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Feedforward Responses of Transversus Abdominis Are Directionally Specific and Act Asymmetrically: Implications for Core Stability Theories

Anticipatory postural adjustments (APA) are involuntary and automatic adjustments to posture occurring prior to a predictable postural perturbation. Postural muscle activity is considered to be anticipatory if it occurs prior to focal muscle activity during voluntary movements. There is continuing debate on the specific role of the feedforward muscle activation patterns associated with the APA. APAs have been attributed roles in controlling the center of mass,[9,11] segmental stability,[18] and even in the generation of movement itself.[34]

The onset of the transversus abdominis (TrA) electromyographic (EMG) signal in response to rapid arm movements has been a basis of many research and commentary papers examining motor control in individuals with low back pain (LBP).[15-17,21,25,37] A critical feature of this research is that, in contrast to healthy control subjects, individuals with LBP do not demonstrate feedforward activity of the TrA during rapid limb movements.[22,24,38] The loss of the feedforward onsets in the presence of LBP is the foundation of the proposal that there is an underlying motor control dysfunction of the deep abdominal muscles in individuals with LBP. It has been further proposed that

• **STUDY DESIGN:** Experimental laboratory study supplemented with a repeated case study.

• **OBJECTIVE:** To examine bilateral muscle activity of the deep abdominals in response to rapid arm raising, specifically to examine the laterality and directional specificity of feedforward responses of the transversus abdominis (TrA).

• **BACKGROUND:** Based on the feedforward responses of trunk muscles during rapid arm movements, authors have concluded that the deep trunk muscles have different control mechanisms compared to the more superficial muscles. It has been proposed that deep trunk muscles such as TrA contribute substantially to the stability of the lumbar spine and that this is achieved through simultaneous bilateral feedforward activation. These inferences are based on unilateral fine-wire electromyographic (EMG) data and there are limited investigations of bilateral responses of the TrA during unilateral arm raising.

• **METHODS AND MEASURES:** Bilateral fine-wire and surface EMG data from the anterior deltoid, TrA, obliquus internus (OI), obliquus externus, biceps femoris, erector spinae, and rectus abdominis during repeated arm raises were recorded at 2 kHz. EMG signal linear envelopes were synchronized to the onset of the anterior deltoid. A feedforward window was defined as the period up to 50 ms after the onset of the anterior deltoid, and paired onsets for bilateral muscles were plotted for both left and right arm movements.

• **RESULTS:** Trunk muscles from the group data demonstrated differences between sides (laterality), which were systematically altered when alternate arms were raised (directional specificity). This was clearly evident for the TrA but less obvious for the erector spinae. The ipsilateral biceps femoris and obliquus externus, and contralateral OI and TrA, were activated earlier than the alternate side for both right and left arm movements. This was a consistent pattern over a 7-year period for the case study. Data for the rectus abdominis derived from the case study demonstrated little laterality or directionally specific response.

• **CONCLUSION:** This is the first study to show that the feedforward activity of the TrA is specific to the direction of arm movement and not bilaterally symmetrical. The asymmetry of TrA activity during arm raising suggests that the interpretation of the role of TrA as a bilateral stabilizer during anticipatory postural adjustments needs to be revised. Future research needs to examine muscle synergies associated with the asymmetrical function of the TrA and the underlying mechanism associated with low-load stability training.

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this dysfunction results in suboptimal stability of the lumbar spine and, maybe, a mechanical factor in the underlying pathogenesis of LBP.[15,37] Many rehabilitation and core stability programs incorporate these concepts and conclude that all forms of perturbation or functional tasks 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 and not contribute to the control of the center of mass or to the focal task (usually arm raising). There are studies that suggest that the TrA may contribute to spinal segmental stability while acting bilaterally in a "corset" action[14] in conjunction with a bony leverage to stabilize the sacroiliac joint (SIJ),[39] or via a tensioning of the thoracolumbar fascia.[10,41] Some authors, utilizing engineering models, have questioned the magnitude of the stabilizing capacity of bilateral activation of the TrA.[12]

The central and peripheral mechanisms that explain the apparent clinical efficacy of core stability programs based on isolated TrA activation are unclear and may incorporate central changes in cognitive processing. For example, a low score on the Fear Avoidance Beliefs Questionnaire is associated with a lesser likelihood of responding to core stability training programs.[13] Similarly, changes in the feedforward activation profile of the TrA have been demonstrated in healthy subjects when they have increased anxiety or stress or have experimentally induced pain.[31,33] Following specific trunk muscle fatigue, the baseline activity of the trunk muscles are altered differently,[29] which may influence the ability to detect onsets in the feedforward window.[4] In spite of these cognitive and peripheral factors that may influence the behavior of the feedforward response of the TrA, the literature in recent years has consistently linked the changes of the activity onset of the TrA as a marker of motor control dysfunction that directly reflects an impairment resulting in less than optimal mechanical stability of the lumbar spine. Clearly, however, the delay in onset of the TrA is not specific to the diagnosis of LBP and researchers have not exhausted the possibility of other factors being significant control parameters influencing the activity onset of the deep abdominals.

