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Deep and Superficial Fibers of the Lumbar Multifidus Muscle Are Differentially Active During Voluntary Arm Movements

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Study Design. A cross-sectional study was conducted.

Objective. To determine the activity of the deep and superficial fibers of the lumbar multifidus during voluntary movement of the arm.

Summary of Background Data. The multifidus contributes to stability of the lumbar spine. Because the deep and superficial parts of the multifidus are near the center of lumbar joint rotation, the superficial fibers are well suited to control spine orientation, and the deep fibers to control intervertebral movement. However, there currently are limited *in vivo* data to support this distinction.

Methods. Electromyographic activity was recorded in both the deep and superficial multifidus, transversus abdominis, erector spinae, and deltoid using selective intramuscular electrodes and surface electrodes during single and repetitive arm movements. The latency of electromyographic onset in each muscle during single movements and the pattern of electromyographic activity during repetitive movements were compared between muscles.

Results. With single arm movements, the onset of electromyography in the erector spinae and superficial multifidus relative to the deltoid was dependent on the direction of movement, but the onset in the deep multifidus and transversus abdominis was not. With repetitive arm movements, peaks in superficial multifidus and erector spinae electromyography occurred only during flexion for most subjects, whereas peaks in deep multifidus electromyography occurred during movement in both directions.

Conclusions. The deep and superficial fibers of the multifidus are differentially active during single and repetitive movements of the arm. The data from this study support the hypothesis that the superficial multifidus contributes to the control of spine orientation, and that the deep multifidus has a role in controlling intersegmental motion. [Key words: EMG, lumbar spine, motor control, multifidus, stability] **Spine 2002;27:E29–E36**

It is widely accepted that the lumbar multifidus muscle contributes to stabilization and control of the lumbar spine in humans. Biomechanical models[9] and *in vitro* studies[31,39] indicate a role for this muscle in spine stiffness and control of intervertebral motion, particularly in the sagittal and frontal planes.[39] Furthermore, *in vivo* data from a porcine model have confirmed that spine motion is controlled by electrically evoked activity of the multifidus after instability induced by ligamentous disruption.[23]

The multifidus has five fascicles that arise from the spinous process and lamina of each lumbar vertebrae and descend in a caudolateral direction.[27] The most superficial fibers of each fascicle cross up to five segments and attach caudally to the ilia and sacrum. In contrast, the deep fibers attach from the inferior border of a lamina and from the inferior edge of the spinous process.[4,27] They cross a minimum of two segments to insert into a mamillary process and facet joint capsule.[4,24,27] These are the deepest muscle fibers in the lumbar spine because there are no rotatores in this region.[4] In biomechanical terms, the superficial fibers are distant from the centers of lumbar vertebra rotation and have an effective moment arm for extension of the lumbar spine and control of lumbar lordosis.[26] In contrast, the deep fibers are near the centers of lumbar vertebra rotation, and thus have a limited ability to extend the spine.[31] Furthermore, because the moment arm of this muscle is small, it may exert its effect throughout the range of spine motion without compromise from its length–tension relation.[29] It is accepted that whereas many trunk muscles are suited architecturally to the control of spine orientation, most have a limited ability to control intervertebral shear and torsion.[4,31] The deep fibers of the multifidus are ideally placed to control these motions *via* intervertebral compression. The proximity of the deep multifidus to the center of rotation means that it produces compression with minimal movement torque, which would need to be overcome by antagonistic muscle activity.[23,31] Despite the biomechanical differentiation of the different lumbar multifidus components, few studies have compared their recruitment and control.

Electromyographic (EMG) recordings from the multifidus have been made with surface or intramuscular electrodes. Most data recorded with surface electrodes suggest that the multifidus extends the vertebral column.[10,11,22,30] Others suggest that the multifidus also is associated with rotation of the spine.[10,30] This activity is consistent with the control and production of spine motion. However, if the deep fibers of the multifidus control intersegmental motion (*e.g.*, shear forces), these muscle fibers may be active irrespective of the direction of spine

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motion or external/internal forces. Indeed, it has been argued that tonic activity of the multifidus increases spine stiffness.[7] While some studies report activity of the multifidus, recorded with intramuscular electrodes, that is consistent with this proposal, there is little consensus. For instance, studies variably report continuous activity,[38,40] phasic activity,[10] and silence[30,32] during quiet standing. Although simultaneous recording of deep and superficial fibers has suggested differences in activity, clear data are lacking.[40] The disparity, both between and within studies, is likely the result of nonselective electrodes,[1,10,25,32,40] variable placement of intramuscular electrodes,[32,35,37,40] and lack of quantitative evaluation of the EMG activity.[1,10,22,30,32,38]

