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Manual Therapy 10 (2005) 144–153
MANUAL THERAPY
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Original article

Abdominal muscle recruitment during a range of voluntary exercises

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Received 5 March 2003; received in revised form 11 August 2004; accepted 27 August 2004

Abstract

Various exercises are used to retrain the abdominal muscles in the management of low back pain and other musculoskeletal disorders. However, few studies have directly investigated the activity of all the abdominal muscles or the recruitment of regions of the abdominal muscles during these manoeuvres. This study examined the activity of different regions of transversus abdominis (TrA), obliquus internus (OI) and externus abdominis (OE), and rectus abdominis (RA), and movement of the lumbar spine, pelvis and abdomen during inward movement of the lower abdominal wall, abdominal bracing, pelvic tilting, and inward movement of the lower and upper abdominal wall. Inward movement of the lower abdominal wall in supine produced greater activity of TrA compared to OI, OE and RA. During posterior pelvic tilting, middle OI was most active and with abdominal bracing, OE was predominately recruited. Regions of TrA were recruited differentially and an inverse relationship between lumbopelvic motion and TrA electromyography (EMG) was found. This study indicates that inward movement of the lower abdominal wall in supine produces the most independent activity of TrA relative to the other abdominal muscles, recruitment varies between regions of TrA, and observation of abdominal and lumbopelvic motion may assist in evaluation of exercise performance.

Keywords: Exercises; Abdominal muscles; Transversus abdominis; Low back pain

1. Introduction

A diverse range of exercises is used clinically to retrain the trunk muscles. However, recruitment of the abdominal muscles during exercises that aim to restore motor control have not been clearly defined. Most studies have used surface electromyography (EMG) to investigate these techniques (Partridge and Walters, 1960; Kennedy, 1980; Richardson et al., 1990; Jull et al., 1995; Allison et al., 1998; O'Sullivan et al., 1998; Vezina and Hubley-Kozey, 2000) and the results of the small number of intramuscular EMG studies are inconclusive (Carman et al., 1972; Strohl et al., 1981; Goldman et al., 1987; De Troyer et al., 1990). For example, three different recruitment patterns were reported when six subjects were instructed to "pull in" their abdominal wall (De Troyer et al., 1990).

A contemporary approach for low back pain (LBP) involves recruitment of transversus abdominis (TrA) with minimal activity of the superficial abdominal muscles in the early stages of rehabilitation. This approach is based on evidence that activity of TrA contributes to spinal control (Cresswell et al., 1992; Hodges et al., 1999) and dysfunction of this muscle occurs in people with LBP (Hodges and Richardson, 1996b, 1998; Hodges, 2001). Although recruitment of TrA is emphasized initially, all of the trunk muscles are considered to be important for the restoration of normal function and progression involves strategies for

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1356-689X/$ - see front matter
doi:10.1016/j.math.2004.08.011

re-education of the whole muscle system (Richardson et al., 1999). The efficacy of this method has been established in randomized control trials with acute and chronic LBP patients (Hides et al., 1996; O'Sullivan et al., 1997b,c). The technique involves inward movement of the lower abdominal wall without movement of the spine or pelvis (Richardson et al., 1999). Surface EMG studies indicate that activity of the superficial abdominal muscles is minimal during this manoeuvre (Jull et al., 1995), and indirect measurements of TrA activity with a pressure cuff under the abdomen to indicate movement of the abdominal wall, are related to direct EMG measures of TrA motor control (Hodges et al., 1996a). However, no study has directly investigated TrA activity during this, or other exercise approaches.

Other exercise strategies have also been argued to be beneficial in LBP management. Abdominal bracing (lateral flaring of the abdominal wall) (Kennedy, 1980) and posterior pelvic tilting have been proposed to improve lumbopelvic control by elevation of intra-abdominal pressure and by reduction of the lumbar lordosis, respectively (Kennedy, 1980; Vezina and Hubley-Kozey, 2000). However, there is controversy regarding the specific patterns of abdominal muscle recruitment during these exercises. A recent review concluded that muscle activation patterns during pelvic tilting are not clearly defined in people with or without LBP (Vezina et al., 1998).

An additional consideration is that there are differences in the morphology and recruitment of regions of TrA and obliquus internus abdominis (OI) (Askar, 1977; Rizk, 1980; Hodges et al., 1999; Urquhart et al., 2001, 2004). Upper fascicles of TrA that attach to the rib cage are horizontal, and middle and lower fascicles that fuse with the thoracolumbar fascia and the iliac crest are inferomedial (Urquhart et al., 2001). Fibres of upper TrA are also active with the opposite direction of trunk rotation to lower and middle fibres (Urquhart et al., 2004), and activity of lower and upper fibres of OI vary during posterior pelvic tilting (Carman et al., 1972). Although these reports suggest regional differences in activity of the abdominal muscles, their recruitment has not been comprehensively investigated during voluntary exercises. The aims of this study were to investigate recruitment of regions of the abdominal muscles during exercises used in LBP management, and to determine if common clinical techniques, such as observation of abdominal, spinal and pelvic motion, assist differentiation of patterns of abdominal muscle recruitment.