The research on the TrA to date has been dominated by the experimental regimen utilizing a right-arm perturbation (rapid raising), with electrodes attached to abdominal muscles on the contralateral side. A few authors have examined and reported in the scientific literature bilateral activation patterns of the deep abdominals. Allison and Henry[4] reported pooled bilateral TrA onset data and were unable, for their asymptomatic subjects, to replicate the consistent feedforward onsets of the TrA for all normal subjects, as reported by other researchers (eg, Richardson et al[37]). Earlier research data[16] also demonstrated that sometimes the TrA does not activate in a feedforward manner during (bilateral) arm-raising tasks. Specifically, Hodges et al[16] found that for more than 70% of the trials the right TrA was not activated prior to the onset of the deltoid in 3 of 8 healthy control subjects performing bilateral arm flexion. These findings were discounted due to the probability "that control of spinal stiffness may not be optimal in these subjects"[16] and because the researchers' previous work demonstrated that individuals with chronic LBP have delayed TrA onsets.[24] Although these articles are a decade old, 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. A plausible explanation for both Hodges et al[16] and Allison and Henry[4] data was that there are different laterality responses between the sides of the TrA, and that bilateral arm flexion does not generate the same response as unilateral arm flexion.

The purpose of this study was to examine the impact of laterality of the arm movement on the onset of TrA and other trunk muscles in healthy subjects. Our hypothesis is that if the deep abdominal muscles have a predominant role of stabilization and are directionally independent, then there will be symmetry between sides, independent of the arm used to induce the spinal perturbation. A case study is included that shows repeated measurements on 3 testing occasions over 7 years. The purpose of this case study is to show the stability over time of the abdominal muscle activation. For completeness in understanding the trunk muscle activation patterns, the case study includes data from rectus abdominis, which is not recorded in the other subjects. Preliminary data from this case study have been reported previously.[1,6,7]

METHODS

Subjects

The study used a repeated-measures design for a group of 7 subjects, in addition to repeated testing (3 occasions) on a single subject. All data collection protocols were approved by the University of Western Australia Institutional Human Research and Ethics Committee and informed consent was obtained.

In the group data collection 7 of 8 consenting volunteers (2 males; mean ± SD age, 37 ± 8.2 years; height, 174 ± 11.1 cm; body mass, 75 ± 20.3 kg) completed the study. One subject withdrew due to stress reaction with the needle insertions.

EMG Acquisition

The EMG signals were collected simultaneously at 2 kHz, bilaterally from TrA, obliquus internus (OI), and obliquus externus, using intramuscular fine-wire electrodes (2 strands, nylon-insulated stainless steel, with 0.5-mm stripped bare and inserted with 25-gauge sterile needle). An hour before the insertions, 2.5 g of topical cream anesthetic (EMLA: 2.5% lidocaine, 2.5% prilocaine) was applied to the skin over the insertion site. Insertions were undertaken using ultrasound guidance (Sonolayer SSA-270A; Toshiba Corporation, Tokyo, Japan) with a 5-MHz curved array sound head between the anterior superior iliac spine and the ribcage, with insertions approximately 20 mm apart. Surface EMG profiles were recorded following skin preparation of shaving, abrasion, and alcohol wipe, from the anterior deltoid, biceps femoris (mid lateral femur), and erector spinae (paravertebral at level L3-4) in the group subjects. In the first 2 testing sessions of the case study rectus abdominis (caudal and lateral to the umbilicus) was recorded instead of the biceps femoris.[5] Surface recordings were made using 3 Ag/AgCl surface electrodes (Clear Trace; ConMed, Utica, NY), 38 mm in diameter, centers placed 20 mm apart, using a double-differential electrode configuration. Early case study data were collected using a single-differential (2-electrode) method. In all protocols the bony aspect of the clavicle was used as the common earth electrode site. Electrodes were positioned following skin preparation and all electrode pairs were tested with volitional activation.

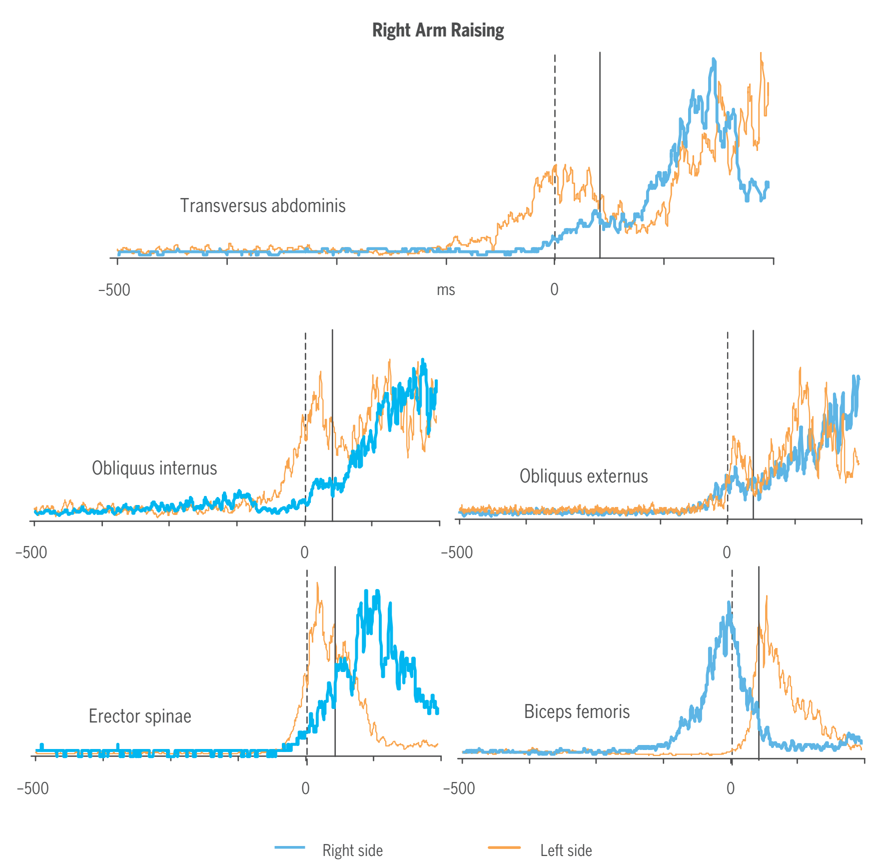

FIGURE 1. The ensemble group mean of the median linear envelopes from 6 trials of right arm raising for 7 subjects. Solid vertical line is 50 ms after the onset of anterior deltoid (dashed line). Note the clear laterality response of the transversus abdominis (TrA) and obliquus internus (OI) that have a contralateral (left) early activation, and the biceps femoris that has an ipsilateral (right) early response. The obliquus externus does not show substantial laterality.