To clarify this argument, it is necessary to make selective recordings from deep and superficial components of the multifidus while using novel methods to discriminate whether separate strategies are used for their control. One technique for investigating the control strategies of the multifidus is to evaluate the recruitment of this muscle when spine stability is challenged, for example as a result of limb movement. When a limb is moved, reactive moments are imposed on the spine that are equal in magnitude but opposite in direction to those that produced the movement.[3,6,8,9] Strategies are initiated before the movement of the limb to prepare the body for the perturbation. These responses are generally specific to the direction of movement.[2] However, the activity of one deep trunk muscle, the transversus abdominis (TrA), is not influenced by the direction of reactive moments and may contribute to the control of spine stiffness.[17] The authors hypothesized that if the superficial multifidus contributes to the control of spine orientation as an extensor, its activation should be influenced by the direction of reactive moment. However, the deep fibers may be active in a non–direction-specific manner to modulate spine compression for the control of intervertebral shear and rotation forces.

■ Methods

Participants. The participants in this study were six males and two females with a mean age of 29 ± 8 years, a mean height of 175 ± 0.07 cm, and a mean weight of 74 ± 11 kg. Subjects were excluded if they had any respiratory or neurologic condition, or if they had experienced low back pain in the preceding 2 years. Written informed consent was obtained. All procedures were approved by the institutional research ethics committee and conducted in accordance with the Declaration of Helsinki.

Electromyography. Electromyographic activity of the multifidus was recorded with bipolar intramuscular electrodes fabricated from Teflon-coated stainless steel wire 75 μm in diameter (Carlsborg, Washington, AM Systems). One millimeter of insulation was removed from the cut ends of the wire, and the tips were bent back approximately 1 to 2 mm from the end to form a hook. The electrodes were threaded into a hypodermic needle (0.70 × 0.50 mm or 0.32 × 0.50 mm).

Three electrodes were inserted into the right multifidus muscle at L4 under ultrasound guidance. For electrode insertion, the participant sat with the trunk supported and the hips flexed approximately 100°. The L4 spinous process was identified, and the morphology of the multifidus was imaged sonographically using a 5-MHz linear transducer (128XP/4; Acuson, Mountain View, CA). Before electrode insertion, approximately 0.5 to 1 mL of lignocaine (lidocaine) was injected beneath the skin.

The first electrode was inserted approximately 4 cm laterally to the midline and directed medially until it reached the lamina to make recordings from the fibers of the multifidus immediately adjacent to the lamina of the L4 vertebrae, most likely those arising from the inferior edge of the L3 spinous process (*i.e.*, deep multifidus) (Figure 1A). The second electrode was inserted approximately 4 cm from the midline and advanced to a depth of approximately 1 cm, medial to the lateral border of the multifidus, to make recordings from the laterally placed superficial fibers of the multifidus that arise from the upper lumbar vertebrae (*i.e.*, lateral multifidus; Figure 1C). Gentle pelvic movements clarified the lateral border of the multifidus and helped to avoid placement of the electrode in the longissimus. The third electrode was inserted approximately 2 cm laterally to the midline and advanced until it reached the spinous process approximately 1 cm from the superficial border of the multifidus to make recordings from the superficial fibers of multifidus adjacent to the L4 spinous process (*i.e.*, superficial multifidus) (Figure 1B). After removal of the needles, gentle traction of the wires under ultrasound visualization confirmed the position of each electrode. The electrode for TrA

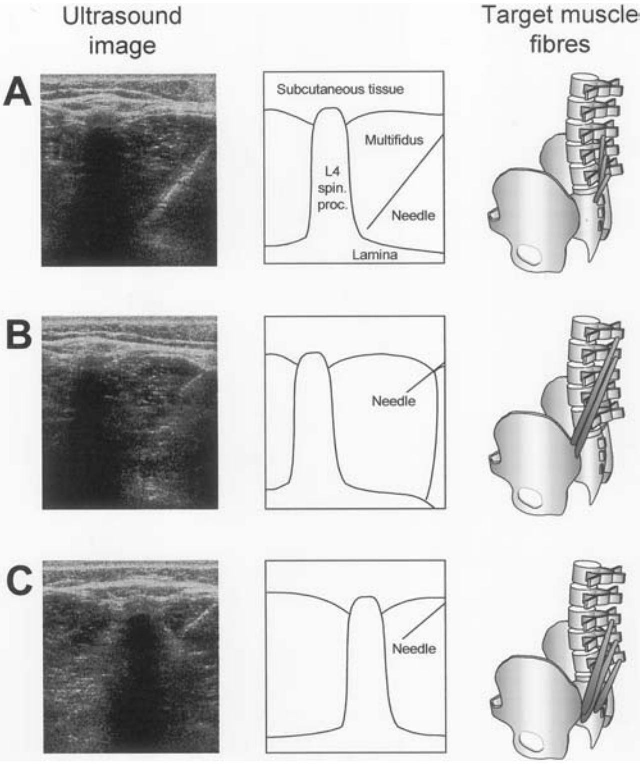

Figure 1. Technique for electrode placement into the deep (**A**), lateral (**B**), and superficial (**C**) fibers of the multifidus. Ultrasound images show the location of the needles to record the activity of each component. Line drawings provide a guide to the ultrasound images. Anatomic drawings demonstrate the muscle fibers targeted with each insertion.