2. Methods

2.1. Subjects

Seven subjects (4 male, 3 female), with a mean (SD) age, height, and weight of 30(4) years, 174(9) cm, and 68(15) kg, participated in the study. Subjects were excluded if they had a history of low back or leg pain that affected function in the preceding 2 years, or any abdominal, gastrointestinal, neurological or respiratory condition. All subjects had an 'average' activity level, as determined by the habitual physical activity questionnaire (Baecke et al., 1982). Five subjects had performed the exercises previously and all subjects were involved in another study (Urquhart et al., 2004). All procedures were approved by the institutional research ethics committee and conducted in accordance with the declaration of Helsinki.

2.2. Electromyography

Recordings of EMG were made using bipolar fine-wire electrodes inserted into three regions of the abdominal wall under the guidance of real-time ultrasound imaging (5 MHz curved array transducer) (128XP/4, Acuson, Mountain View, CA). Electrodes were fabricated from two strands of Teflon-coated stainless steel wire (75 μm) (A-M Systems Inc., Everett, Washington, USA), with 1 mm of Teflon removed from the ends. The electrodes were threaded into a hypodermic needle (0.70 × 38 mm) and the tips bent back 1–2 mm to form hooks. Electrodes were inserted into the upper region of TrA (adjacent to the 8th rib), the middle region of TrA, OI and obliquus externus abdominis (OE) (midway between the iliac crest and inferior border of the rib cage), and the lower region of TrA and OI (adjacent to the anterior superior iliac spine (ASIS)) (De Troyer et al., 1990; Cresswell et al., 1992; Hodges and Richardson, 1997; Urquhart et al., 2004). Pairs of surface EMG electrodes (Ag/AgCl discs, 1 cm diameter and 2 cm inter-electrode distance) were placed over rectus abdominis (RA), halfway between the umbilicus and the pubic symphysis. A ground electrode was placed on the iliac crest. EMG data were bandpass filtered between 50 Hz and 1 kHz and sampled at 2 kHz using a Power1401 data acquisition system and Spike2 software (Cambridge Electronic Design, Cambridge, UK). The data was exported and analysed using Matlab 6 (release 12; MathWorks, Natick, MA, USA).

2.3. Video motion analysis

A video motion analysis system was used to quantify displacement of the upper, middle and lower regions of the abdominal wall and movement of the lumbar spine and pelvis in prone. Data were captured with a digital video camera (Sony DCR TRV20, Tokyo, Japan), positioned 2 m away and perpendicular to the subject. A diffuse light source, placed under the subject's abdomen, and a black background were used to highlight the edge of the abdominal wall in the video image (Fig. 1). A marker was placed on the spinous process of the L3 vertebrae and the left ASIS to allow measurement of linear displacement of the lumbar spine and pelvis. The border of the upper and middle abdominal regions (lower border of the rib cage), and the middle and lower abdominal regions (upper border of the iliac crest) were also identified. Video data were transferred to computer and edited using iMovie editing software (Apple Computer, Inc., Cupertino, CA). An edge detection program was written using Igor Pro (WaveMetrics Inc., Lake Oswego, USA) to measure displacement of the abdominal wall, and spine and pelvic motion was measured with NIH Image (National Institute of Health, Bethesda, MD, USA). Distances were calibrated to an object of known dimensions filmed in the same plane as the abdominal wall. Resolution was 0.5 mm. The motion parameters were found to be accurate and repeatable over a 24-h interval (ICC[2,1] = 0.99) (Urquhart, 2002).

2.4. Procedure

Subjects were positioned in prone with raised supports placed underneath the xiphisternum and pubic symphysis (Fig. 1). This allowed the edge of the anterior abdominal wall to be visible. The spine was positioned in neutral and the hips were flexed to 45°. In separate trials, subjects were positioned in supine with similar lumbar spine, hip and knee positions.

Subjects were trained by physiotherapists, experienced in exercise prescription for the abdominal muscles, to perform four manoeuvres using standard instructions (Table 1); inward movement of the lower abdominal wall (Richardson et al., 1999), abdominal bracing (flaring of the lateral and anterior abdominal wall) (Kennedy, 1965, 1980), posterior pelvic tilting (posterior rotation of the pelvis), and combined inward movement of the lower and upper abdominal wall. Contemporary exercise interventions focus on low level contractions (Richardson et al., 1999), which is consistent with evidence that suggests low effort is sufficient to provide muscle stiffness required for joint control (Hoffer and Andreassen, 1981; Cholewicki and McGill, 1996). Thus, each task was performed with "mild" effort, which is equivalent to a rating of 2 on the Borg scale (Borg, 1982). Subjects were trained with instruction and verbal and tactile feedback until they were able to perform the manoeuvres correctly. Three repetitions were performed and the order of tasks was randomized. A trigger was activated by the subject to signal when they were relaxed (baseline) and had performed the task.