Test Protocol

After a familiarization period subjects were asked to perform 12 rapid arm movements, alternating left and right arms, resulting in 6 trials for each arm. Data in this manuscript are limited to unilateral arm raises, which were self-paced and initiated after an audio cue. Subjects were instructed to focus on the acceleration of the arm only. Subjects were not asked to preactivate, deactivate, or undertake any unusual abdominal pre-emptive maneuvers that might be used to prepare the subject and thus alter the natural postural set. Any advice in this way could alter the role of the TrA activation patterns and it is unclear if these comments would be interpreted in a similar manner by healthy controls when compared to individuals with LBP.

Data Processing

The data were collected for 5 seconds (10-k data points), with at least 1 second of data prior to initiation of the arm movement. The EMG signals for the group data were collected using a Bagnoli-16, with a CMRR of 87 dB at 50 Hz (Delsys, Inc, Boston, MA) and Grass series 7 amplifiers for the surface and fine-wire, respectively. Postprocessing involved filtering using a zero-lag, fourth-order Butterworth filter band pass (20-450 Hz) and then full-wave rectification. For the case study, EMG data were band-pass filtered (10-1000 Hz) with the analogue amplifier (Grass series 7; CMRR, 90dB at 50 Hz) and then recorded to disc using a 16-bit AD card (National Instruments, Austin, TX). Muscle activity onset for the anterior deltoid was determined using the integrated protocol.[3] This protocol has been shown to be robust, reliable, and valid for situations where the signal-noise ratio (SNR) is greater than 6, which was always the case for the anterior deltoid in this experimental model. Paired (left and right) trunk muscle onsets, to examine the laterality response, were determined in a window from 150 ms before to 100 ms after anterior deltoid onset, using the same algorithm. Onsets were visually inspected for trials where SNR values of less than 6 were detected. Differences between the matched sides of the onsets were determined for each muscle (laterality) and compared for the left and right upper extremity flexion (directional specificity of movement), using a 2-sample unequal variance *t* test. The alpha level of confidence was set at .05 and corrected for multiple comparisons (5 muscles by 2 directions) to establish a significance level at $P<.005$.

Linear envelopes were created using a 100-data-point (50-ms integrated EMG) moving average and amplitude normalized to the peak of the linear envelope ±200 ms from the onset of anterior deltoid. All data sets were truncated to 1500 points (750 ms), with 500 ms prior to anterior deltoid onset and 250 ms after. Anterior deltoid onset was defined at t = 0 and the feedforward window defined as the activation prior to +50 ms. The 50 ms reflects the estimated electromechanical delay of the anterior deltoid for the arm-raising task.[8]

Individual, EMG, linear-envelope ensembles were created by determining the median point by point for each of 6 trial linear envelopes. This nonparametric central tendency method, as opposed to using mean values, was utilized to reduce the influence of any extreme values that would impact unduly on the resulting linear envelope. This meant that no trials were excluded due to subjective examination of trial "quality." A 10-point moving average was used to create the linear-envelope ensemble, which was then quintated (1:5) to create the graphics in Excel.

The case study using the arm-raising protocol (blocks of 10 consecutive trials) examined the activation of the abdominal muscles, including rectus abdominis, on 2 occasions 3.5 and 7 years previously. Data from the first 2 studies have been reported earlier.[1]