was inserted with ultrasound guidance midway between the rib cage and iliac crest.[17]

Pairs of surface EMG electrodes (Ag/AgCl discs, 1 cm in diameter and 2 cm in interelectrode distance) were placed over the right erector spinae at L3 approximately 5 cm from the midline and over the posterior and anterior portions of the left deltoid. A ground electrode was placed over the iliac crest. Electromyographic data were amplified differentially with a gain of 10,000 to 50,000, band-pass filtered between 50 Hz and 1 kHz, then sampled at 2 kHz using Spike2 software (Cambridge Electronic Design, Cambridge, UK). Data were exported for analysis with Matlab 5.1 (Mathworks, Natic, MA).

Upper Limb Movement. Angular displacement of the left arm was measured using a potentiometer attached to a lightweight bar, which was strapped to the wrist of the straight left arm. The bar's axis of rotation was aligned with the approximate center of glenohumeral joint rotation. Motion of the arm was displayed on an oscilloscope so that feedback about movement amplitude and frequency was available as required.

Procedure

Single Movements of the Upper Limb. In a relaxed standing position with feet shoulder-width apart, the participants moved the left upper limb as quickly as possible in response to a light. In separate trials, subjects either flexed the upper limb to approximately 60° from the start position with the arm beside body or extended the upper limb to approximately 40°. Emphasis was placed on the speed of movement rather than the distance moved. The participants were given a verbal warning to move at a randomly determined time 0.5 to 2 seconds before the stimulus.

Repetitive Movements of the Upper Limb. The participants performed repetitive movements of the left upper limb in different positions of the arm in a relaxed standing position with the feet shoulder-width apart. The two tasks were 1) sagittal plane movement between 15° of extension and 15° of flexion from the initial position, with the arm beside the body, and 2) sagittal plane movement between 15° of extension and 15° of flexion from the initial position, with the arm flexed to 90° in front of the body.

On the basis of biomechanics it was predicted that sagittal plane movements in 90° shoulder flexion would produce larger vertical reactive forces (compression and distraction) than movements of the arm beside the body. The participants were instructed to hold their breath at normal end-expiratory volume while they moved their arm "as fast as possible" for 10 to 15 seconds. Verbal feedback about the time elapsed was provided.

Data Analysis. For the single-movement trials, the onset of EMG was identified visually from the raw data as the point at which EMG increased above the baseline level. To remove the possibility of observer bias, traces were displayed individually, with consecutive traces drawn from separate trials. There was no reference to muscle or trial number, to any parameter of movement, or to EMG of another muscle. Because of the selective electrodes used for the intramuscular recordings, the onset of EMG could be clearly identified from the onset of discrete motor unit action potentials. The onset times for each muscle were assessed by two separate examiners using the data from 15 trials in each direction in two participants. There were no significant differences between examiners ($P = 0.31$).

The relative latencies between the onset of deltoid EMG and that of the trunk muscles were used for analysis. Trials were excluded if the onset of trunk muscle EMG occurred more than 200 ms before or after that of the deltoid. Fewer than 5% of the trials were excluded, and 15 successful trials were recorded for each participant. This latency is thought to be too short to be the result of afferent input from movement of the limb or trunk.[2]

Analysis of the repetitive movement trials involved identifying the temporal and spatial features of trunk muscle EMG relative to the arm movement cycle from time-locked averages and analysis in the frequency domain. Rectified EMG averages were triggered from the onset of forward arm movement. The time and amplitude of the peaks and troughs in the averages were identified visually. A peak was identified if the magnitude of the nearest trough on either side was less than the peak by at least 15% of the maximum peak amplitude. To remove observer bias, all the averages were displayed individually without reference to the muscle being measured.

Statistical Analysis. For single-movement trials, the onsets of EMG relative to deltoid onset were averaged. Because the data were normally distributed, a two-way analysis of variance (ANOVA) was conducted to compare relative onsets of each muscle between movement directions. *Post hoc* testing of EMG onsets between muscles was undertaken with Duncan's multiple-range test. The number of peaks during repetitive movement was assessed with Fisher's exact test. Alpha was set at 0.05.

