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Differential activity of regions of transversus abdominis during trunk rotation

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Abstract The role of the abdominal muscles in trunk rotation is not comprehensively understood. This study investigated the electromyographic (EMG) activity of anatomically distinct regions of the abdominal muscles during trunk rotation in six subjects with no history of spinal pain. Fine-wire electrodes were inserted into the right abdominal wall; upper region of transversus abdominis (TrA), middle region of TrA, obliquus internus abdominis (OI) and obliquus externus abdominis (OE), and lower region of TrA and OI. Surface electrodes were placed over right rectus abdominis (RA). Subjects performed trunk rotation to the left and right in sitting by rotating their pelvis relative to a fixed thorax. EMG activity was recorded in relaxed supine and sitting, and during an isometric hold at end range. TrA was consistently active during trunk rotation, with the recruitment patterns of the upper fascicles opposite to that of the middle and lower fascicles. During left rotation, there was greater activity of the lower and middle regions of contralateral TrA and the lower region of contralateral OI. The upper region of ipsilateral TrA and OE were predominately active during right rotation. In contrast, there was no difference in activity of RA and middle OI between directions (although middle OI was different between directions for all but one subject). This study indicates that TrA is active during trunk rotation, but this activity varies between muscle regions. These normative data will assist in understanding the role of TrA in lumbopelvic control and movement, and the effect of spinal pain on abdominal muscle recruitment.

Keywords Transversus abdominis · Trunk rotation · Regional recruitment · Abdominal muscles · Electromyography

Introduction

There is consistent evidence that the oblique abdominal muscles are major axial rotators of the trunk. Obliquus externus abdominis (OE) has been reported to be active with contralateral trunk rotation (rotation of the thorax relative to a fixed pelvis), and obliquus internus abdominis (OI) with ipsilateral trunk rotation [1, 6, 7, 15, 25, 32]. However, the role of transversus abdominis (TrA) in trunk rotation is controversial.

Cresswell and colleagues [7] reported both unilateral and bilateral recruitment of TrA during trunk rotation, with greater electromyographic (EMG) activity on the side to which the trunk was rotated. Juker et al. [24] also reported bilateral activity of TrA, but found no difference in activation between sides with movement in different directions. However, inspection of the latter study's average data suggests a trend for direction specific activation. In contrast, De Troyer and co-workers [10] observed minimal activity of TrA during trunk rotation and Misuri et al. [29] reported no significant changes in muscle thickness with ultrasound imaging. Furthermore, no difference in recruitment of TrA was evident with changes in the rotatory forces associated with rapid limb movement in different directions [19].

To further complicate the issue of the contribution of TrA to trunk rotation, anatomical studies have highlighted variation in the attachments and morphology of separate regions of the abdominal muscles [2, 43]. For instance, the upper fibres of TrA that arise from the rib cage have a horizontal orientation, while the middle and lower fibres that attach to the thoracolumbar fascia and the iliac crest respectively are inferomedial. In contrast, the orientation of OI fascicles ranged from superomedial in the upper and middle regions to inferomedial in the lower region [43]. Due to differences in the mechanical advantage of fascicles in each region, it is possible that differences in recruitment may exist.

In accordance with these reports, there is preliminary evidence from EMG studies to indicate differential activation of regions of TrA and OI. Greater tonic activity of lower TrA was reported with limb movement [18] and activity of the lower region of OI predominated with ipsilateral straight leg raise and pelvic tilting in standing [6]. A few studies have also investigated recruitment of compartments of the abdominal muscles during trunk rotation. Activity of the upper region of OI has been reported to be greater than that of the lower region [6] and activity of the lateral fibres of OI greater than the anterior fibres [8, 28]. However, in the former study there was only a small difference in activity between regions and no statistical analyses were performed, and in the latter study interpretation of results is difficult as EMG recordings were made with surface electrodes [8, 28]. The aims of the current investigation were to compare activity of the abdominal muscles, and to compare recruitment of regions of TrA and OI during isometric trunk rotation at the end of range. This is a fundamental step towards understanding the role of the abdominal muscles in trunk rotation (a risk factor for low back pain [23]), and the motor control changes associated with these muscles in people with spinal pain.