Maximum voluntary isometric trunk flexion, ipsilateral and contralateral trunk rotation, and a maximal valsalva and forced expiratory manoeuvre were performed in supine for normalization of RA, OI, OE and TrA EMG, respectively (Hodges et al., 1999). The peak activity of each muscle across these tasks was selected for normalization. A submaximal isometric manoeuvre was performed as an alternative task for EMG normalization and involved elevation of both legs so that the heels were 5 cm from the supporting surface.

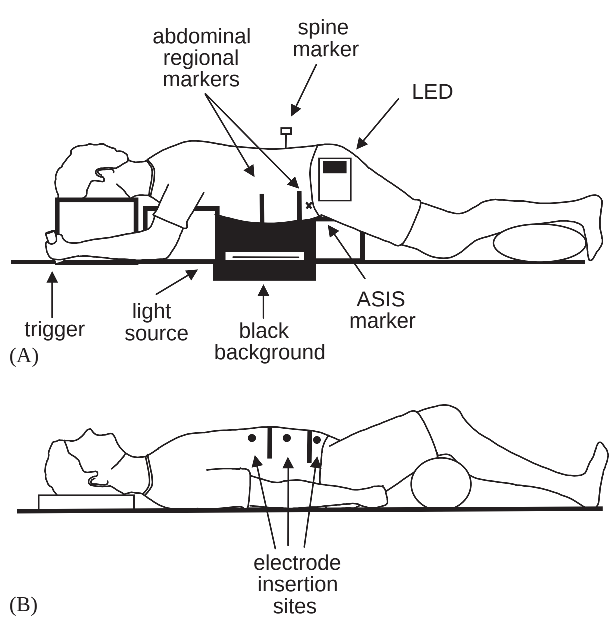


Fig. 1. Experimental set-up. Subjects were positioned in prone with supports underneath the xiphisternum and pubic symphysis (A), and in supine with their hips flexed to 45° (B). A marker was placed on the spinous process of the L3 vertebrae and the left ASIS, and borders of the abdominal regions were marked. A black background was used and a light source was placed inferior to the abdominal wall.

2.5. Data processing

The root mean square (RMS) EMG amplitude was calculated for 2 s at baseline and for 2 s during the manoeuvre (at the time indicated by the trigger). The mean displacement of the upper, middle and lower regions of the abdominal wall, and the motion of the spine and pelvis in the vertical and horizontal planes was also determined for these periods.

EMG activity recorded during the maximal and submaximal tasks was used to normalize the RMS EMG amplitude. Although reduced variance has been reported with normalization of surface EMG recordings to a submaximal task (Allison et al., 1998), maximal efforts have been considered to provide more meaningful values for interpretation (Andersson et al., 1998; Burden and Bartlett, 1999).

2.6. Statistical analysis

A two-way repeated-measures ANOVA was used to compare activity between exercise tasks and between muscles/regions. Duncan's multiple-range test was used for post-hoc analysis. To examine the association between EMG activity of the abdominal muscles and

Table 1
Standardized instructions used for the voluntary exercises

Exercise	Instructions[a]
Inward movement of the lower abdominal wall	Breathe in and out. Gently and slowly draw in your lower abdomen below your navel without moving your upper stomach, back or pelvis.
Inward movement of the lower and upper abdominal wall	Breathe in and out. Gently and slowly draw in your lower and upper abdomen without moving your back or pelvis.
Abdominal bracing	Breathe in and out. Gently and slowly swell out your waist without drawing your abdomen inwards or moving your back or pelvis.
Posterior pelvic tilting	Breathe in and out. Gently and slowly rock your pelvis backwards.

[a]Subjects were also instructed to perform each exercise with 'mild' effort (a rating of 2 on the Borg scale).

Table 2
Standard deviation data for the RMS EMG amplitude of the abdominal muscles normalized to maximal (Mx) and submaximal (SMx) isometric voluntary contractions and results of the F_{max} test (F) for comparison of the variance between these normalization techniques