■ Results

Recordings During Single Rapid Arm Movements

Raw data from a representative subject in Figure 2 show that when standing subjects performed rapid flexion of the upper limb in response to a visual cue, the EMG activity of all the trunk muscles began before the onset of the upper limb movement. The EMG onsets occurred between 50 ms before and 50 ms after anterior deltoid EMG onset. For the group, there was no significant difference in EMG onset between any of the muscles. Similar to the flexion condition, when the participants performed rapid extension of the upper limb, the onset of EMG for all the trunk muscles occurred before limb movement (Figure 2). However, whereas the onset of EMG in the deep fibers of the multifidus and TrA occurred before that of posterior deltoid or at the same time, the onset of EMG for all the other trunk muscles occurred after that of deltoid ($P < 0.02$) (Figure 3). When the different directions of limb movement were compared, the EMG onsets of erector spinae and the superficial and lateral fibers of multifidus relative to those of the deltoid were longer for upper limb extension than for upper limb flexion ($P < 0.03$). In contrast, the onsets of the deep multifidus and TrA EMG relative to that of deltoid were not different between movement directions ($P = 0.76$ and 0.82, respectively) (Figure 3).

Recordings During Repetitive Arm Movements

When the participants moved their arm repetitively beside the body in the sagittal plane, EMG activity of the

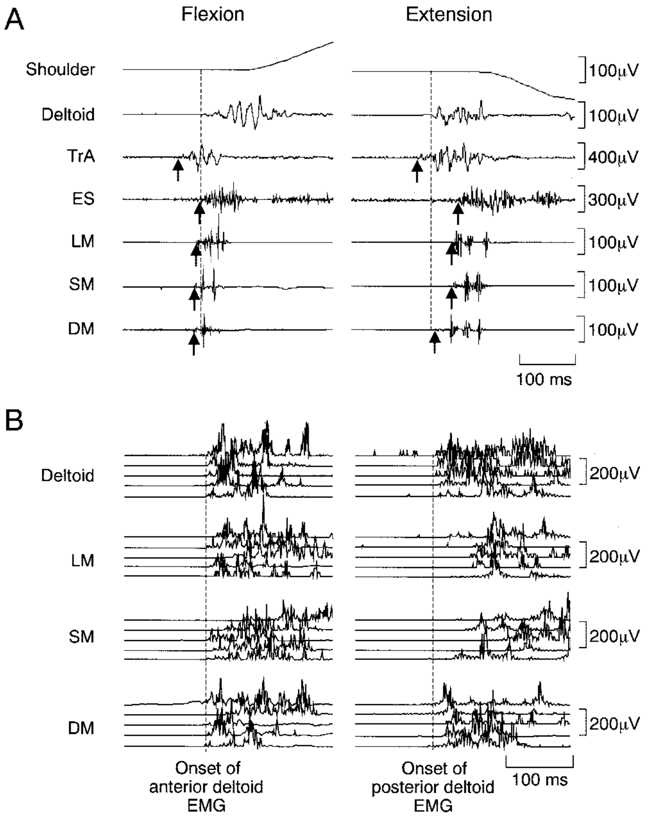

Figure 2. Raw electromyographic (EMG) and movement data from representative subjects during single rapid arm movements. The left panels show data for upper limb flexion, and the right panels show extension. Panel **A** shows electromyographic data for the deep (DM), superficial (SM), and lateral (LM) fibers of the multifidus, erector spinae (ES), transversus abdominis (TrA), anterior deltoid (flexion), or posterior deltoid (extension), and shoulder movement for a single repetition. Panel **B** shows EMG data for deep (DM), superficial (SM), and lateral (LM) fibers of the multifidus and anterior or posterior deltoid, for five repetitions from a single subject. The dashed vertical lines represent the onset of deltoid EMG, and the arrows in Panel **A** indicate the onset of EMG for each muscle.

deep multifidus occurred in a biphasic manner. Although because of electromechanical delay it is difficult to determine precisely the point at which EMG activity is associated with mechanical effect, the data suggest that a burst of EMG activity in the deep multifidus was associated with movement in each direction in all subjects. Raw EMG data from a representative subject are shown in Figure 4. The time-locked averages of EMG for each muscle for a representative subject are shown in Figure 5, demonstrating two peaks in deep multifidus EMG activity. The deep multifidus demonstrated two peaks in all participants, whereas the superficial and lateral multifidus demonstrated two peaks in only three participants (Figure 6A). This difference was significant ($P = 0.02$). When the arm was moved repetitively in the sagittal plane from the start position with the arm flexed to 90°, a single peak in EMG activity was recorded for all muscles (Figure 6B). This burst of activity occurred consistently as the arm was flexed.