Materials and methods

Subjects

Six subjects (three male, three female) with a mean age, height, and weight of 30 years (SD, 4 years), 1.74 m (SD, 0.09 m), and 68 kg (SD, 15 kg) participated in the study. Subjects were excluded if they had a history of spinal or leg pain in the preceding 2 years that limited function or for which they sought medical or allied health intervention, a history of a neurological, respiratory or gastrointestinal disorder, previous abdominal surgery, an abdominal or inguinal hernia, observable spinal deformity or recent pregnancy. The activity level of the subjects was "average", as determined by a standard activity questionnaire [3]. All procedures were approved by the institutional ethics committee and conducted in accordance with the Declaration of Helsinki.

Electromyography (EMG)

EMG activity of the abdominal muscles was recorded with bipolar fine-wire electrodes fabricated from Teflon-coated stainless steel wire (75 μm) (A-M Systems, Everett, WA, USA). One millimetre of Teflon was removed from the ends of the wires and the ends were bent back 1 mm and 2 mm to form hooks. The wires were threaded into a hypodermic needle (0.70 mm×38 mm) and inserted into the right TrA, OI and OE under the guidance of ultrasound imaging (5 MHz curved array transducer) (128XP/4, Acuson, Mountain View, CA, USA) [7, 10, 16]. Fine-wire electrodes were inserted immediately adjacent to the eighth costal cartilage in the upper region of TrA, halfway between the iliac crest and lower border of the rib cage in the middle region of TrA, OI and OE, and adjacent to the anterior superior iliac spine (ASIS) in the lower region of TrA and OI (Fig. 1A). Although the use of selective intramuscular EMG electrodes results in sampling from a small population of motor units, this technique was critical to investigate differences between muscles and between regions of muscles with minimal cross-talk.

As rectus abdominis (RA) is distant from the other abdominal muscles near the midline, it was considered that cross-talk would be less problematic than for OE, OI and TrA, and surface recordings would be suitable. Pairs of surface EMG electrodes (Ag/AgCl discs, 1 cm diameter and 2 cm inter-electrode distance) were placed over RA, halfway between the umbilicus and the pubic symphysis. A ground electrode was positioned over the iliac crest. EMG data were bandpass filtered between 20 Hz and 1 kHz and sampled at 2 kHz using a Power1401 and Spike2 software (CED, Cambridge, UK). Analysis was performed using Matlab 6 (release 12; MathWorks, Natick, MA, USA).

Trunk rotation

Rotation of the trunk was recorded using a 3-Space Fastrak motion analysis system (Polhemus, Colchester, VT, USA). Two motion sensors were attached to the undersurface of a rotating chair. Data were sampled at 100 Hz and used to identify the end of rotation.

