

**Role of transversus abdominis muscle in spinal stability**

**ABSTRACT**

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This is a descriptive review of specific topic areas regarding the function of the transversus abdominis muscle (Tra) in context of the Tra having a central role in spinal stabilization.

A literature search was made to examine the experiments supporting a spinal stabilizing role of the transversus abdominis muscle and to compare to findings of other physiological research on the functions of the Tra.

The proposed generation of extension moment of the lumbar spine produced through tension of the thoracolumbar fascia or through raised intra abdominal pressure caused by the action of transversus abdominis muscle and the diaphragm does not appear to be supported by experiments. Experimental support for the stated earliest contraction of the Tra in response to perturbation appears to be lacking. There are many reports of the presence of several reflexive mechanisms by which movements of the limbs initiate respiratory activity of the Tra and of the diaphragm which could explain the activation of the Tra and the diaphragm in response to perturbation.

The co contraction of the Tra and the diaphragm associated with limb movements is likely to be a respiratory response and is also likely to create the necessary transdiaphragmatic pressure for protection and containment of the thoracoabdominal viscera; a spinal stabilization role is likely to be secondary.

**Keywords.** Transversus abdominis muscle; diaphragm; spinal stabilization; intra abdominal pressure.

**INTRODUCTION**

### **Role of transversus abdominis muscle in spinal stability**

This is a descriptive review of specific topic areas regarding the function of the transversus abdominis muscle (Tra).

There are many articles supporting a central role of the Tra in spinal stabilization (Hodges PW & Richardson CA 1997 Exp Brain Res).

Allison, Morris & Lay commented that many authors conclude that all form of perturbation or functional task require the Tra to be bilaterally preactivated to provide optimal spinal stability; this assumes that the predominant role of the feedforward Tra activation is to stabilize the spine. They also said that the link between early Tra activation and spinal stability has been a consistent theme in subsequent publications and the search for this link a common research focus (Allison GT, Morris SL & Lay B 2008).

The purpose of this study is to explore this suggestion of the Tra having a central stabilizing role. This was done under the heading of earliest contraction of Tra, extensor moment generated by its action, raised intra abdominal pressure (IAP) and non direction dependent response of Tra to perturbations. Function of the diaphragm is closely linked and is considered together. Findings of many accepted physiological researches on responses of the respiratory muscles, transversus abdominis and the diaphragm to stimuli such as limb movements, thoracic compression and lung volume change are noted, attempting to link them with the outcome of experiments supporting a spinal stabilizing role of these muscles. Any pathological process has not included in the study.

#### **METHOD**

A literature search was made through PubMed and Google Scholar in the context of transversus abdominis and diaphragm function under the heading of spinal stabilization, abdominal muscle anatomy and function, thoraco lumbar fascia, CT and MRI imaging of abdominal muscles and abdominal cavity and the diaphragm and the pelvic floor, anatomy and function of the diaphragm, postural function of diaphragm and evolution of diaphragm. A search regarding transversus abdominis muscle was made under the heading of anatomy, function, evolution, respiration, spinal stabilizing role, electromyography. Also intra abdominal pressure and its role in spinal stabilization, intra abdominal volume measurement, rapid arm movement, non arm movement perturbation, spinal unloading, inter vertebral disc compression, inter vertebral disc pressure, anatomy and action and activation of pelvic floor muscles,

lumbopelvic stabilization, thoracic compression and respiration, chest wall compression and respiration, respiration with upper limb elevation and use, respiratory reflex induced by arm and limb movement, afferent impulse from arms and limbs and respiration, respiratory loading, lung volume change and respiration, respiration

locomotion entrainment. It is not possible to estimate the number of articles examined. Text book chapters' pertinent to above topics were also examined.

The exclusion criteria were any consideration of a pathological process and any topic not directly or indirectly related to the function of the spine and muscles of abdomen and pelvis and diaphragm.