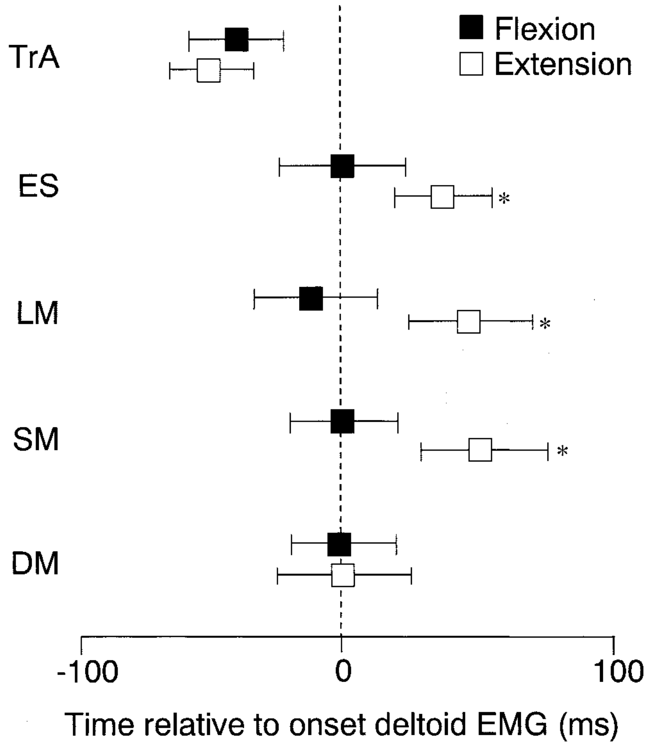

Figure 3. The mean latency of trunk muscle electromyographic (EMG) onset relative to that of deltoid EMG during flexion (filled squares) and extension (open squares) for eight subjects is shown. All the muscles were active in a feedforward manner. The asterisk (*) denotes a significant difference ($P < 0.05$) in relative onset latency between movement directions. Standard errors of the mean (SEM) are shown. Note that, unlike the other muscles, the onset of the TrA and deep multifidus EMG is not different between directions of upper limb movement.

■ Discussion

The results of the current study support the hypothesis that both the deep and superficial fibers of the multifidus are controlled differentially during movements of the arm that challenge the stability of the spine. The data are consistent with the biomechanical evidence that the superficial fibers of the multifidus act to control spine orientation, whereas the deep fibers of the multifidus control intersegmental motion.

The data from the single-movement trials add to a growing body of knowledge concerning anticipatory postural adjustments. The onset latency for all muscles relative to the deltoid, despite the fact that some occurred after deltoid onset, was too short for even the fastest reflex response to afferent input caused by arm or trunk movement,[2] and can therefore be considered feedforward activity, which is in agreement with the findings of others.[2,6,14,20,28] The erector spinae and the superficial and lateral fibers of the multifidus were active earlier relative to the deltoid during flexion than during extension. This supports previous data, but as expected, it is opposite the data on the superficial abdominal muscles.[2,6,8,20] Direction-specific activity is matched to the direction of reactive forces caused by limb movement

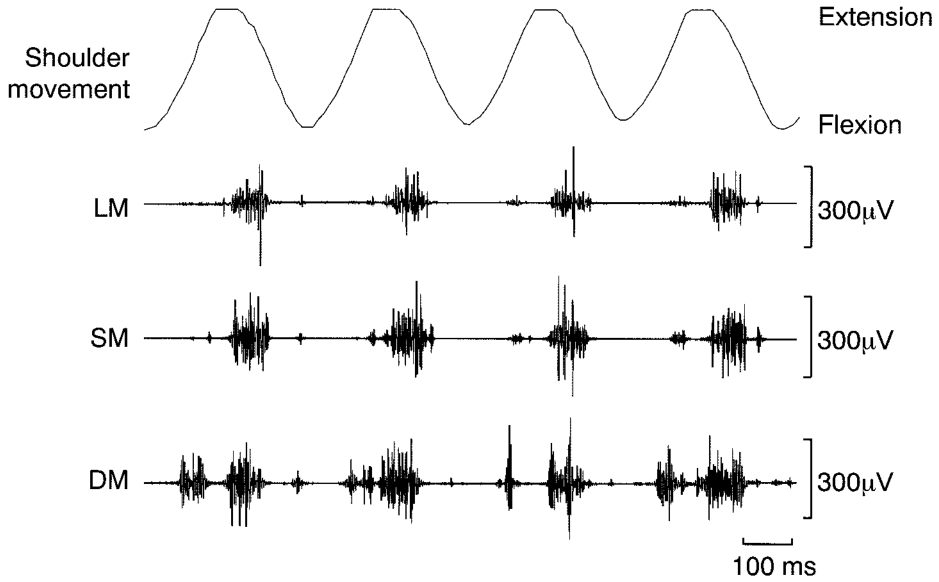

Figure 4. Raw electromyographic (EMG) and movement data from four movement cycles in a representative subject during repetitive arm movement with the arm by the side. The EMG from the deep (DM), superficial (SM), and lateral (LM) multifidus and shoulder movement are shown. Note that there are two bursts of EMG activity in deep fibers of the multifidus with each movement cycle.