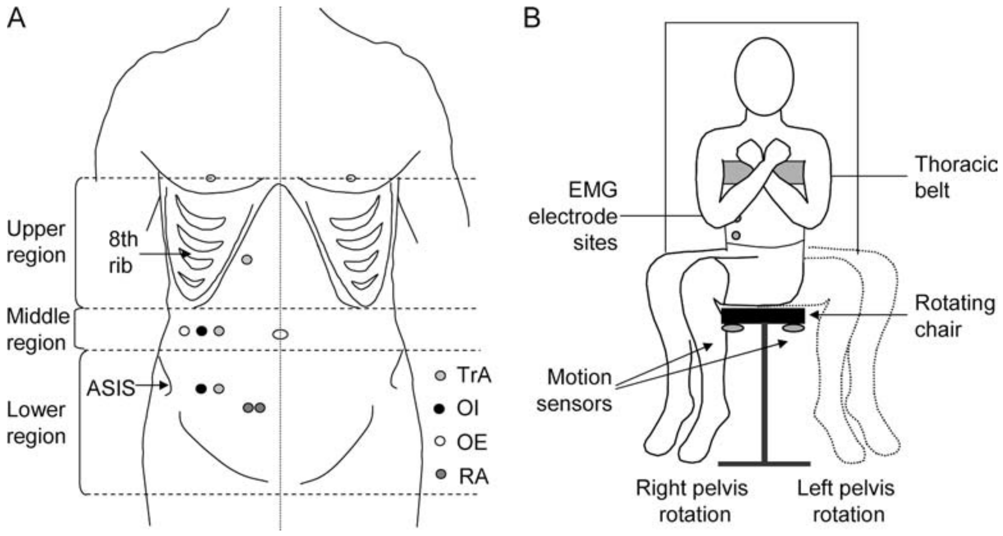

Fig. 1 **A** EMG electrode sites. *Horizontal lines* indicate the borders of defined regions of the abdominal wall and *shaded circles* represent the electrode insertion sites; **B** Experimental setup. Subjects sat on a rotating chair with electrodes in situ and their thorax fixed firmly to an immobile backrest with a belt

Procedure

Subjects sat on a rotating seat with their thorax fixed firmly to an immobile backrest to prevent trunk movements other than rotation occurring (Fig. 1B). Neutral position of the trunk and pelvis was ensured before each trial, as pre-rotation of the trunk has been reported to affect muscle recruitment [35]. With arms across their chest, subjects performed two repetitions of rotation of their pelvis and lower limbs in each direction. Rotation was performed with effort just sufficient to hold end range. EMG recordings were made during relaxed sitting (with back support) prior to movement and at the end of range of trunk rotation. To determine the EMG amplitude of each muscle/region in sitting relative to the signal with no or minimal activity, recordings were also made in supine (with arms beside the trunk, and hips and knees in neutral). In order to normalise the EMG data, maximum voluntary isometric contractions were performed in supine with hips and knees flexed to approximately 45° against manual resistance for 5 s. The normalisation tasks involved isometric trunk flexion (RA), and ipsilateral (OI) and contralateral rotation (OE), and a maximal Valsalva and forced expiratory manoeuvre (TrA). The peak activity for each muscle across these tasks was selected for normalisation.

Data processing

Root mean square (RMS) EMG amplitude was calculated for 2 s of steady state EMG in the neutral sitting and supine positions, and for 2 s from the time the subject reached the end range of movement. To investigate the activity of the abdominal muscles in quiet sitting prior to movement, the difference in RMS EMG amplitude between sitting and supine was determined and normalised to that recorded during maximal voluntary manoeuvres. To reduce inter-subject variability and to ensure there was maximum sensitivity to detect differences between directions of rotation, the activity in sitting was subtracted from that recorded at the end of range of trunk rotation, and the activity in each direction was expressed as a proportion of the peak activity recorded during rotation for that muscle in either direction. Thus, a value of "1" indicated the direction in which the muscle was most active. The calculation of absolute scores (normalised to maximum) allowed the amplitude of the data for each muscle region to be examined (Table 1), while ratio scores (normalised to peak activity recorded for either direction of rotation) enabled activity between movement directions to be

Table 1 Group median (minimum : maximum) change in RMS EMG amplitude from relaxed sitting to end range of rotation for each muscle and muscle region expressed as a percentage of RMS during maximal change. Negative values indicate a decrease in EMG activity from tonic activity in sitting. (*RMS* root mean square, *L* lower, *M* middle, *U* upper, *TrA* transversus abdominis, *OE* obliquus externus abdominis, *OI* obliquus internus abdominis, *RA* rectus abdominis)

Muscle/region	*Left rotation RMS EMG (%)	*Right rotation RMS EMG (%)
LTrA	24 (0:74)	0 (-2:2)
MTrA	17 (5:107)	1 (-23:7)
UTrA	1 (-46:9)	6 (1:194)
LOI	4 (1:8)	0 (-1:1)
MOI	14 (0:53)	3 (1:15)
OE	7 (-1:30)	9 (5:283)
RA	10 (-2:65)	2 (0:4)

*Left trunk rotation = rotation of the pelvis to the left (relative to a fixed thorax)

*Right trunk rotation = rotation of the pelvis to the right (relative to a fixed thorax) compared irrespective of the absolute amplitude of the EMG data.

Statistical analysis

To compare the EMG activity of the abdominal muscles and regions during quiet sitting (baseline), a one-way analysis of variance (ANOVA) was performed. A two-way repeated measures ANOVA was also undertaken using the ratio scores to compare the activity between movement directions and between muscle regions. Post hoc testing was performed using Duncan's multiple range test. The alpha level was set at 0.05.