Muscle/region	Abdominal exercise														
	Lower (supine)			Pelvic tilting			Bracing			Lower (prone)			Lower/upper		
	Mx	SMx	F	Mx	SMx	F	Mx	SMx	F	Mx	SMx	F	Mx	SMx	F
LTrA	0.05	3.21	S	0.02	1.00	S	0.03	1.25	S	0.04	0.78	S	0.03	3.00	S
MTrA	0.05	0.67	S	0.02	3.67	S	0.01	1.59	S	0.02	3.68	S	0.01	1.78	S
UTrA	0.02	0.37	S	0.003	0.02	S	0.01	0.29	S	0.001	0.01	S	0.03	0.19	S
LOI	0.03	2.13	S	0.005	0.11	S	0.01	0.21	S	0.004	0.20	S	0.02	0.43	S
MOI	0.03	0.09	NS	0.02	0.11	S	0.02	0.21	S	0.06	0.45	S	0.05	0.47	S
OE	0.005	0.05	S	0.03	0.15	S	0.03	0.04	NS	0.06	0.26	S	0.07	0.07	NS
RA	0.02	0.02	NS	0.02	0.06	NS	0.02	0.05	NS	0.01	0.02	NS	0.04	0.10	NS

L—lower; M—middle; U—upper; Lower (supine)—inward movement of the lower abdominal wall in supine; pelvic tilting—posterior tilting of the pelvis; bracing—abdominal bracing; lower (prone)—inward movement of the lower abdominal in prone; lower/upper—inward movement of the lower and upper abdominal wall; NS—non-significant; S—significant ($P<0.05$).

abdominal, spinal and pelvic motion, Pearson product-moment correlations were calculated. The F_{max} statistic was used to investigate differences in variance between the mean RMS EMG for each muscle normalized to a maximal and submaximal task (Winer et al., 1991). Statistical significance was set at 0.05.

3. Results

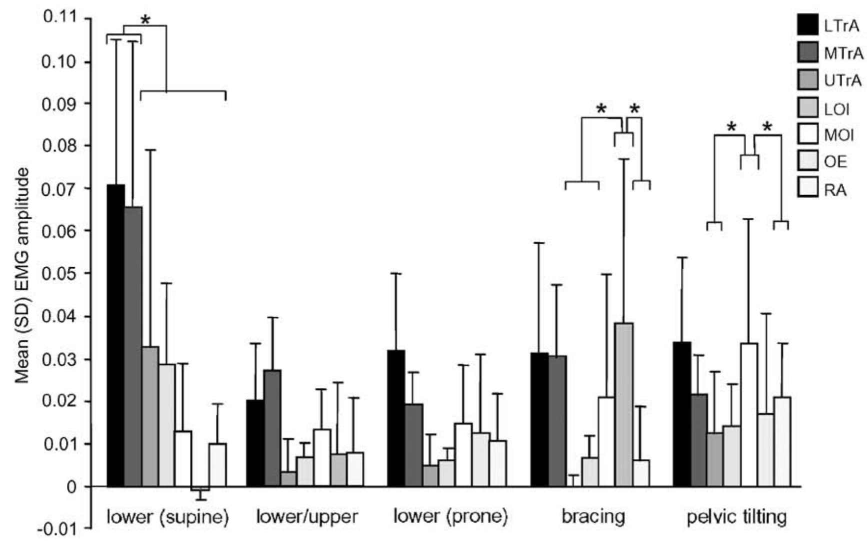
3.1. EMG normalization

Prior to analysis of the abdominal tasks, the maximal and submaximal EMG normalization methods were compared. There was greater variability in the mean RMS EMG amplitude with normalization to the submaximal procedure for all muscles except RA (Table 2). The standard deviations for the RMS EMG of lower and middle TrA were up to 180 times greater compared to the maximal normalization. Therefore, the intramuscular EMG data was normalized to EMG activity recorded during the maximal manoeuvre.

3.2. Comparison of abdominal muscle recruitment for each exercise

There were differences in recruitment between the abdominal muscles during inward movement of the lower abdominal wall in supine, abdominal bracing and pelvic tilting ($P<0.001$) (Fig. 2A). In contrast, no difference between the abdominal muscles was observed with inward movement of the lower abdominal wall in prone ($P>0.05$) and combined inward movement of the lower and upper abdominal wall ($P>0.009$).

During inward movement of the lower abdominal wall in supine, TrA EMG was 70%, 100% and 65% greater than that of OI, OE and RA, respectively ($P<0.01$). Minimal activity of OI, OE and RA (1.3%, 0.9%, −1.8%) was also observed for one subject. There were regional differences in TrA recruitment. Mean RMS EMG amplitude of the upper region was approximately half that of the lower and middle regions ($P<0.001$). In contrast, OI EMG was less than lower and middle TrA ($P<0.02$), but similar to RA and OE ($P>0.07$). In addition, no difference in OI EMG was