and linked to the control of spine orientation[2,8,17] and the displacement of the center of mass.[2]

The data from the superficial fibers of the multifidus are consistent with the findings of several previous studies. Surface EMG, which is more likely to record from nearby superficial fibers, has demonstrated the greatest multifidus activity during extension and rotation of the vertebral column[11,22] or during resistance of lumbar flexion.[1] Electromyographic data obtained from intramuscular electrodes placed superficially in the multifidus also have showed direction-specific activity during standing trunk movements[30,32] and limb movements in prone subjects.[30,32]

In contrast to the superficial fibers, the EMG onset of the deep multifidus and TrA fibers was not altered temporally by movement direction. That is, the deep multi-

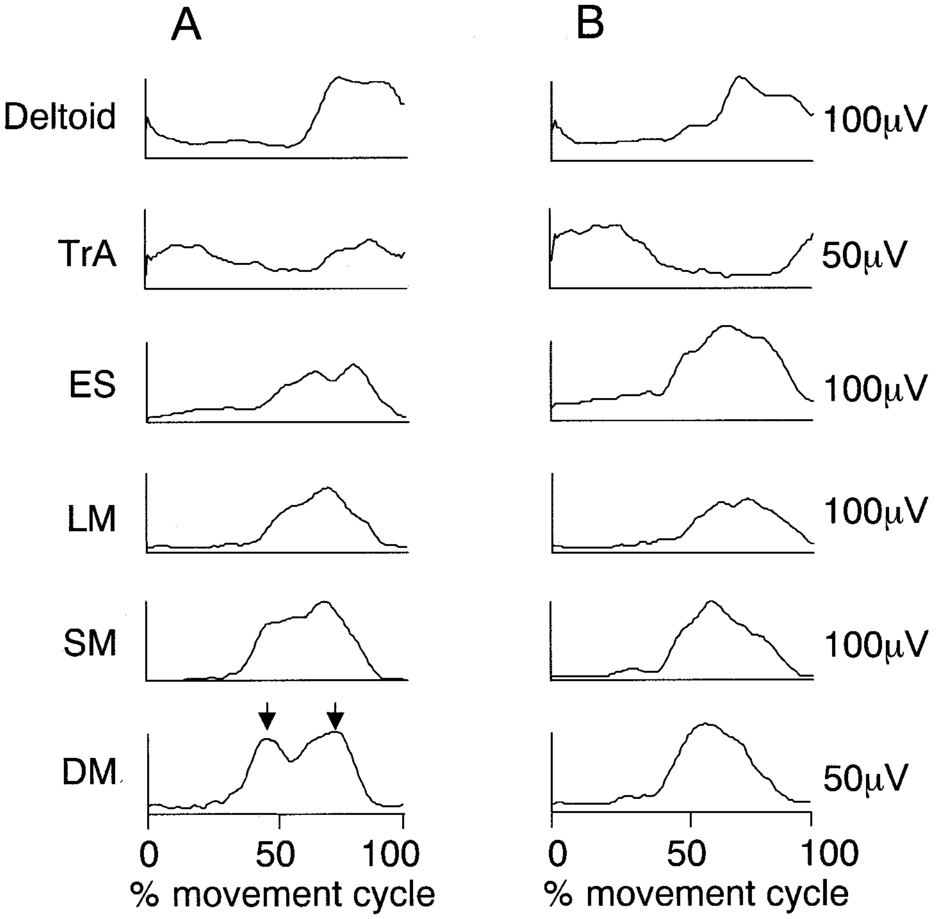

Figure 5. Time-locked averages of electromyography (EMG) in a representative subject for repetitive movement of the upper limb in the sagittal plane with the arm beside the body (**A**), and with the arm horizontal in front of the body (**B**). Note that unlike the other muscles, the deep fibers of the multifidus were active in a biphasic manner with movement beside the body (peaks denoted by vertical arrows) (**A**). However, the activity of all muscles had a single peak when the arm was moved repetitively in the horizontal position (**B**).