Results

When subjects sat quietly in the experimental apparatus prior to rotation, activity of the abdominal muscles was greater than that recorded in supine for the majority of subjects. Data for individual subjects are shown in Fig. 2. Although there was no difference in the mean EMG amplitude between the muscle regions (due to the large inter-subject variability) ($p = 0.4$), several subjects had greater tonic activity of the lower region of TrA compared with the other regions of this muscle and the other abdominal muscles. The median (minimum / maximum) tonic activity of lower TrA was 13.7% (0.2% / 26.1%) of the activity recorded during the maximal voluntary effort, while activity of the middle and upper regions was 3.3% (0.5% / 29.3%) and 1.4% (0.02% / 27.5%) respectively.

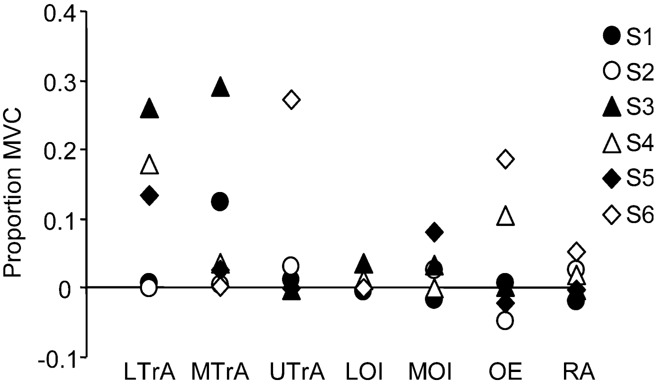

Fig. 2 Mean RMS EMG amplitude of abdominal muscles and regions of these muscles in sitting minus that recorded in supine and expressed as a proportion of that during a maximal voluntary contraction (*MVC*). Note there is recruitment of all the abdominal muscles and regions in the majority of subjects, but a trend for greater recruitment of lower TrA and minimal or reduced activity of OE (*RMS* root mean square, *L* lower, *M* middle, *U* upper, *TrA* transversus abdominis, *OE* obliquus externus abdominis, *OI* obliquus internus abdominis, *RA* rectus abdominis)

For analysis of abdominal muscle recruitment associated with trunk rotation, the resting level of tonic activity in sitting was subtracted from that recorded during the isometric hold at the end of trunk rotation range. Therefore, these data provide a sensitive measure of abdominal muscle activity that relates to rotation. The results of this analysis indicated that during trunk rotation, each abdominal muscle (with the exception of RA) was active to a greater degree in one direction of rotation (Figs. 3 and 4). OE was more active with right rotation of the trunk ($p < 0.01$), and the lower region of OI was more active in the opposite direction of rotation ($p < 0.004$). The middle fascicles of OI were not different between directions of rotation ($p = 0.1$), however greater activity was evident with rotation of the trunk to the left for all subjects except one. Although there were somewhat higher levels of activity of RA during left rotation, there was no difference in activity of RA between movement directions ($p = 0.4$), as greater activity was evident in half of the subjects for each direction.

All regions of TrA were active during rotation of the trunk (relative to a fixed thorax). However, there was greater activity of the upper region of TrA with right trunk rotation ($p < 0.02$), and greater activity of the lower and middle regions with left rotation (lower region (both directions): $p < 0.009$; middle region (both directions): $p < 0.003$). While activity of the upper region of TrA was different from the lower and middle regions (left rotation: $p < 0.02$; right rotation: $p < 0.01$), the lower and middle regions were similar in their activation in both movement directions (left rotation: $p = 1.0$; right rotation: $p = 0.6$). Although the activity of the lower region of OI was found to be direction specific and the middle region did not differ between movement directions, there were no differences in activity between these regions of OI with rotation to the left ($p = 0.6$) or right ($p = 0.2$).