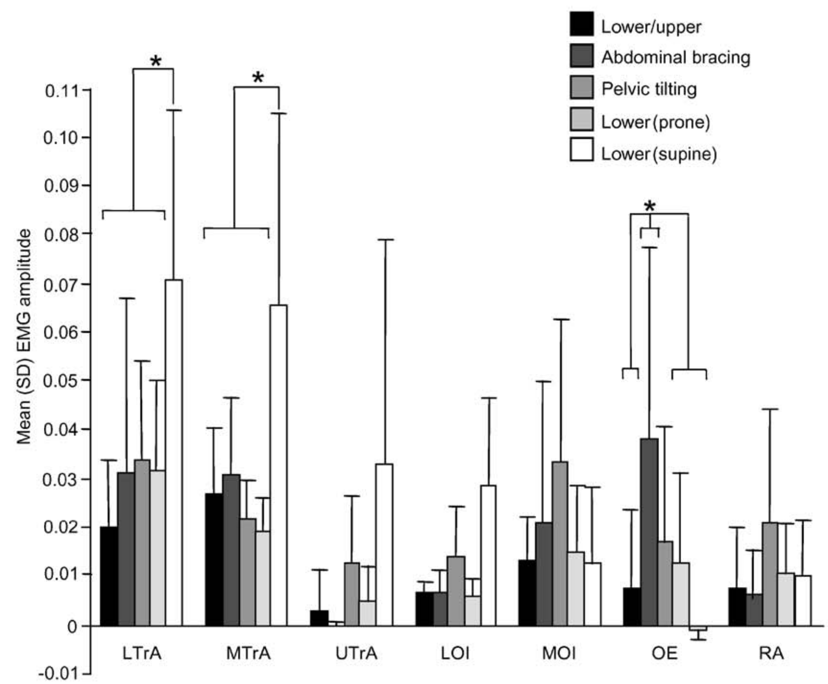


Fig. 2. RMS EMG amplitude of abdominal muscles/regions during different exercise conditions (normalized to a maximal voluntary contraction). Mean (SD) RMS EMG of lower and middle TrA and OI, and upper TrA, OE and RA during inward movement of the lower abdominal wall (supine (lower supine) and prone (lower prone)), bracing, posterior tilting of the pelvis (pelvic tilting) and combined inward movement of the lower and upper abdominal wall (lower/upper). Note the greater and more independent activity of TrA in supine compared to prone. Similarities in activation of the lower and middle regions of TrA, contrast with differences in activation of the upper region of the muscle. The standard deviations are large indicating variability in abdominal muscle recruitment between subjects. * $P<0.05$.

identified between regions of the muscle ($P = 0.3$). Mean OE RMS EMG was negative, indicating reduction in activity from baseline.

With abdominal bracing, OE EMG was greater than that of upper TrA, lower OI, and RA ($P<0.05$). There was minimal activity of upper TrA, and although there was a trend for differences in the EMG activity of regions of TrA, this was not significant (lower TrA: $P = 0.07$; middle TrA: $P = 0.051$). There was also similar activity of the lower and middle OI during abdominal bracing ($P = 0.09$).

When subjects tilted their pelvis posteriorly, middle OI had greater activity compared to RA ($P = 0.03$) and upper TrA ($P = 0.01$). In contrast, there was no difference between the abdominal muscles during inward movement of the lower abdominal wall ($P>0.05$), and the lower and upper abdominal wall in prone ($P>0.09$). However, there was a trend towards greater TrA activity compared to the other abdominal muscles.

3.3. Comparison of abdominal muscle recruitment between exercises

Recruitment of lower and middle TrA, and OE differed between the exercise conditions ($P<0.001$) (Fig. 2B). Lower and middle TrA EMG was greater during inward movement of the lower abdominal wall in supine than other tasks ($P<0.05$). In contrast, OE EMG was greater during abdominal bracing than the other techniques (except pelvic tilting) ($P<0.05$). Activity of lower and middle OI, RA and upper TrA was similar between exercises and between the supine and prone positions.

3.4. Movement of the abdominal wall, spine and pelvis

Abdominal wall displacement differed between tasks ($P<0.001$), but not between the upper, middle and lower abdominal regions ($P=0.1$) (Fig. 3). Greater abdominal motion occurred during pelvic tilting compared to the other abdominal manoeuvres ($P<0.001$), and abdominal displacement with inward movement of the upper and lower abdominal wall was greater than abdominal bracing and inward movement of the lower abdominal wall in prone ($P<0.002$; $P<0.001$). The later two exercises did not differ in abdominal motion ($P=0.5$).

Lumbar spine and pelvic motion was minimal and did not differ between tasks, with the exception of posterior pelvic tilting, in which greater spine and pelvic motion occurred ($P<0.001$) (Fig. 4). There was a high correlation between movement of the lumbar spine and pelvis ($r=0.9$), and a significant negative correlation between lumbopelvic motion and TrA EMG (as a proportion of total activity) was found ($r=-0.6$) (Fig. 5). Although there was no significant correlation between displacement of the lumbopelvic region and OI and RA EMG, there was a positive correlation between OE EMG and lumbopelvic motion. In addition, there was a low to moderate correlation between movement of the abdominal wall and TrA EMG ($r=0.4$, $P<0.05$) (Fig. 5).