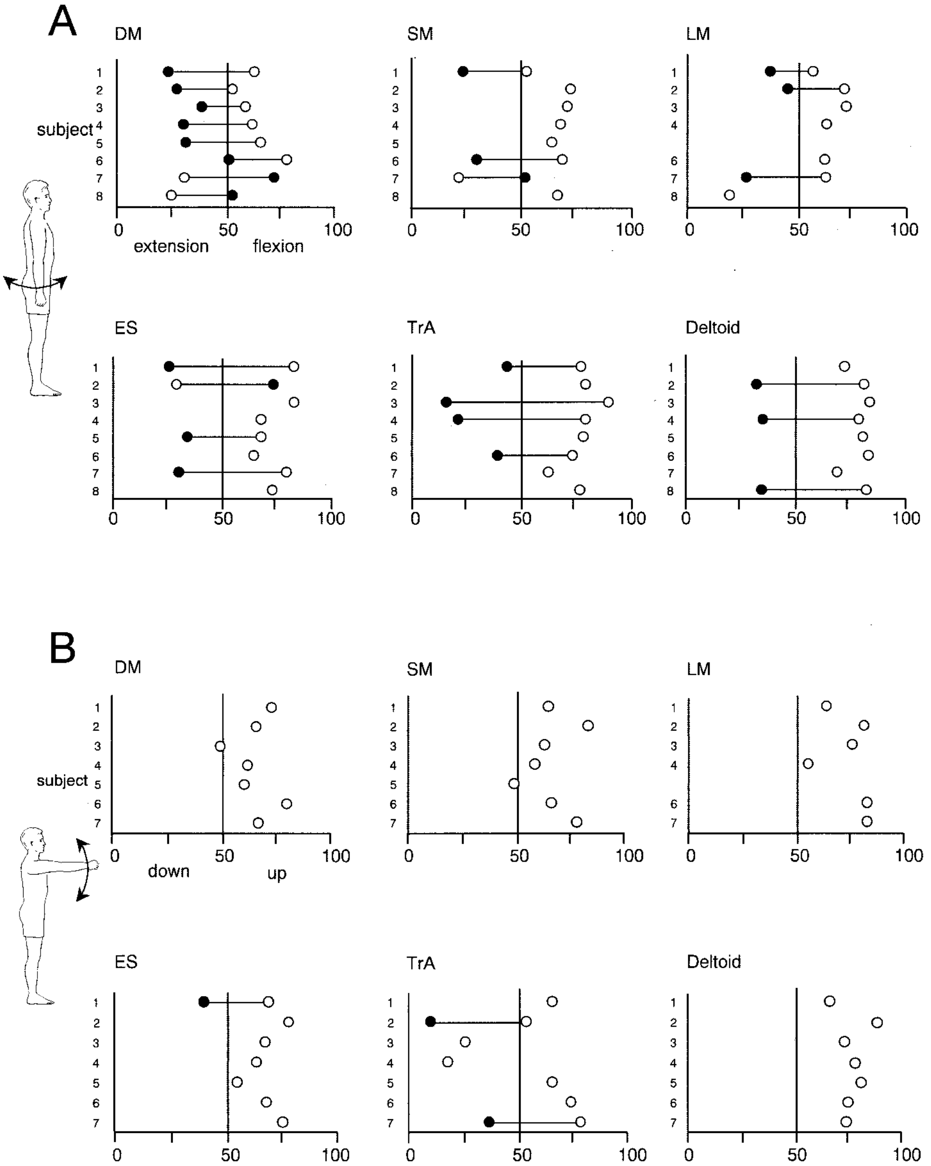

Figure 6. Times of peak electromyographic (EMG) activity identified from the time-locked EMG averages for each subject for movement of the upper limb in the sagittal plane with the arm beside the body (**A**), and with the arm at 90° flexion in front of the body (**B**). The open circles denote the highest peak, and the closed circles denote a second peak.

fidus and TrA demonstrated a non–direction-specific pattern of activity.[15,17,19] With repetitive arm movement, the deep multifidus is active with movement of the arm in both directions, even though the forces imposed on the spine are in the opposite direction. Whereas the superficial and lateral fibers of the multifidus and erector spinae occasionally demonstrated biphasic activity during repetitive movement about the neutral position (in fewer than 50% of trials), the deep multifidus demonstrated biphasic activity in all the participants, again suggesting that in this movement condition, activity of the deep multifidus is independent of reactive force direction, and may therefore control intersegmental motion.