Discussion

The results of this study provide evidence that TrA is active during trunk rotation. A novel finding was that compartments of TrA differed in their activity between movement directions, indicating that regions of TrA have differential recruitment patterns. Given the attachments, fibre orientation and recruitment patterns of TrA, it is hypothesised that this muscle may contribute to torque production and/or stabilisation of the rib cage (upper), lumbosacral region (middle and lower) and/or the anterior aponeuroses (all regions) during rotation. Greater activity of OI and OE in one direction of rotation, along with some degree of activity in the opposite direction, may indicate that these muscles serve several roles during rotatory tasks.

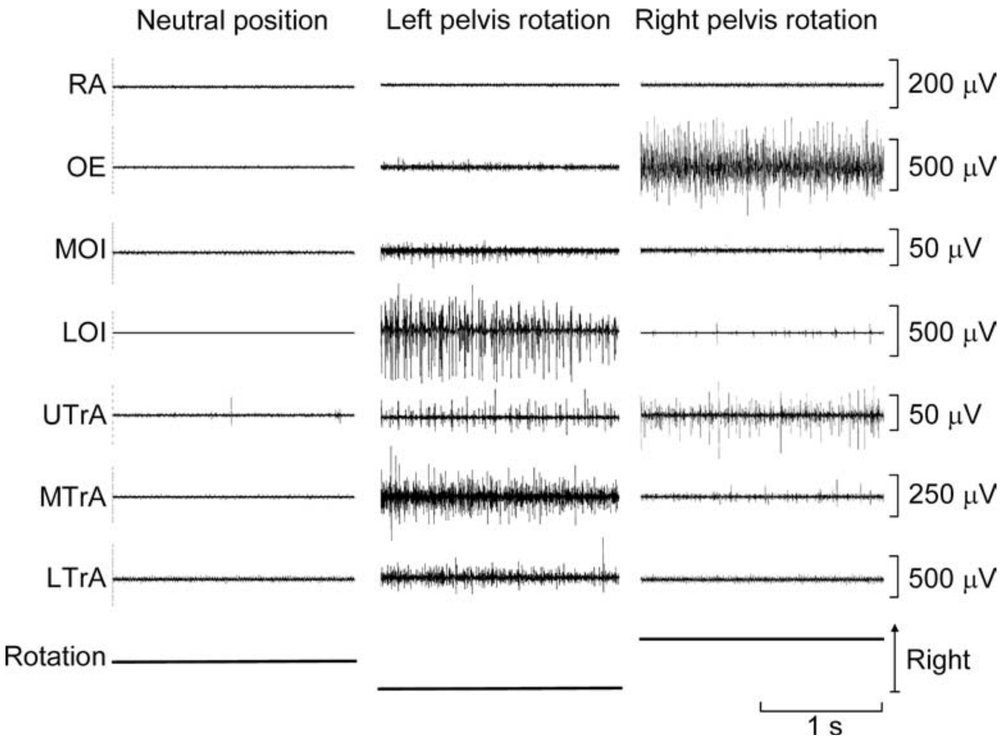

Fig. 3 Raw EMG data from a representative subject in neutral and at the end range of trunk rotation. Note greater activity of the upper region of TrA in the opposite direction to that of lower and middle regions. While the activity of ipsilateral upper TrA and OE predominates during right rotation, contralateral lower and middle TrA and lower OI are most active during left rotation, and recruitment of middle OI and RA does not vary between movement directions (*L* lower, *M* middle, *U* upper, *TrA* transversus abdominis, *OE* obliquus externus abdominis, *OI* obliquus internus abdominis, *RA* rectus abdominis)

Abdominal muscle recruitment in relaxed sitting

As predicted from the numerous studies of upright trunk postures [5, 9, 12, 24, 32, 42], tonic activity of the abdominal muscles was present at rest in sitting. Specifically, our data are consistent with reports by Snijders et al. [39] that indicate the oblique abdominals are active during quiet sitting, and are also in accordance with the results of Juker et al. [24] that TrA is recruited in this upright position. In the current study, tonic activity of the abdominal muscles was quantified as a change in activity from that recorded in supine. There were no identifiable motor unit action potentials in the EMG recordings in supine for the majority of cases, and thus our data indicate the true increase in activity from the relaxed state of the muscle. However, in some instances there may have been small amounts of activity in the supposedly relaxed muscle [13], indicating a change from baseline activity rather than an absolute level of recruitment. Negative values in Fig. 2 indicate that tonic activity at rest in supine was present for some muscles in specific subjects. Although there were no significant differences between muscles/regions (probably due to the high inter-subject variability), mean scores indicate a graduated increase in TrA activity from the upper to the lower regions of this muscle. This may reflect a greater need to support the lower abdominal contents in dependent parts of the abdomen in which hydrostatic pressure is elevated [9] and/or to control stability of the lumbar spine and pelvis [17, 38, 40].