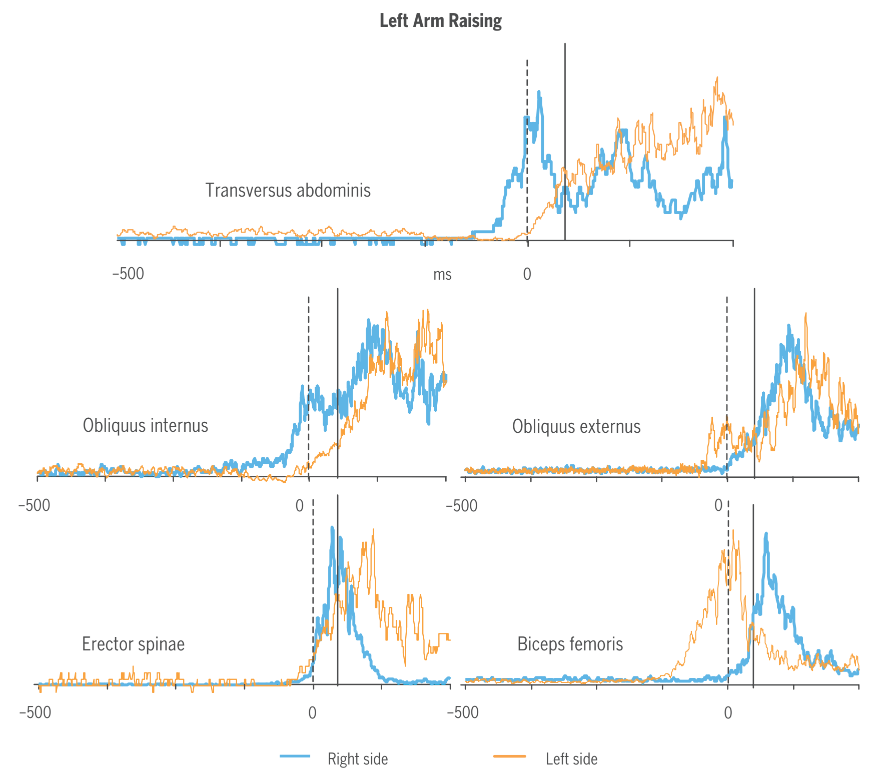

FIGURE 2. The ensemble group mean of the median linear envelopes from 6 trials of left arm raising for 7 subjects. Solid vertical line is 50 ms after the onset of anterior deltoid (dashed line). Note laterality responses reversed when compared to Figure 1. Obliquus externus has an ipsilateral (left) early response. Erector spinae shows little laterality response during left arm raising.

RESULTS

During unilateral rapid right (**FIGURE 1**) and left arm raising (**FIGURE 2**), the group EMG ensemble profiles clearly showed asymmetrical bilateral responses in the deepest 2 layers of the anterior trunk muscles (TrA and OI) and the biceps femoris. The contralateral side to the arm raised demonstrated an increase in amplitude in the feedforward window well before the ipsilateral muscle. These laterality responses were replicated when arms were alternated, demonstrating that the response was independent of electrode placements. This indicates that the activity of the TrA and OI were specific to the direction of the perturbation to posture.

The erector spinae and the obliquus externus did not show clear amplitude laterality responses with perturbations for both arms (**FIGURES 1** and **2**). The obliquus externus demonstrated a greater laterality response with the dominant (right) arm raising. The erector spinae seemed to show a greater rate of activation on the contralateral side and, noticeably, the onsets of the ipsilateral erector spinae muscle activation could be considered to occur at the similar times.

The latency of the muscles (TrA, OI, obliquus externus, erector spinae, biceps femoris) relative to anterior deltoid was matched between sides for each muscle for each arm-raising task (**FIGURE 3**). For a muscle to have simultaneous onsets, irrespective of the relative variance to the anterior deltoid onset, the points should lie along the line of identity. Points lying below the line indicate that the left side was activated prior to the right and points above the line show that the right side had an earlier onset than the left. **FIGURE 3A** shows the distribution for the biceps femoris, indicating a dichotomy of responses where the ipsilateral muscle is activated prior to the contralateral muscle substantially for both left and right arm raises. Trunk muscles onsets were plotted when onsets of both muscles were within 150 ms before and 100 ms after the onset of anterior deltoid. **FIGURE 3B** shows that the TrA laterality response was the reverse (contralateral before ipsilateral), with greater variance compared to the biceps femoris. A similar pattern existed for OI (**FIGURE 3C**), with a greater variance, particularly for

