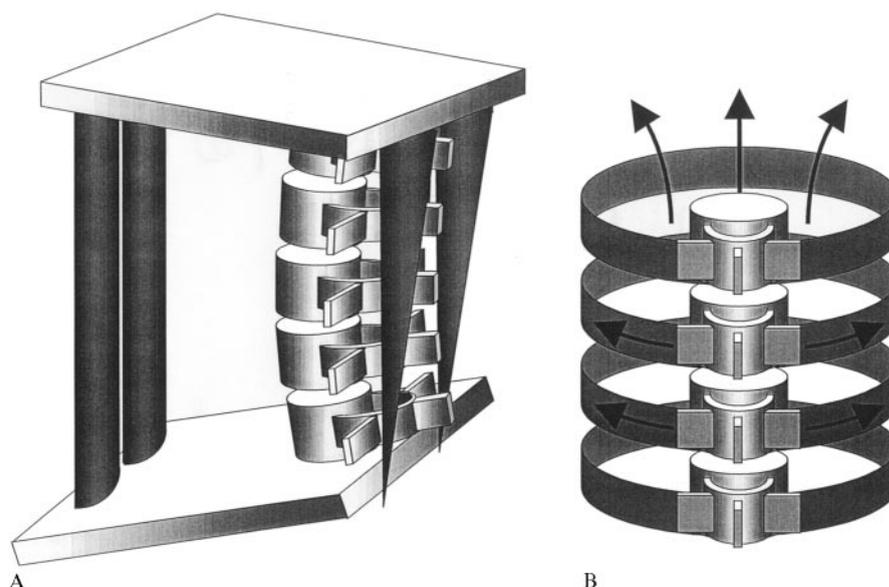


Fig. 7—Model for the differential contribution of the trunk muscles to spinal stability. (A) The superficial trunk muscles (rectus abdominis, obliquus externus abdominis, obliquus internus abdominis and erector spinae) have the mechanical advantage to control the overall orientation or posture of the spine. (B) In contrast, transversus abdominis is unable to directly control external forces and may control intersegmental motion in a general manner by increasing the pressure in the abdominal cavity and tension in the thoracolumbar fascia.

tion by the superficial muscles (Cresswell et al. 1994; Hodges et al. 1999).

This model of differentiation in the contribution of the trunk muscles to spinal stability is consistent with the proposal of Bergmark (1989), which defines muscles as either 'local' or global'. In Bergmark's biomechanical model the 'local' muscles were those with attachments to the lumbar vertebrae and hence an ability to influence inter-segmental control. In contrast, the 'global' muscles were those with attachments to the thorax and pelvis and were suitable for control of external forces acting on the spine, in other words, the control of spinal orientation. Although TrA was not considered in Bergmark's model, the behavioural evidence presented in this review is consistent with the classification of TrA in the 'local' group.

On the basis of the hypothesis that TrA contributes to a separate aspect of spinal stability, it was predicted that the CNS may control components of spinal stability independently. This possibility was tested in an attempt to provide further support for the model. In the limb movement studies it was identified that TrA was active at the same latency prior to deltoid irrespective of movement direction (Hodges & Richardson 1997b; Hodges et al. 1999) while the temporal relationship of the other superficial muscles varied. It was hypothesized that if TrA was controlled independently to provide intersegmental stiffness then the CNS would not need to know which direction of limb movement would be performed. In contrast the CNS would need information of movement direction in order to plan the response of the superficial muscles. If there was uncertainty about the movement direction then the CNS would need to wait until the direction of movement was determined in order to initiate a response. This hypothesis was tested by having subjects perform either shoulder abduction or flexion in response to a visual stimulus after receiving preparatory information about which movement they would be expected to perform (Hodges & Richardson 1998d). In the majority of trials the preparatory information was correct, in other trials subjects were given a signal that provided no information of the required movement direction and in a small number of trials the preparatory information was wrong. In the trials where the preparatory information was correct the reaction time was rapid. In the conditions where no preparatory information was provided or the preparatory information was wrong the reaction times of deltoid and the superficial trunk muscles were delayed. In contrast, the activation of TrA was unchanged. This finding suggested that TrA was controlled independently of the other trunk muscles and provided further evidence that this muscle contributed to stiffness of the spine in a general manner.

This finding provides initial evidence that the CNS controls segmental stability and orientation of the spine independently. Several modes of coordination between the anticipatory postural muscle activity and limb movement have been presented. A 'hierarchical' model suggests that postural networks in the CNS are controlled by pathways involved in limb movement production (Gahéry & Massion 1981; Paulingnan et al. 1989; Massion 1992). In this model the latency between the activation of the postural and limb movement commands is relatively fixed (Paulingnan et al. 1989). Alternatively, limb movement and associated postural responses may be controlled in a 'parallel' manner where separate commands are generated in the CNS for each component (Lee et al. 1987; Gurfinkel 1994), thus allowing for uncoupled activation (Brown & Frank 1987).