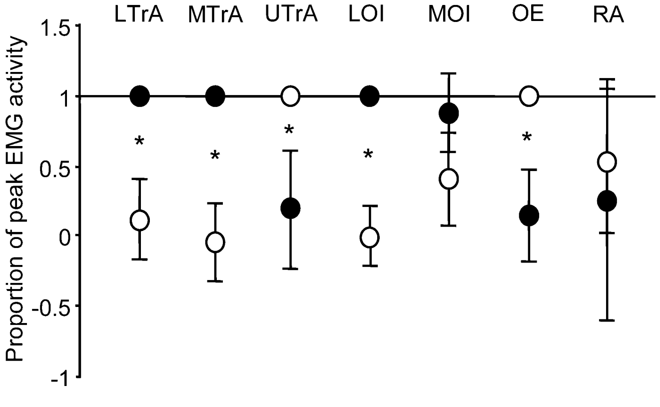

Fig. 4 Peak EMG activity for right (○) and left (●) trunk rotation is represented as a proportion of the greatest activity recorded during rotation in either direction. Note the greater activity of upper TrA and OE during right rotation, and lower and middle TrA and lower OI during left rotation. * $p < 0.05$ (*L* lower, *M* middle, *U* upper, *TrA* transversus abdominis, *OE* obliquus externus abdominis, *OI* obliquus internus abdominis, *RA* rectus abdominis)

Abdominal muscle recruitment during trunk rotation

As expected the oblique abdominal muscles were active with trunk rotation, with ipsilateral OE recruited with rotation to the right and the lower and middle regions of contralateral OI active with rotation to the left. These findings are consistent with previous EMG studies that have recorded the opposite activity of OI and OE during rotation of the trunk [6, 15, 27, 32], and biomechanical models that have calculated muscle forces associated with rotatory motion [22, 36]. It is important to note that these similarities were present even though subjects in the present study had their trunk fixed and rotated their pelvis (in order to control thoracic movement), which differs from the task performed in other studies.

The finding that OE and OI were direction specific in their recruitment is consistent with a role in torque production. However, it has been argued that EMG activity cannot be used to predict the axial torque produced during trunk movement [27, 34]. Previous investigations have also reported bilateral activity of the abdominal muscles during rotatory tasks [6, 24, 32, 34], and it has been hypothesised in biomechanical models that this activity provides stability to the lumbar spine [14]. Although in the current study some degree of bilateral activity of both OI and OE was observed with rotation in each direction, the activity of the lower fascicles was greater with left rotation and all but one subject showed greater activity of middle OI in one direction. These findings may differ from those of the earlier studies, as EMG recordings were previously made with surface electrodes, and activity from the adjacent muscles OE and TrA (which may differ from OI) is likely to have affected the results.

In agreement with previous studies, activity of RA did not vary with the direction of trunk rotation [15, 24, 32, 34]. This is consistent with its vertical fascicle orientation [30] and its primary role as a trunk flexor [6, 10]. However, as reported by Pope and colleagues [35] the EMG amplitude of RA was relatively large. This may be a result of complex coupling of trunk flexion with rotation [26, 31] or may indicate that RA contributes to tensioning of the anterior aponeuroses and the linea alba to provide a stable base from which the other abdominal muscles can generate force.