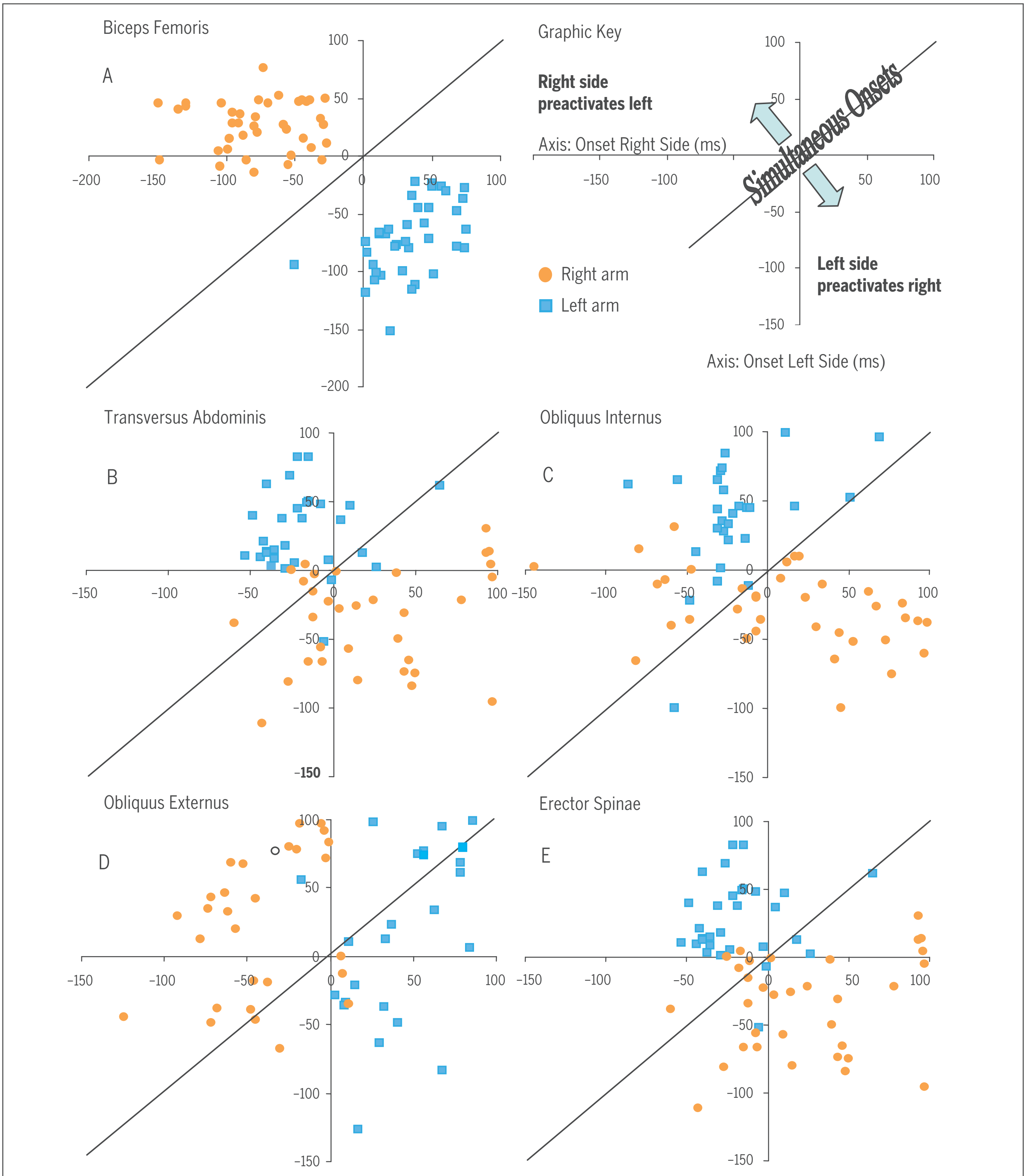

FIGURE 3. Scatter plots of the onsets of the paired left and right sides of muscles during left and right arm raising. Points below the diagonal indicate that the left side was activated prior to the right side, points above the diagonal line indicate the right side was activated prior to the left side. The biceps femoris (A) is tightly clustered with clear laterality response. The transversus abdominis (TrA) (B), obliquus internus (OI) (C), and erector spinae (E) tend to have similar laterality response. (D) The obliquus externus has a unique pattern with the right side modulated by arm but less so for the left side. Note that the horizontal axis is right-side onset, and the vertical axis is left-side onsets.

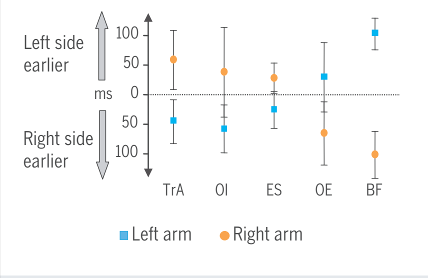

FIGURE 4. The mean (SD) of the difference between paired side-to-side (laterality) onsets of the trunk muscles for left and right arm raising. Onsets calculated only for paired data and between –150 to +100 ms. Paired onsets identified for each muscle transversus abdominis (TrA) (75%), obliquus internus (OI) (76%), erector spinae (ES) (92%), obliquus externus (OE) (60%), and biceps femoris (BF) (93%). All muscles show statistical differences ($P<.0001$, unpaired unequal-variance *t* test) for an effect of directional specificity. Note the relative symmetry of the laterality responses for each arm.

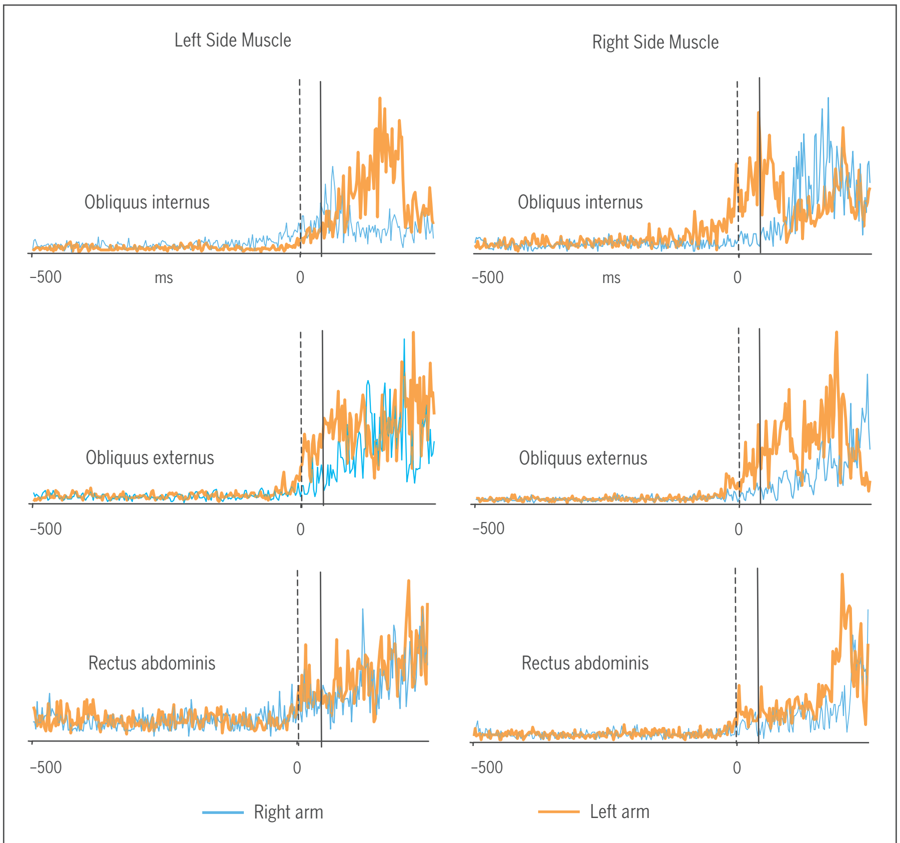

FIGURE 5. Linear envelopes for the right and left arm movements of the case study (block of 10 trials) for bilateral trunk muscle EMG signal profiles. Note that the relative signal amplitudes (within muscles) can be compared. The rectus abdominis shows very little laterality for either arm movement during the feedforward window. This has implications on the relative stiffness or hoop stressors of the central fascial sheath during the anticipatory postural adjustment for the unilateral transversus abdominis on which to act. Laterality in the feedforward window is observed for obliquus internus. This is more pronounced for the right side. For the obliquus externus the left (nondominant) arm evokes greater amplitude of response for both sides.