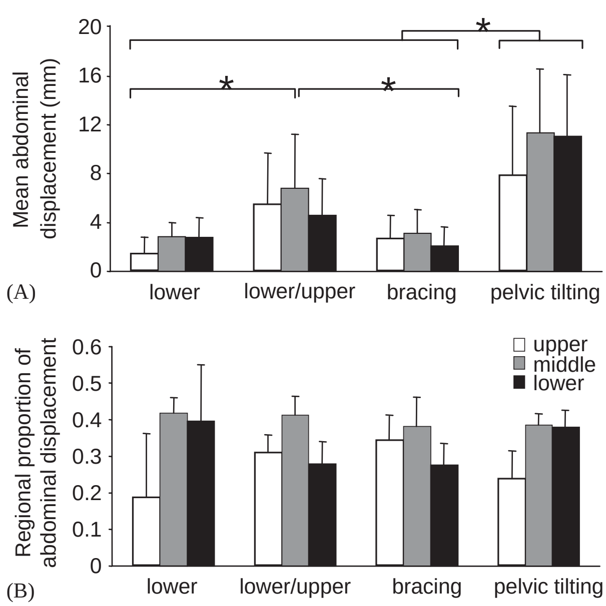


Fig. 3. Displacement of regions of the abdominal wall. Abdominal displacement expressed as the mean (SD) of absolute movement (A) and the mean expressed as a proportion of the total abdominal movement (B) during inward movement of the lower abdominal wall in prone (lower), pelvic tilting, abdominal bracing, and combined inward movement of the lower and upper abdominal wall (lower/upper). Note the differences in abdominal displacement between the exercise conditions. $*P<0.05$.

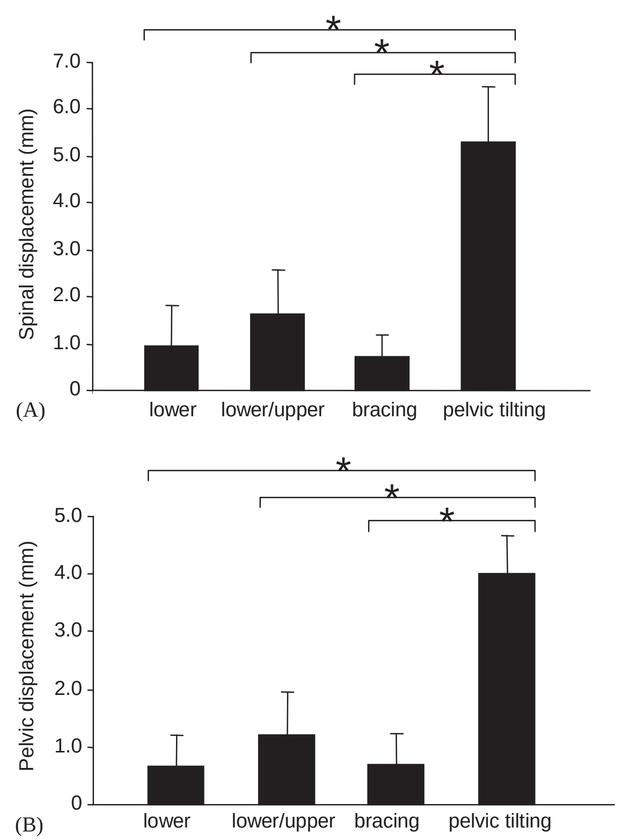


Fig. 4. Mean (SD) displacement of the lumbar spine and pelvis. Movement of the lumbar spine (A) and pelvis (B) during inward movement of the lower abdominal wall in prone (lower), pelvic tilting, abdominal bracing, and combined inward movement of the lower and upper abdominal wall (lower/upper). Note greater movement of the pelvis and spine during posterior pelvic tilting. $*$ $P<0.05$.

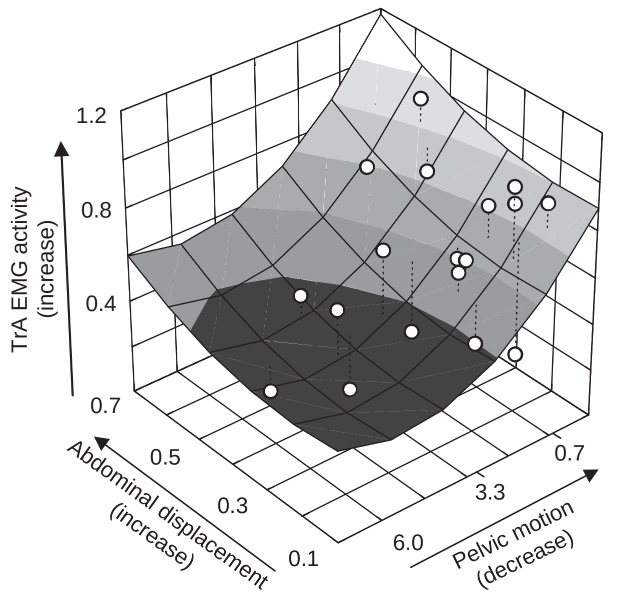


Fig. 5. Association between EMG activity, abdominal displacement and lumbopelvic motion. A three-dimensional graph depicting the relationship between EMG activity of all regions of TrA (as a proportion of the total abdominal muscle activity) (y axis), maximal abdominal displacement (x axis), and pelvic motion (z axis). EMG activity of TrA, relative to the other abdominal muscles, was greater when abdominal movement was performed without pelvic motion.