Rotatory function of TrA

This study indicates that TrA is active during trunk rotation. In agreement with Cresswell and colleagues [7], greater activity of the lower and middle regions of TrA was evident with rotation of the pelvis to the contralateral side. This similarity in results was present despite differences in the task, as Cresswell and colleagues [7] investigated rotation of the thorax relative to a fixed pelvis. Although Juker et. al. [24] reported no difference in activation between sides of TrA with each direction of trunk rotation, observation of the mean data indicate a trend towards direction specific activation, which may not have been detected due to high variability in the data and insufficient statistical power. If the change from tonic activity in sitting (also reported in their paper) was accounted for in the analysis, the sensitivity to detect a change in TrA activity with rotation may have increased. Other investigations have suggested TrA has no or a minimal role in trunk rotation [10, 29]. For instance, Misuri et al. [29] reported no overall changes in thickness of TrA with sonographic imaging and measurement. However, increases in thickness were evident in three of the six subjects during contralateral trunk rotation and in four during ipsilateral rotation. Although the relationship between changes in muscle thickness measured with ultrasound imaging and EMG activity is non-linear, an association between these two measures has been demonstrated [21]. Furthermore, although De Troyer et al. [10] qualitatively reported minimal activity of TrA during rotation, it is difficult to evaluate the absolute EMG activity recorded without comparison to standardised manoeuvres.

The contribution of TrA to trunk rotation has also been investigated during challenges to postural control [19]. Although unilateral flexion and extension of the arm produces rotatory trunk moments in opposing directions, the activity of TrA did not vary between movement directions [19]. These data are inconsistent with a rotatory function of TrA, however reactive moments evoked in multiple directions during the unilateral movements may have obscured rotatory activity. In addition, these tasks may not have imposed rotation moments of sufficient magnitude to evoke contraction of TrA. Recent data suggest that there may be a threshold magnitude of rotation required to produce rotatory activity of TrA. For instance, bilateral activity of TrA recorded during low load rotatory arm movements becomes asymmetrical as postural demand increases (Hodges, unpublished observations).

Regional recruitment

Regions of TrA differed in their activation with trunk rotation. The upper region was active in an opposing direction to that of the ipsilateral lower and middle regions. This is consistent with dissection studies that have documented distinct anatomical compartments of TrA that vary in their muscle attachments and fascicle orientation [2, 43]. Furthermore, intramuscular septa have been identified [11, 33, 45], particularly between the middle and upper regions [43], that may limit lateral transmission of forces and allow regions of TrA to act independently [43].

Differential activation of regions of other muscles, such as trapezius [37] and gluteus medius [41], has been reported. Four compartments of trapezius have been identified according to their varying attachments and morphology. Distinct differences in recruitment of these compartments have been observed, with the action of the upper fibres opposing that of the lower fibres [37].

The observations of this current study are consistent with compartments within a muscle displaying differential activity.

Role of TrA in rotation

Previous studies have argued that the contribution of TrA to trunk movement is minimal due to its horizontal fascicle orientation and poor mechanical advantage for torque generation [36]. However, variation in fascicle orientation of TrA has been documented, with the fascicles of the lower and middle regions being oriented inferomedially and those of the upper region horizontally [43]. Although these findings suggest that TrA may have a minor role in torque production, the horizontal upper fascicles of TrA were recruited during ipsilateral rotation, while the inferomedial lower and middle fascicles, with a greater mechanical advantage for this movement, were relatively silent.

There are several possibilities for the function of activity of different regions of TrA during rotation. For instance, the lower and middle fascicles may stabilise the anterior aponeuroses and linea alba against the superior, lateral pull of contralateral OE, and the upper fascicles may oppose the inferolateral pull of contralateral lower and middle OI. This would provide a stable platform from which OE and OI can generate rotatory forces. Alternatively, due to the limited mechanical advantage of TrA it may be hypothesised that during rotation TrA controls motion of the rib cage, lumbar spine and/or sacroiliac joints via tensioning of its musculofascial attachments [4, 44] and/or generation of intra-abdominal pressure [20]. However, further investigation of these hypotheses is required.

Conclusion

This study indicates that TrA is recruited during rotation of the trunk, with activity of the upper region opposing that of the lower and middle regions. The results have implications for biomechanical modelling of the lumbar spine and pelvis, indicating the importance of using multi-vector methods to represent regions of the abdominal muscles, and for future studies that investigate the effect of spinal pain on abdominal muscle recruitment during trunk rotation.

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