the right arm movement (orange circles). The obliquus externus (**FIGURE 3D**) had a large variance in the onsets, with a pattern different to the other muscles. The right obliquus externus showed greater laterality responses than the left, suggesting that they might be influenced by other factors, including arm dominance. **FIGURE 3E** shows the erector spinae data formed a closer cluster around the line of identity, suggesting limited laterality difference; but this still demonstrated a directional specificity associated with the different arm movements.

The degree of laterality response for each muscle pair is shown in **FIGURE 4**, where the least laterality difference was observed in the erector spinae and the greatest in biceps femoris. The laterality responses (side-to-side differences in the same muscle) were clearly dependent ($P<.0001$) on the arm used to perturb the posture and, therefore, all muscles showed significant directional specificity.

Case Study Repeatability and Amplitude Assessment

One of the participants in the study had been tested 3.5 and 7 years previously, using a very similar protocol. The data of the case study for all 3 testing occasions reflected the majority pattern of the group findings. The significance of the case study is the consistency of the responses between 3 different assessments over a 7-year period and, most importantly, the comparison of the amplitude of the same muscle under different arm perturbations. **FIGURE 5** shows the linear envelopes of the more superficial abdominal muscles, including the rectus abdominis. This graphic shows the change in amplitude response of the same muscle under different perturbations. There was no laterality response observed in the rectus abdominis and, importantly, the rectus abdominis is not substantially activated before the onset of the anterior deltoid.

FIGURE 6 shows the block of 10 trials for this same subject tested on 3 different occasions over a 7-year period for the TrA in response to right arm raising. The pattern of activation was very consistent in the APA window and there was some variability in the feedback window. Again, this case study shows a consistent pattern of contralateral TrA preactivation, with a lag in the ipsilateral side and up to 5-fold increases in activation of the contralateral TrA compared to the ipsilateral TrA in the feedforward window.

DISCUSSION

The vast body of stability and rehabilitation literature, often based on single-arm-raising experimental models, discusses the role of feedforward TrA activation patterns.

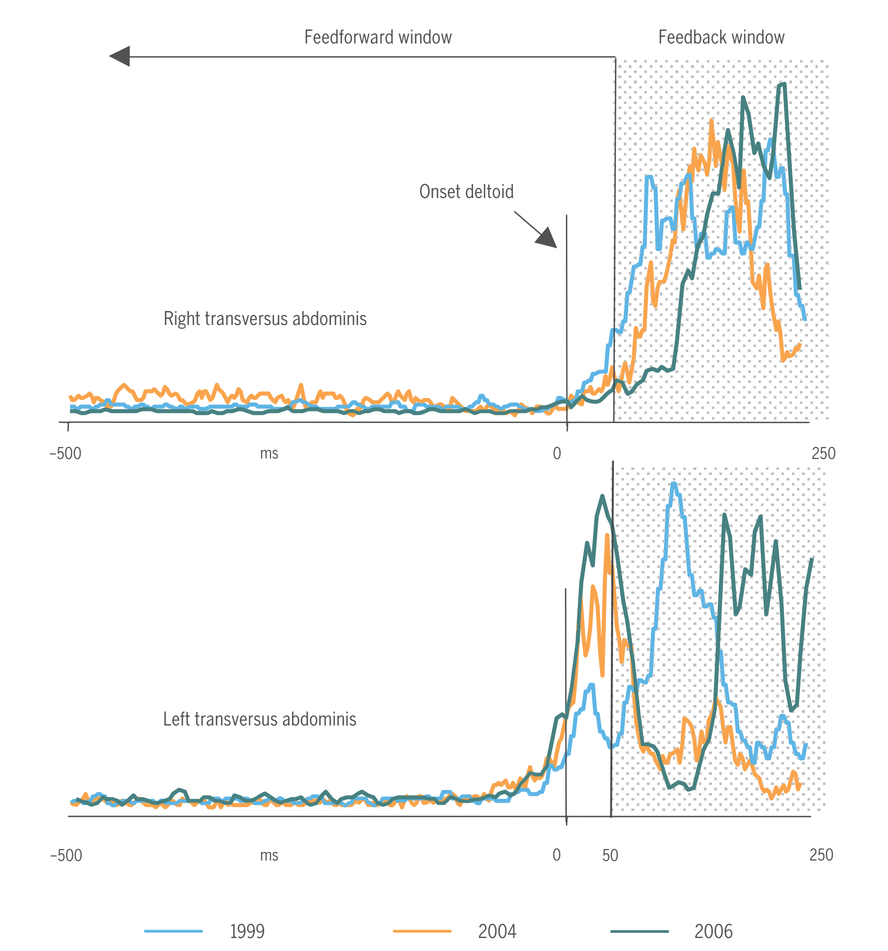

FIGURE 6. Reliability of linear envelopes of the transversus abdominis (TrA), recorded in the same subject over a 7-year period (1999, 2004, and 2006), from 10 consecutive trials of right arm raising. Onset detection protocols would result in similar values. The onset of the right (ipsilateral) TrA is difficult to detect in the feedforward window. In comparison, the left TrA clearly has a feedforward response. TrA is consistently directionally specific and shows consistent patterns over 7 years within 1 subject.