#### **PHYSIOLOGICAL BACKGROUND**

The transversus abdominis muscle (Tra) is the most important abdominal expiratory muscle; it has an additional role of containment of the abdominal viscera. On account of transverse direction of fibres (the oblique fibres in humans originate from the iliac crest and are inserted to the pubic bone) the Tra cannot flex or extend the spine. In humans there is a natural tendency of flexion of the lumbar spine, in quadrupeds the force of gravity causes the lumbar spine to sag (extension), this also occurs cyclically with locomotion. The oblique hypaxial muscles, the internal and external obliques, contribute to spinal stabilization in the sagittal plane in quadrupeds (Fife, Bailey, Lee, Carrier 2001).

"The chest and the abdomen are inexorably linked and must be considered as a single unit" (Kirkpatrick, Pelosi, De Waele & Malbrain et al. 2010) and any discussion of the function of the Tra needs to include the diaphragm function as well.

There are several reflexive mechanisms by which movements of the limbs initiate respiratory activity of the Tra and that of the diaphragm.

The use of unsupported upper limbs, even simple elevation, causes restriction of the ribcage movement initiating Tra and diaphragm activation (Mackey, Ellis & Nicholls 1998; Couser, Martinez & Celli 1992; Romagnoli, Gorini, Gigliotti & Bianchi et al. 2006; Celli, Criner & Rassulo 1988; Cerny & User 2004). This is because the shoulder girdle is attached to the ribcage and spine only by muscles and fascia, and the clavicle is attached to the spine indirectly through the ribcage.

Pressure on the rib cage, even if it is small, causes activation of respiratory muscles (D'Angelo, Miserocchi, Agostoni 1976; Shannon 1979; Hagan,

### **Role of transversus abdominis muscle in spinal stability**

Bryan, Bryan & Gulston 1997). The movement of the upper limbs may activate the Tra and the diaphragm by this mechanism as well.

Afferent stimuli from the upper and lower limbs initiate reflexive action of the Tra and the diaphragm (Agostoni & D'Angelo 1976; Haxhiu, van Lunteren, Mitra & Cherniack et al. 1984; Potts, Spyer & Paton 2000; Oliven, Haxhiu & Nelson 1990; Hussain, Ward, Gatensby, Roussos et al. 1991; Ward, Vanelli, Hashefi & Hussain et al 1992; Schroeder, Tao & Farkas 1991; DiMarco, Romaniuk, Von Euler & Yamamoto 1983). These reflexive activities are associated with activation of upper airway dilators, therefore the responses are truly respiratory.

The observation of Deban & Carrier (2002) that the Tra was active during mid-forelimb support in both the coupled averages and the uncoupled stride averages in a running dog is in accord with the above mechanism.

Elevation of the shoulders causes lung volume changes (Cala, Kenyon, Ferrigno, Carnevali et al 1996). Lung volume changes elicit strong respiratory responses in the Tra and the diaphragm (Romaniuk, Kowalski & Dick 1997; Erickson, Forster, Lowry & Pan et al 1994; Yoshimura, Abe & Tomita 1995; Brice, Forster, Pan & Lowry et al. 1991; Romaniuk, Dick, Kowalski & Dimarco 2007; LeEVERS & Road 1993).

On account of low atmospheric oxygen levels from the Permian through Triassic and Jurassic periods the diaphragm evolved in mammals as an adaptive trait (Klein and Owerkowicz 2006). The *Gata4-Fog2* transcriptional pathway controls the bronchoalveolar development of the lung and the development of the diaphragm, and the two are linked in mammalian respiratory evolution (Hirasawa and Kuratani 2013). The evolution of the diaphragm allowed full respiratory excursion of the lungs, preventing translation of the abdominal

Many authors have described that unlike other abdominal muscles the latency and magnitude of the Tra response is invariant with the direction of perturbation; therefore the Tra has a special stabilising function (Hodges and Richardson 1997 Exp Brain Res; Hodges, Cresswell & Thorstensson 1999; Carpenter, Tokuno, Thorstensson & Cresswell 2008; Eriksson Crommert & Thorstensson 2008).

The above points are discussed below under appropriate individual heading.

Earliest onset of Tra action

viscera into the thorax (Klein and Owerkowicz 2006; Buchholtz, Bailin, Laves & Yang et al. 2012).