While a fixed latency between the postural and agonist limb muscle activity has been identified under stable conditions (Lee 1980; Friedli et al. 1984), the majority of studies have failed to find a fixed relationship which questions the 'hierarchical' model (Marsden et al. 1977; Cordo & Nashner 1982; Brown & Frank 1987). Evidence that interaction occurs between the voluntary and postural responses also questions the 'parallel' model. For instance, limb movement is delayed in tasks where the postural demand is increased (Cordo & Nashner 1982; Zattara & Bouisset 1986) and both limb movement and its appropriate postural response are initiated by electrical stimulation of the cortex in animals (Gahéry & Massion 1981). The most likely hypothesis for the coordination of limb movement and the associated postural muscle activation has been presented by Massion (1992). In this model the coordination of postural control and movement occurs at a lower level in the CNS where both the planning of movement and postural control are known (Gahéry & Massion 1981; Gurfinkel 1994). Evidence has come from studies of patients with absence of the corpus callosum where postural responses in the contralateral limb is retained without communication between the brain cortexes (Massion et al. 1989).

The differential influence of preparation for limb movement on the activation of the trunk muscles (Hodges & Richardson 1998d) adds another dimension to this problem. These findings suggest that postural control should be further subdivided and that the CNS deals with control of segmental stability of the spine (and potentially other regions of the body) in a separate manner. This has significant implications for the manner in which training of the abdominal muscles should be addressed in clinical practice. With this new model of the contribution of TrA to spinal stability and the evidence that the CNS controls TrA independently of the other abdominal muscles it was important to test whether changes occurred in the presence of pain.

EVIDENCE OF DYSFUNCTION

Interest regarding the relationship between spinal stability and low back pain has stimulated a wealth of investigation of this parameter (Nachemson 1985; Panjabi 1992a). Evaluation of the function of TrA in people with low back pain has provided additional indirect insight into this discussion. A study was undertaken on a group of 15 patients with chronic recurrent low back pain and a group of age and sex matched controls using an identical limb movement model to that used previously (Hodges & Richardson 1996). The results for the control subjects were identical to those found in the initial studies (Hodges & Richardson 1997b). However, when the subjects with low back pain performed rapid limb movement the onset of TrA was significantly delayed and failed to occur in the pre-movement period with movement in all directions (Fig. 8). The onsets of activation of RA, OE, OI were also delayed but only with movement in a single direction. In addition, the onset of TrA activity was significantly different between movement directions (along with the superficial abdominal muscles) and the response of TrA became more phasic. Additional studies revealed that TrA was delayed with movement of leg (Hodges & Richardson 1998b), that the threshold for activation of TrA was increased (a finding consistent for all the abdominal muscles) (Hodges & Richardson 1998c) and that TrA was no longer activated independently

of the superficial trunk muscles (Hodges & Richardson 1998a) in people with low back pain.

The implications of these findings are considerable. If the model of the contribution of TrA to spinal stability is correct then the specific dysfunction of this muscle in low back pain implies that it is this aspect of spinal stability that is deficient. The motion of the spine associated with limb movement has not been investigated in people with low back pain. In order to confirm this hypothesis it would be necessary to evaluate both segmental motion and spinal orientation during limb movement. With methods being developed for the direct measurement of inter segmental motion (Willems et al. 1997) this presents as an exciting possibility for the future.

Two further groups of studies provided additional indirect evidence for a change in the activation of TrA in low back pain patients. Several studies have been undertaken to investigate the ability of low back pain patients and control subjects to perform an abdominal manoeuvre thought to activate TrA specifically. In this task subjects gently draw in their abdominal wall (Richardson & Jull 1995; Richardson et al. 1998) and the displacement of the abdominal wall is measured as the reduction in pressure in an air-filled bag placed under the abdomen. Interestingly the ability to consciously perform this manoeuvre is related to the timing of onset of contraction of TrA associated with rapid limb movement (Hodges et al. 1996). A major finding has been that the majority of