Generally, there is an assumption that in the feedforward window (even prior to activation of other trunk muscles and anterior deltoid) the TrA is activated bilaterally and symmetrically and is not related to the direction of the perturbation—or, is not directionally specific. Many authors use this assumption to support the hypothesis that the role of TrA in the period before the onset of other trunk muscles contributes significantly to spinal stability. This study provides clear evidence to contradict the assumptions of (*a*) bilateral feedforward symmetry and (*b*) the activation's independence of the direction of perturbation.

Laterality of the Feedforward Response of Transversus Abdominis

Although the results of this study may suggest controversy, the controversy lies in the interpretation of the previous findings and the subsequent concepts of the isolated role of TrA in spinal stability and not the actual data. In fact, if only the contralateral data are considered, then the findings of this study are consistent in many ways with previous literature. That is, the (contralateral) TrA is a feedforward muscle and preactivates other trunk muscles during rapid arm raising.[23,37] The EMG assessment of muscles bilaterally rather than unilaterally, however, indicates that the majority of healthy subjects have a clear laterality response of the TrA. During unilateral arm raising, the activation of the ipsilateral TrA lags behind that of the contralateral side. Furthermore, because the laterality responses of the respective sides of the TrA muscle are replicated for left and right arm flexion perturbations, and repeated across time, the findings cannot be attributed to signal amplification or in vivo errors in fine-wire placements. Therefore, this study is the first to show that the feedforward response of TrA is clearly directionally specific to the side of the arm movement, and is not bilaterally symmetrical. These additional findings are counter to the interpretation of earlier studies stating that bilateral feedforward responses of the TrA are highly consistent in healthy controls, and this isolated activation contributes substantially to the segmental stability of the lumbar spine.

Previous reports provide data that are in agreement with the findings of this current study.[4,26-28] Allison and Henry[4] made the assumption (albeit incorrect) that the TrA muscle functioned bilaterally, therefore pooling the left and right sides, which increased the variance of their data. Studies that have failed to replicate clear TrA/OI feedforward onsets in normal control subjects may be explained partly by the laterality response identified in this study. For example, Lehman et al[26] utilized surface EMG to examine the right-side onsets during right arm flexion and found about 50% of healthy controls had onsets later than 50 ms after the deltoid activation (mean, 59 ms; 95% CI: 22-96). Similarly, Marshall and Murphy[28] found that 20% of healthy subjects did not have feedforward TrA/OI onsets detected by surface EMG during ipsilateral arm raising, and that the group mean (SD) onset was 25 (26) ms after the onset of anterior deltoid.

On examination of the TrA/OI muscle, onsets relative to anterior deltoid, of 50 patients with nonspecific LBP, Marshall and Murphy[27] documented a distinct laterality response (mean ± SD ipsilateral muscle onset of 49 ± 35 ms compared to 2 ± 59 ms for the contralateral side). This is consistent in magnitude with the finding in this study, suggesting that the laterality response is still present in individuals with LBP. Interestingly, the TrA, like the IO and biceps femoris, tended to show the greatest laterality responses (for onset detection).

Transversus Abdominis and Directional Specificity

The contralateral preactivation of the TrA is considered not to be directionally specific when the arm is flexed or extended.[23,24,42] This invariance to the direction of perturbation is quoted as evidence of a stabilizing role.[23,42] This study examining bilateral activation illustrates that unilateral left and right arm flexion generates different APA responses in the TrA showing clear directional specificity. This directional specificity is also clearly observed in the biceps femoris and OI, suggesting a similar pattern of laterality response. This may be explained by the different direction of the rotation torque applied to the trunk with each arm flexion.[30] The fiber orientation of the TrA may suggest that it plays an important role in rotatory torques of the trunk.[43] However, it does not explain why different onsets were not detected with extension and flexion of the same arm in previous research.[23] In contrast, the clear directional specificity shown in this study is consistent with the data from Marshall and Murphy,[28] who found in healthy controls that the ipsilateral TrA/OI has an earlier onset with arm extension when compared to the same arm flexion.

Further evidence of directional specificity is also supported by the substantial changes in both magnitude and onset of the same muscle when different upper extremities (right versus left) are used to perturb the posture. Onset detection protocols alone may not be able to emphasize the significance of these magnitude changes and also may themselves be influenced by factors such as variability in the baseline muscle activity due to stress, fatigue, presence of pain, fear of pain, or premovement experimental instructions.[5,20,29,33] This onset data when used in clinical research is clearly valid for the interpretation for motor control strategies and activation sequences, but are less valid in terms of inferring a similar contribution to stability via force generation. This is an important area of investigation for future research.