The diaphragm, in addition to its inspiratory function, is the sole generator of transdiaphragmatic pressure (Pdi). A common method of determining diaphragmatic muscle force is the measurement of Pdi (Mador & Tobin 1992; Mantilla, Seven & Sieck 2014; Greising, Sieck, Sieck & Mantilla 2013).

To summarise: the Tra and the diaphragm through multiple reflexive mechanisms respond as respiratory muscles to limb movements and perturbations caused by the same, also to create Pdi and protect thoraco abdominal viscera. This mechanism could explain better the results of much of the spinal stabilization research as we shall see.

#### Central role of Tra in spinal stabilization

Many authors consider that the Tra has a central role in spinal stabilization. The reported earliest activation of the Tra in response to rapid arm movements is one of the reasons for this conclusion (Eriksson Crommert and Thorstensson 2008; Cholewicki and VanVliet 2002; Cholewicki, Ivancic, Radebold 2002).

Additional observations that support the central role of the Tra are that it stiffens the spine and produces an extension moment (Barker, Guggenheimer, Grkovic, Briggs et al 2006; Hodges, Kaigle, Holm, Ekström 2003).

Also the concept that the Tra, along with the diaphragm and pelvic floor muscles, creates an intra-abdominal pressure (IAP) column that unloads the spine (Daggfeldt and Thorstensson 1997), places the Tra in a central role.

The Tra may contract in the anticipatory period but it is doubtful if it is the first muscle to contract in all fast arm movement conditions. A search was made through PubMed under various headings to examine the given raw data regarding the time of onset of the Tra activation in electromyography (EMG) in response to rapid movements of limbs, compared to the time of onset of other trunk muscles. Such data was available in 18 articles; in only 3 articles the Tra was always the first muscle to contract but not in the remaining 15 articles (Table 1).

Additionally in some articles where the raw data was not available, it was found that the Tra

### **Role of transversus abdominis muscle in spinal stability**

was not the first muscle to contract in response to rapid arm movements (Westad, Mork, Vasseljen 2010; Takahashi, Yamaji, Wada, Shirakura et al 2015; Masse-Alarie, Beaulieu, Preuss & Schneider 2015).

Excessive zeal with the "as fast as possible" may have created an artefactual "Tra was invariably the first muscle that was active" (Hodges and Richardson 1997 Phys Ther). For example when an arm thrusting motion was carried out at maximum speed, the onset of the masseter muscle EMG was 100ms earlier than that of the prime mover. When the action was performed at a rate of 50% of the maximum speed, the masseter EMG onset was 150 ms after that of the prime mover (Kimura, Murakami, Yamamoto, Yokoyama et al 2007).

With arm movements at normal speed, the tra was not the first muscle to contract (Hodges and Richardson 1999; Hodges and Richardson 1997 Ergonomics), this also happened in experiments with the movement of arms and legs at normal speed (Sjödahl, Kvist, Gutke, Oberg 2009).

It is well documented that perturbations of the trunk that are not caused by movement of the limbs (examples are support surface translations, load release from the trunk etc.) do not activate the Tra before all other muscles (Eriksson Crommert and Thorstensson 2008; Eriksson Crommert and Thorstensson 2009; Tokuno, Cresswell, Thorstensson, Carpenter 2013; Carpenter, Tokuno, Thorstensson, Cresswell 2008).

An earliest onset of action has been used as the reason for placing the Tra in a central role in spinal stabilization but it is obvious from above that there is no basis for that reasoning. The Tra is rarely the earliest one to contract.

The question as to why and how the Tra contracts early if it is not to perform "feed forward stabilizing function", can be readily explained through several mechanisms. The latency of reflexive responses of Tra can be well under 50 ms after an expected as well as an unexpected perturbation (Cresswell AG, Oddsson L & Thorstensson A 1994; Eriksson Crommert & Thorstensson 2009; Hodges, Cresswell & Thorstensson 2001). Coordination of respiratory and locomotor rhythm could be generated by central feedforward mechanism (Yazawa 2014) allowing an early Tra response. Noah, Boliek, Lam & Yang observed "multiple neurogenic mechanisms, classified as either feedforward or feedback, are proposed to act in concert to produce initial increase in ventilation with

exercise". Thus the respiratory response of Tra to perturbations could be early through a feedforward or a short latency reflex mechanism.