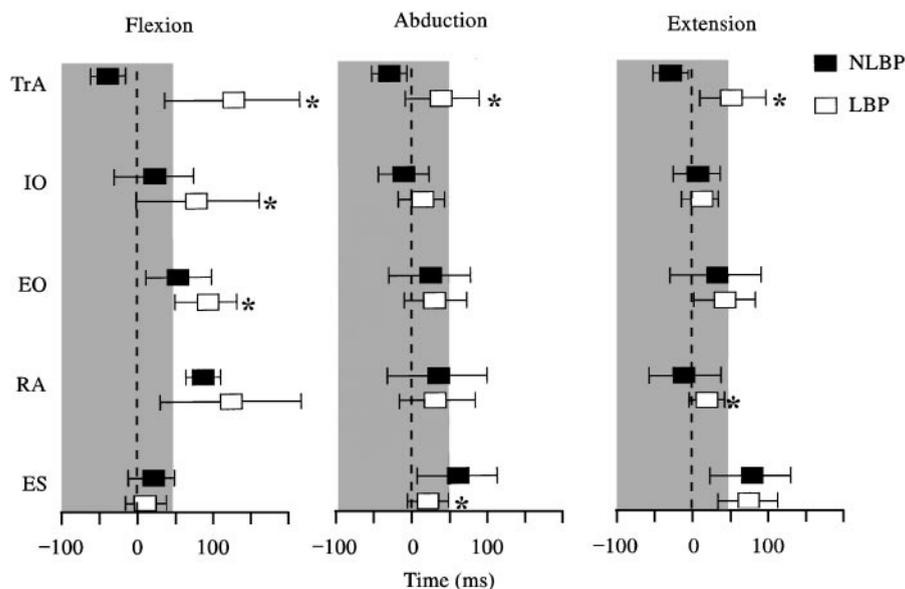


Fig. 8—Changes in recruitment of the trunk muscles in low back pain patients. Mean time of onset of electromyographic activity (SD) of the trunk muscles (Transversus abdominis [TrA]), obliquus internus abdominis [OI], obliquus externus abdominis [OE], rectus abdominis [RA] and erector spinae (ES) associated with rapid movement of the shoulder averaged over ten repetitions for 15 subjects. The onsets are aligned to the onset of deltoid EMG at zero. The shaded areas indicated the time period in which a muscle must be active in order to be pre-programmed by the central nervous system. Any activity occurring more than 50 ms after the onset of deltoid EMG may be mediated reflexly from the perturbation produced by the movement. Significant differences are noted. Note the delayed activation of TrA with movement in each direction and the direction specific changes of the other muscles. (Adapted from Hodges & Richardson [1996]).

people with a history of low back pain are unable to perform the manoeuvre adequately while people with no history of low back pain can (Jull et al. 1995; Richardson et al. 1995).

A randomized, controlled clinical trial has been undertaken in which TrA was being trained in people with chronic low back and a radiological diagnosis of spondylolisthesis/spondylosis (O'Sullivan et al. 1997). Following training these patients achieved a reduction in pain and reduction in functional disability that was maintained at 30 months after the completion of the training period. While TrA was not directly measured in this study and it is impossible to determine whether the contraction of TrA was altered by this training, this study provides additional indirect support for the relationship of TrA to low back pain.

RELEVANCE TO CLINICAL PRACTICE

With the apparent efficacy of TrA training in the management of low back pain, it is imperative that several points be considered when training this muscle:

- TrA is controlled independently of the other trunk muscles and should be trained separately from the other trunk muscles:
- TrA is the principle abdominal muscle affected in low back pain and should be trained separately from the other trunk muscles.
- TrA should be trained to contract tonically but not at a constant level.
- TrA loses its tonic function in low back pain and needs to be trained to regain this function.
- The functional interaction between TrA, diaphragm and pelvic floor muscles should be considered.
- TrA has a similar function in many situations and exercise may not need to be performed in functional positions initially.

CONCLUSION AND DIRECTIONS FOR THE FUTURE

Many questions remain unanswered regarding the contribution of TrA to spinal stability. While the studies presented here provide indirect evidence of the function of TrA, it is imperative that data is obtained to confirm the mechanical contribution of TrA to stability and the consequence of changes in its activation in the presence of low back pain. Further studies are required to further document the feedforward and feedback mechanisms of control of this muscle and the coordination between breathing and spinal stability. Additional investigation is required to confirm, (or exclude) the proposed model of the

contribution of TrA to spinal stability. One question that remains unsolved is the possible contribution of TrA to trunk rotation. While some studies have found activation of TrA with ipsilateral trunk rotation (Cresswell et al. 1992; Hemborg 1997) others have failed to find a relationship (DeTroyer et al. 1990). In addition, the temporal parameters of the response of TrA are unaffected by changes in direction of rotation provoked by unilateral upper limb movement in different directions (Hodges & Richardson 1997b).

Thus while the initial evidence for a specific and crucial role of TrA in providing stability to the lumbo-pelvic region exists, further work is needed to confirm these findings.

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