4. Discussion

This study presents several important findings. First, there were distinct patterns of abdominal muscle recruitment between exercise tasks. Notably, the greatest and most independent activity of TrA was recorded with inward movement of the lower abdominal wall in supine. Second, abdominal muscle activity was dependent on body position, with differential activity of TrA evident in supine, but not in prone. Third, there were regional differences in the recruitment of TrA, with greater activity of the lower and middle regions of TrA compared to the upper region. Finally, activity of TrA was greater relative to the other abdominal muscles when lumbopelvic motion was limited. These results have important implications for selection of exercise techniques, positions and strategies for assessment and retraining of abdominal muscle function.

4.1. Methodological issues

Two methodological issues require consideration. Firstly, due to the invasive nature of the study only seven subjects were recruited. Although this number is relatively consistent with previous intramuscular EMG investigations, it is important to consider that this may limit the statistical power of the study. Second, data in this study were normalized to maximal voluntary contractions. Variability in the present study was less when data were normalized to maximal manoeuvres rather than submaximal tasks. Although this contrasts with a previous study (Allison et al., 1998), the differences may be explained by the use of surface EMG in that investigation.

4.2. Inward movement of the lower abdominal wall in supine

The results suggest that recruitment of TrA with minimal activity of other abdominal muscles may be best achieved during inward movement of the lower abdominal wall. These findings agree with reports that TrA is most consistently active during a ''belly in'' manoeuvre (Strohl et al., 1981; Goldman et al., 1987; De Troyer et al., 1990), and that minimal superficial abdominal muscle activity occurs during this task (Jull et al., 1995; Richardson et al., 1995). The results are also consistent with an exercise approach for the management of LBP, which involves retraining the activity of TrA to be independent of the other abdominal muscles (Richardson et al., 1999).

Three randomised control trials of different subgroups have reported improvements in pain and function with exercise interventions that involve inward movement of the lower abdomen (Hides et al., 1996; O'Sullivan et al., 1997b,c). These outcomes have been hypothesized to result from improved motor control of TrA (and multifidus). Each of these studies involved training in a variety of positions, including supine (O'Sullivan et al., 1997b,c) and standing (Hides et al., 1996) in the early stages of rehabilitation, and during functional activities as exercise retraining was progressed (Hides et al., 1996; O'Sullivan et al., 1997b,c). Although it is unlikely that the improvements were solely due to changes in TrA function, this is the common feature of the interventions. As the results of the present study suggest that the ability to activate TrA may vary between positions and it cannot be confirmed that the same manoeuvre examined in the current study was implemented, further research is required to determine whether TrA activity can be changed with this intervention.

Activation of TrA with minimal superficial abdominal muscle activity has been argued to be an important feature of inward movement of the lower abdominal wall. In this study mean EMG activity of these muscles was considerably less than that of TrA. In addition, minimal activity of OI, OE and RA in one subject suggests that it may be possible to activate TrA almost independently from the other abdominal muscles, at least with training during this task.

There was no difference between OI, OE and RA during inward movement of the lower abdominal wall in supine. However, the slightly greater activity of OI may have reached significance with a greater number of subjects. Dowd (1992) reported similar findings using intramuscular EMG but did not record from TrA. In contrast, surface EMG studies have reported greater activity of OI and/or OE relative to RA (O'Sullivan et al., 1997a; Vezina and Hubley-Kozey, 2000). These differences may be explained by cross-talk from deeper and adjacent muscles, possibly resulting in overestimation of the superficial muscle activity.

There were regional differences in TrA recruitment during inward movement of the lower abdominal wall in supine. This is a novel finding. Although activity of upper and lower/middle TrA varies during trunk rotation (Urquhart et al., 2004) and repetitive limb movements (Hodges et al., 1999), no studies have identified regional differences during voluntary manoeuvres.