Extension moment generated by Tra

In humans, as there is a natural tendency of the lumbar spine to flex forward by the weight of the trunk, an extension moment could be equated with segmental stabilization.

Barker, Guggenheimer, Grkovic, Briggs et al (2006) experimented on cadaver spine segments. They suggested that application of tension to the Tra aponeurosis was mainly conveyed by the middle layer of lumbar fascia and significantly increased resistance to flexion moment at all lumbar segments. They concluded that there was compelling evidence that tra could contribute, via the lumbar fascia, to control of neutral zone moment. However it is of note that in this experiment the tension was applied lateral wards (transversely) but the actual direction of fibres of the Tra is anteromedially (the anatomy of muscles and other structures in the "living" are clearly seen in MRI pictures supplied by Hides, Wilson, Stanton, McMahon et al 2006) therefore from this experiment one cannot predict the result of an actual contraction of the Tra. Tesh, Dunn & Evans (1987) did not find it to be feasible to study the stabilizing influence of the middle layer of thoracolumbar fascia on isolated motion segments because of technical difficulties.

Tesh, Dunn & Evans (1987) carried out a three part experiment on cadaver spines. They concluded that the middle layer of the thoracolumbar fascia emerged with a more important role than was expected in providing support in the coronal plane. The cumulative effect on the spine in the sagittal plane was *small* for both the raised IAP and raised tension in the muscles of the abdominal wall. The in vivo experiment by Hodges, Cresswell, Daggfeldt & Thorstensson (2001) to determine the torque production at L3 spine level by inducing contraction of the diaphragm by electrical stimulation of the phrenic nerve showed that in neutral posture, contraction of the diaphragm raised the IAP but the spinal extension torque change was negligible. The other part of the experiment with a posture of 50 degree of spinal flexion plus wearing an abdominal belt was unphysiological.

From the in vivo experiment on porcine lumbar spine (Hodges, Kaigle, Holm, Ekström et al 2003) the authors concluded "These data

### **Role of transversus abdominis muscle in spinal stability**

argue that Tra contraction increases lumbar stiffness and decreases relative inter vertebral displacement, but only in response to caudal displacement. As this corresponds to the task of the simulated inter vertebral flexion at L3-L4, this is consistent with the hypothesis that increased IAP tensions the spine and produces an extension moment." This conclusion is incorrect, if the movement of the whole of the lumbar spine is considered in terms of the ease of movement of the spinous process to the rostral direction, there is overall flexion of the lumbar spine (L6 flexes on sacrum, L5 flexes on L6, L4 flexes on L5, L3 flexes on L4 etc.) with flexion at lumbosacral junction and extension at thoracolumbar junction. The flexion would be the expected physiological response of a quadruped spine to counteract the force of gravity. Flexion of the spine in the manner described in the above experiment would be a benefit as a by-product of other functions of Tra like respiration and containment of abdominal viscera (De Troyer 1983).

In the article on force transfer through the thoracolumbar fascia (TLF) by Vleeming, Schuenke, Danneels & Willard (2014) the main point of interest was the inflation induced configuration change of the paraspinal muscular compartment (PMC) and its effect on force transfer through TLF from the combined internal oblique and Tra tendons. It is apparent from figures 7ai & ii that a tension of the combined tendons substantially counteracts the effect of the PMC inflation. No data was given about the force transmission through the TLF before the inflation of the PMC and the given data indicates that only a little of the force is transmitted from the combined abdominal muscle tendon to the TLF after the inflation. The fascial sheath bounding the PMC was cut into 2 cm wide strips which could have substantially alter its response to inflation. It is not possible to deduce from this article that the Tra causes an extensor moment of the lumbar spine.

There are many experiments measuring the contribution of Tra in causing a flexion or an extension of the trunk, generated either reflexively or volitionally. The Tra was equally active in generating an extension or a flexion (Eriksson Crommert, Thorstensson 2009; Eriksson Crommert, Thorstensson 2008; Carpenter, Tokuno, Thorstensson, Cresswell 2008), however in other instances the Tra was more active causing a flexion rather than an extension of the spine (Cresswell 1993;

Cresswell, Oddsson & Thorstensson 1994).