Transversus Abdominis and Spinal Stability in the Feedforward Window

Stability of the spine may be influenced by the TrA activation through various subsystems.[35,36] It may contribute directly via mechanical actions, or secondarily through sensory information or indirect mechanisms of changing cognition or kinesiophobia. Mechanically, the TrA has been hypothesized to provide lumbopelvic stability via a "corset" action,[14] the leverage system,[39] or the hydraulic amplifier effect of tensioning the thoracolumbar fascia.[10,41] Hodges et al[19] argued that any activation of the TrA for spinal segmental stabilization needs to be bilateral, because unilateral TrA activation was found not to increase the segmental stiffness in a porcine model. Mathematical models suggest that there is little, if any, stabilizing role performed by the TrA in isolation.[12] But, clearly, all of these studies suggest that any segmental stabilizing role which may be present is minimized or nullified when the muscle is acting in isolation and predominantly unilaterally. In the majority of cases in this study, the feedforward activation is substantially unilateral. Therefore, because the proposed mechanisms linking the TrA to segmental stability predominantly rely on early bilateral activation, it is unclear how a mechanical hypothesis can be upheld for this specific functional task. These findings in combination suggest that, with bilateral activation, the TrA possibly stabilizes the spine. But clearly this mode of action is not apparent prior to the activation of the anterior deltoid during rapid arm raising in healthy control subjects.

One could argue that one side of the TrA may act on the lumbar spinal fascia if the central common fascia is stiffened by the rectus abdominis or opposed by the common fascial attachment of the opposite obliques. But in the included case study, like other studies,[4,23,28] the activation of the rectus abdominis was substantially delayed compared with the preactivation of the contralateral TrA, suggesting that if the rectus abdominis provides a central support structure it is entirely due to passive resistance. The contralateral OI may be able to influence the TrA via a common anatomical link, particularly at levels below the umbilicus[40]; yet the OI has a similar laterality response to that of the TrA and, therefore, is not substantially active during the feedforward window period when it would be required to provide a stable attachment.

If one takes the biomechanical point of view that a 30- to 50-ms delay may not be of significance in generating spinal segmental stability, then the lag observed in the laterality response in this study may not be mechanically significant. If this view is taken, however, because the magnitude of the difference in the laterality response is similar to the difference observed in individuals with LBP and healthy controls, then onset delays in LBP or between sides (laterality) need to be interpreted in terms of motor control and not assumed to make mechanical differences to feedforward spinal stability. This study also found laterality and directional specificity of the other trunk muscles and a degree of symmetry of pattern (**FIGURE 5**) when the upper extremity movements are alternated. Therefore, future research may examine the synergistic patterns of other trunk muscles acting with the TrA.[30]

From either point of view, we question the link between the asymmetrical and isolated function of TrA acting in the feedforward window and any attributed mechanical segmental stability of the spine.

Implications for Transversus Abdominis Training

The findings of this study do not impact on the validity of undertaking specific TrA bilateral activation training programs. But, our findings suggest that the underlying rationale that the training program directly influences the mechanical stability of the spine via the isolated role of bilateral activation of TrA in the feedforward window is not supported. We propose that changes in functional stability of the spine occur secondarily through the cognitive or sensory changes associated with the specific, low-load exercises,[2] and that there may be common elements to successful training programs of different loads and treatment philosophies. We would argue that because the TrA is less likely to reflect a mechanical stability role in the activation profile prior to the onset of the anterior deltoid, and because it has been shown to relate to cognitive and sensory processing factors of the sequelae of LBP, then the cognitive and functional process of undertaking the rehabilitation may be as important as the specific training load. This may suggest that comparative studies between these types of interventions could match not just the load or level of activation,[42] but also the cognitive effort to learn how to undertake these exercises or the postures in which these exercises are performed.

Finally, bilateral activation of the TrA in isolation does not reflect the normal motor pattern for rapid unilateral ballistic patterns of movement and, therefore, future research may examine if such training may detrain individuals who require such fast actions (eg, elite athletes). Because rapid unilateral shoulder flexion is a very rare motor pattern used in normal activities of daily living, the training of bilateral activation of the isolated TrA may be better suited to slow movement patterns. The delayed onset of the contralateral TrA observed in chronic LBP may be a strategy by individuals with a memory of symptoms to avoid the rotatory function of the TrA working in synergy with other diagonally aligned muscles. Such patterns may be inappropriately maintained in chronic LBP and high-stress situations resulting in limited variability of movement patterns.[32]

CONCLUSION

The TrA is a feedforward muscle during unilateral rapid arm raising. This is a predominant characteristic of the contralateral side to the perturbing arm. The ipsilateral TrA shows a delayed pattern of activation. This side-to-side difference switches when the perturbing arm is changed, showing clearly that the activation of the TrA is directionally specific and that symmetrical, bilateral preactivation is not a normal activation pattern during a unilateral ballistic action. Overall, although a delay in the contralateral TrA onset could be a marker for both the sensory and mechanical sequelae of LBP, the fundamental role of the preactivation of the TrA is still unclear. This study highlights the importance of understanding what constitutes normal function of the deep abdominal muscles and future research warrants examination of how TrA interacts with other trunk muscle synergies. This has particular importance for understanding the role of core stability training for prophylaxis and management of spinal pain syndromes. This manuscript will hopefully generate a wider scope of research hypotheses to examine these issues. The reasons why isolated TrA stabilization exercises should be prescribed in both athletes and individuals with LBP warrants further examination and are not likely to be due to the direct mechanical role of TrA acting bilaterally on the lumbar spine in the feedforward window.

KEY POINTS

FINDINGS: TrA, like other trunk muscles and the biceps femoris, act asymmetrically during single-arm flexion and are clearly directionally specific.

IMPLICATION: Isolated bilateral activation of TrA before the onset of anterior deltoid is not the normal pattern in healthy controls. The rationale for TrA bilateral coactivation—to provide lumbar segmental stability in the period before anterior deltoid activation—needs to be reconsidered.

CAUTION: This study did not include individuals with either acute or chronic LBP for comparisons.

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