4.3. Inward movement of the lower abdominal wall in prone

Unlike supine, there was no differentiation in abdominal muscle activity with inward movement of the lower abdominal wall in prone. This is consistent with previous studies that report differences in abdominal muscle activity between positions (Carman et al., 1972; Richardson et al., 1992). This may be due to the greater gravitational demand in prone, or reflex-mediated activity of the superficial muscles in response to stretch. In addition, an individual's internal body representation has been shown to vary with the relative position of body segments, which may influence movement performance (Gurfinkel, 1994). The absence of differentiation of abdominal muscle activity in prone is not consistent with the use of this position for evaluation of TrA activity in clinical practice (Richardson et al., 1999). Although this technique is widely referenced and the position used in this study differs in several characteristics to the clinical test (e.g. abdominal support), assessment in supine may be more optimal for future clinical and laboratory work.

4.4. Abdominal bracing

Identification of greater OE activity than the other abdominal muscles with abdominal bracing differs from previous reports which indicate greater RA activity compared to the anterolateral abdominals (Richardson et al., 1995), and no difference between muscles (Allison et al., 1998). However, the results suggest that bracing would not be appropriate if the aim of the exercise is to preferentially activate TrA or OI.

4.5. Posterior pelvic tilt

Similar to our data, Partridge and Walters (1960) reported greater activity of OI than RA and OE with posterior pelvic tilt. However, other studies have found greater RA activity compared to the anterolateral abdominals (Richardson et al., 1995), and greater activity of OE than RA (Vezina and Hubley-Kozey, 2000). In addition, similar activity of OI and RA has been observed during this manoeuvre (Flint and Gudgell, 1965; Carman et al., 1972). Although these varying results may have been due to differences in the task, electrode placement or EMG normalization technique, they also provide evidence that body position may contribute to differences in abdominal muscle recruitment.

4.6. Comparison of abdominal muscle recruitment between exercises

In contrast to OI and RA, activity of TrA and OE differed between the tasks, with greater activity during inward movement of the abdominal wall and pelvic tilting, respectively. This is consistent with previous reports of greater OE EMG activity during posterior tilting of the pelvis compared to 'abdominal hollowing' (drawing your navel up and in towards your spine) (Vezina and Hubley-Kozey, 2000). However, activity of RA (Vezina and Hubley-Kozey, 2000) and the 'oblique abdominals' (Richardson et al., 1992) has also been reported to vary between these manoeuvres. Differences between studies may be due to variation in the level of effort. It is important to note that activity of lower OI followed a similar pattern to that of TrA. Although there was no difference in OI activity between the exercises, this may have been due to insufficient statistical power that resulted from the small number of subjects used in this invasive study.

4.7. Abdominal, lumbar spine and pelvic movement

Although abdominal wall movement differed between the tasks, there was no variation in the displacement between regions of the abdominal wall. This may be due to the small size of the displacement. However, there was trend towards greater movement of the lower region during inward movement of the lower abdominal wall. This finding is consistent with clinical observations (Richardson et al., 1999).

Recruitment of TrA and the combined activity of OI, OE and RA (as a proportion of total abdominal muscle activity) was found to vary linearly with the amplitude of lumbar spine and pelvic displacement. This is consistent with clinical hypotheses and indicates that activation of TrA is more independent if there is no pelvis or spinal motion (Richardson et al., 1999). There was also a trend for TrA EMG to be related to abdominal wall movement. This agrees with previous reports of a relationship between pressure change (as measured with an air-filled cuff) associated with inward displacement of the abdominal wall, and function of TrA, recorded as EMG onsets associated with arm movement (Hodges et al., 1996a). Thus, TrA is more likely to represent a greater proportion of total abdominal activity when abdominal movement occurs with limited lumbopelvic motion.

4.8. Clinical implications

This study has implications for abdominal muscle retraining in clinical practice. The results provide further evidence to validate inward movement of the lower abdominal wall in the rehabilitation of TrA in LBP patients. The findings may also assist in selection of exercises for assessment and retraining of the other abdominal muscles. For instance, pelvic tilting is likely to produce greater activity of middle OI relative to upper TrA and RA, and abdominal bracing recruits OE with less activity of upper TrA, lower OI and RA. In addition, incorrect strategies used to mimic the required task may also be identified. To activate TrA independently from the other abdominal muscles, it would be important to discourage movement of the upper abdomen, bracing of the abdominal wall, or posterior tilting of the pelvis.

These results also emphasize the importance of observation for assessment of muscle function. For instance, motion of the abdominal wall and lumbopelvic region may assist in the determination of the muscle recruitment strategy. Furthermore, these results indicate that abdominal muscle recruitment may be influenced by patient positioning. Differential recruitment of TrA may be improved in supine compared to prone, indicating that assessment and re-education of abdominal muscle function in a range of positions should be considered. However, further research is required to determine whether similar strategies are used by people with LBP and to develop improved strategies for restoration of motor control.

Acknowledgments

This work was supported by the Australian Physiotherapy Association (Victorian Branch) and the National Health and Medical Research Council. The authors wish to thank Lorimer Moseley for his assistance with data collection and Beryl Kennedy for discussions on methodology.

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