These are contrary to the proposed generation of extensor moment by Tra action, it should be more active during extension of the spine.

Abdominal draw in manoeuvre causes flexion of the lumbar spine (Barnet & Gilleard 2005; Richardson, Jull, Toppenberg, Comerford 1992; McPherson & Watson 2012). Tra is most likely to be assisted by other muscles to cause the flexion since many other muscles as well as the Tra contract during this manoeuvre (Vera-Garcia, Moreside & McGill 2010).

McGalliard, Dedrick, Brismée, Cook et al. 2010 and Kulas, Schmitz, Shultz, Henning et al 2006 in their experiments demonstrated that the expected stabilizing contraction of the Tra did not occur in a response to a destabilisation into flexion.

From the above discussion it is apparent that experiments that have claimed to have proven that the Tra creates extensor moment have been interpreted incorrectly. There is no evidence that Tra causes extensor moment of the spine, at least of any significance. Contrarily the Tra causes flexion of the spine in an abdominal hollowing procedure and it does not contract as expected when there is a spinal destabilisation into flexion. It is either equally active or more active during the flexion of spine than an extension, confirming its lack of extensor moment generating function.

#### **Tra and IAP**

Bartelink (1957) conceived that the IAP supports the spine. He also described that in some subjects with certain position of flexion of the spine with a given weight in their hands the IAP falls to zero despite maximal lifting efforts. If IAP falls to zero while a maximum effort is being made to lift a weight, IAP is unlikely to have any significant role in spinal support.

A pressure in a fluid medium is transmitted in all directions equally, acting at right angle to the surface it meets and the force generated is proportional to the surface area. According to Pascal's Principle raised IAP would not act on the diaphragm and pelvis alone producing a piston like effect, but it would exert the same degree of pressure on the posterior abdominal wall and spine and the anterior abdominal wall. The resulting outcome is likely to be a flexion of the spine because the combined surface area of the abdominal wall is greater than that of the dome of the diaphragm and the pelvic floor. Daggfeldt & Thorstensson (1997) did not take

### **Role of transversus abdominis muscle in spinal stability**

this into account in their essay. Bergmark (1989) said that IAP is also capable of flexing the lumbar spine by direct local action on the vertebrae which is in keeping with Pascal's Principle. The detail results of individual steps of the previously mentioned experiment by Hodges, Kaigle, Holm, Ekström et al (2003) support the theoretical expectation that a raised IAP causes flexion of the lumbar spine.

Figure 1 in the article Motor control of the trunk during a modified clean and jerk lift (Eriksson Crommert, Ekblom & Thorstensson 2014) shows the trunk muscle activity and the IAP in various stages of lifting a barbell, weighing 30 kg, from the ground to vertically above the head (arms fully extended) and back to the ground. At the onset of the lift and near the point of dropping the load the IAP was highest and the erector spinae (ES) was most active, the Tra was moderately active. At the highest point of the lift the Tra was most active with moderate IAP and slightly active ES. This is strong evidence against the Tra having an important role in spinal stabilization or generating an extensor moment of the spine. During the posture of the maximal destabilising threat to the spine the Tra is least active compared to other positions. With the weight in overhead position the Tra is most active and the IAP is moderate. The authors conclude that the Tra has a role in balancing the trunk in a vertical posture, and that this role gets more pronounced when the postural demand increases. This is unlikely to be true. The Tra was activated by lung volume changes and by thoracic compression (as described in Physiological Background), and that will be the most parsimonious explanation.

The figures in the article Activation of transversus abdominis varies with postural demand in standing (Crommert, Ekblom & Thorstensson 2011) demonstrate the state of muscle activity and the IAP at various arm postures carrying a load of 3 kg in each hand in an erect subject. The authors comment "also, Tra appears to assist in counteracting trunk flexion via increased IAP." Position 1 (shoulders extended, arms straight) and position 3 (shoulder flexed, arms straight) actually disprove that statement. In position 1 with the weight behind the back, the Tra should not contract nor should there be raised IAP if it was the role of the Tra to produce an extensor moment by raising the IAP. In position 3 the Tra is less active and the IAP is less than it is in position 1, the reverse should occur if the Tra

was trying to produce extensor moment by raising the IAP. It is obvious that the spine is subjected to a greater strain in position 4 (arms straight ahead at right angle to the body) than position 6 (arms straight up) yet the highest contraction of Tra happens in position 6 with low IAP. As expected, there is highest IAP in position 4, the Tra is highly active as well but not as much as in position 6. It is most likely that the discrepancy of low IAP and high Tra activation in position 6 is caused by compression of the thorax and change in lung volume as mentioned earlier, it cannot be explained by fascial stiffening and a high IAP mechanism.

Lavender, Marras & Miller (1993) did not find the IAP to function as a preparatory mechanism for anticipatory perturbation. Marras & Mirka (1996) concluded from an in vivo study on 114 subjects that the IAP was a by-product of muscle contraction and cocontraction.

It has been suggested that the diaphragm is a postural muscle (Hodges, Butler, McKenzie & Gandevia 1997; Hodges & Gandevia 2000) however Hodges, Heijnen & Gandevia (2001) have demonstrated that the Tra and the diaphragm are not postural muscles. In that article in figure 4, in the second minute of the arm movement there is no activity of these muscles in relation to the arm movement whereas ES continue to contract as it did in the first minute. The tonic activity of the Tra and the diaphragm in the first minute is most likely to have been due to the tension in the subjects, having to move the non dominant upper limb at a rate of 4 times per second. Figure 2C supports this point of view, in the initial period of the arm movement the breathing was more thoracic than during quiet breathing. Actually there should be less thoracic contribution to the respiration during arm movements and this happens in the 2nd and 4th minutes. Also the IAP was high initially, the Tra was in tonic activity during quiet breathing (fig3) for the same reason. In other words the authors have demonstrated that the Tra and the diaphragm do not contract to stabilize the spine.

If the diaphragm had a postural function, an exercise requiring greater postural demands would cause greater diaphragmatic fatigue but that was not the case (Wüthrich, Eberle & Spengler 2014; Muscat, Kotrach, Wilkinson-Maitland & Schaeffer et al 2015).

To introduce a new point there was a striking difference in the latency of onset of the Tra contraction evoked by perturbation of the trunk in two separate experiments where the chest

### **Role of transversus abdominis muscle in spinal stability**

was free (Carpenter, Tokuno, Thorstensson & Cresswell 2008; Tokuno, Cresswell, Thorstensson & Carpenter 2013) compared to two experiments where the thorax was belted to a fixed object and one experiment when a plastic vest was strapped to the chest carrying 5 kg weights suspended from the front and from the back (Eriksson Crommert & Thorstensson 2008; Eriksson Crommert & Thorstensson 2009; Cresswell, Oddsson & Thorstensson 1994). In the experiments when the thorax was free the Tra latency was twice as long. It is most likely that compression of the thorax caused by the fixation or using the weighted vest influenced the latency. The difference in latency is unlikely to be postural, the latency of Tra response with rapid arm movement was considerably shorter than with the response to support surface translation in an upright posture (Tokuno, Cresswell, Thorstensson, Carpenter 2013). Secondly the experiment, where subjects wore weighted vests, was carried out in an upright posture, also had a short latency response. Through this observation it is quite possible that in other experiments where the thorax was bound the results could be interpreted differently, for example Cresswell, Grundstrom & Thorstensson 1992; Urquhart & Hodges 2005; McCook, Vicenzino, Hodges 2009.

A rise of IAP obviously could be beneficial but the rise is likely to be secondary to muscular activity (Cholewicki, Ivancic & Radebold 2002; Klein & Owerkowicz 2006; Marras & Mirka 1996) rather than the purpose of muscle contraction.

It could be concluded from discussion in this section that the Tra and the diaphragm do not contract for the purpose of raising the IAP to produce extensor moment, the rise of IAP is secondary to muscle contraction which in turn, as we saw, caused flexion of the spine. Apparent unexpected responses could be explained by utilizing the knowledge of the physiological responses of Tra and the diaphragm to a variety of afferent stimuli from limbs and the trunk.

Tra action is not direction dependent

The onset of action of a postural muscle would vary with the direction of movement of a limb depending on whether it is an agonist or an antagonist (Friedli, Hallett and Simon 1984).

However amongst many authors Hodges and Richardson (1997 Exp Brain Res); Hodges, Cresswell & Thorstensson (1999) suggested

that the Tra onset of action does not vary with direction of arm movement. Carpenter, Tokuno, Thorstensson & Cresswell (2008) described that the onset time of Tra action was independent of the direction of support surface translation. Eriksson Crommert & Thorstensson (2008) described similar pattern and magnitude of activation of the Tra in released extension and flexion trials. Eriksson Crommert & Thorstensson (2009) found that the timing and the magnitude of the post-perturbation response of Tra was independent of the direction of perturbation. Authors explain this in terms of special role of Tra in stiffening the spine by tension on thoracolumbar fascia or raised IAP. The observation of some authors do not support this finding (Allison, Morris & Lay 2008; Morris, Lay, Allison 2013). Cresswell, Oddsson & Thorstensson (1994) & Cresswell (1993) described significantly higher level of activation of Tra while creating flexion compared to creating extension of the trunk.

However even if it is assumed that the Tra response is invariant with the direction of perturbation, it could be easily explained, as discussed at length above, by the mechanism of the respiratory response of the Tra to perturbations.

Conclusion .

Experiments supporting the central role of Tra in spinal stabilization have been examined and linked with physiological respiratory responses of Tra to perturbations under the headings of earliest activation of Tra in response to rapid arm movements, its role in stiffening the spine and producing extensor moments, creating an intra-abdominal pressure column unloading the spine, and its invariant response with direction of perturbation. From the long discussion under each heading, that will not be repeated here, it can be concluded that it is unlikely that the Tra and the diaphragm contracts for the purpose of raising IAP for spinal stabilization.

It is apparent that Tra through multiple reflexive mechanisms responds as a respiratory muscle to limb movements and perturbations caused by the same to maintain respiration, assist in maintaining Pdi and to contain the abdominal viscera. The Tra and the diaphragm contract in a coordinated manner to maintain respiration and Pdi and any spinal stabilization function is likely to be secondary.



**Role of transversus abdominis muscle in spinal stability**

Table 1. Was the Tra the first muscle to contract every time?

Hodges, Creswell & Thorstensson 1999.	No, Es first in flexion RA first with extension, fig 2
Hodges & Richardson 1997.	No, Tra not first, extension & abduction, fig3
Allison, Morris, Lay 2008.	No, Tra not first, OI first fig 1 & 2.
Stafford, Ashton-Miller, Sapsford & Hodges 2012	No, Tra not first, sphincter first fig 3 & 5.
Hodges, Creswell & Thorstensson 2001.	No, Tra not first, ES first fig 4BC.
Mosley, Nicholas & Hodges 2004	Yes, Tra first.
Hodges & Richardson 1997	Yes, Tra first
Hodges, Gandevia & Richardson 1997.	No, fig 4 A end expiration
Hodges & Richardson 1997.	No, Tra not first, multifidus first fig 1
Hodges, Creswell & Thorstensson 1999	No, Tra not first, flexion & extension fig2.
Hodges & Richardson 1999	No, Tra not first fig1
Urquhart, Hodges & Story2005.	No, Tra not first fig2.
Hodges & Richardson 1996	No, Tra same as mf, flexion, fig 2
Hodges, Cresswell & Thorstensson 2001.	No, Tra not first, ES, OI first fig 4c.
Eriksson Crommert, Halvorsen & Ekblom 2015.	No, Tra not first, fig2.
Tokuno, Cresswell, Thorstensson & Carpenter 2013	No, Tra not first, fig 1.
Hodges, Richardson 1999	Yes, Tra first
Hodges, Creswell, Daggfeldt & Thorstensson 2000	No, Tra not first, fig 3B OE first abduction & extension.

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**Role of transversus abdominis muscle in spinal stability**

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