One explanation for the functional distinction between the deep and superficial fibers of the multifidus may lie in the control of intervertebral shear and torsion through compressive force between segments. Because of their force vectors, the more superficial trunk muscles exert greater torque. If these muscles were recruited to control torsion and shear by increasing compression, then the component of their output that produces torque would need to be controlled. The resultant coactivation would result in an excessive energy and compressive "cost." In contrast, the deep trunk muscles exert minimal torque, which means that they can produce segmental compression with less resultant "cost." Furthermore, the segmental attachments of deep fibers provide flexibility, allowing the neuromuscular system to control individual segments.[31] An additional explanation may be related to the fiber-type composition of both the deep and superficial multifidus, given that a greater proportion of slow twitch muscle fibers exists in the deep multifidus.[21,36] According to the size principle of motoneuron recruitment,[12] it is possible that there is non–direction-specific input to both the deep and superficial multifidus, but that the input is not sufficient to reach the threshold for motoneurons innervating the superficial multifidus.

Interestingly, the deep multifidus becomes phasic during repetitive movement about 90° flexion, which is similar to the response of the other muscles. It appears that when reactive forces are aligned more vertically, in response to the direction of movement, the requirement that the deep multifidus contribute to the control of reactive forces with both movement directions is reduced. Other factors potentially related to the vertical reactive moments or displaced center of mass may provide control in the phase of movement for which the deep multifidus is inactive. The current data for the deep fibers of the multifidus concur with proposals based on muscle force vector analysis[5,31] or *in vitro* experiments,[39] providing the first *in vivo* evidence. Previous *in vivo* research has produced conflicting results, and although assertions of *in vivo* evidence have been made in the clinical literature,[4,34] they were based largely on an EMG study of multifidus activity during rotation, which identified bilateral activity and activity apparently unrelated to movement direction, but only in 12% and 28% of the subjects, respectively.[10]

There is little consensus as to the "normal" recruitment of the multifidus. The findings of current study suggest that this is the result of discrepant recording from deep and superficial fibers. Several methodologic issues are pertinent. First, intramuscular recordings of the multifidus have been made using nonselective electrodes with large receptive areas, large interelectrode distances,[1,10,25,32,40] and a resultant large pickup area.[1,25] Second, the placement of electrodes often is uncertain.[32,35,37,40] Third, many studies have investigated activity during functional movements, ignoring high variability in movement performance and evaluating the data with inexact qualitative techniques.[1,10,22,30,32,38] The current study used selective intramuscular electrodes inserted under ultrasound guidance, which permitted specific targeting of both the deep and superficial multifidus during controlled and relatively simple movement tasks. The findings support previous assertions of the difference in recordings gained from surface and intramuscular EMG electrodes.[40] Nonetheless, the current data for the deep multifidus is consistent with previous data from nonselective electrodes inserted approximately 30 mm, which showed slight to moderate EMG activity in the quiet standing position,[38] and from electrodes inserted approximately 40 mm,[40] which recorded continuous EMG activity during quiet standing and during subtle postural tasks such as cervical flexion and slow upper limb flexion.

■ Conclusion

The superficial fibers of the multifidus and erector spinae are controlled in a direction-specific manner, consistent with control of spine orientation. However, the deep fibers of the multifidus may have a role in the control of intersegmental rotational and shear forces, probably through the exertion of compressive force between segments. When the vertical forces associated with arm movement are increased, such as during movement about 90° flexion, there may be no requirement for the deep multifidus fibers to contribute to this end. Consequently, the deep multifidus is active in a similar fashion in relation to the other trunk muscles.

The current study raises possible implications for the study and treatment of back pain. Previous research has demonstrated robust abnormalities of TrA motor control, which contributes to spine stability in patients with back pain.[16,18] Other studies have reported changes in multifidus morphology,[13,33] which may affect the deep portion of the muscle. The deep multifidus is controlled in a manner similar to TrA in asymptomatic subjects, and also may contribute to the control of intervertebral motion. Therefore, investigation of deep multifidus activity in clinical populations is warranted.

■ Key Points

- Activity of the trunk muscles is initiated in advance of rapid arm movement, and these muscles may therefore act in an anticipatory way to control reactive forces associated with limb movement.
- The direction of reactive forces caused by movement of the arm is an important determinant of anticipatory activity of the superficial multifidus and erector spinae, but not that of the deep multifidus or transversus abdominis.
- The data from single- and repetitive-movement trials support the hypothesis that the deep fibers of the multifidus control intervertebral motion while the superficial fibers control spine orientation.
- During rapid arm movement with the arm horizontal, the deep multifidus is controlled in the same manner as the superficial trunk muscles.
- Surface and nonselective intramuscular EMG are not appropriate for recording the activity of the deep multifidus fibers.

References

1. Arokoski JP, Kankaanpaa M, Valta T, et al. Back and hip extensor muscle function during therapeutic exercises. Arch Phys Med Rehabil 1999;80:842–50.
2. Aruin AS, Latash ML. Directional specificity of postural muscles in feed forward postural reactions during fast voluntary arm movements. Exp Brain Res 1995;103:323–32.
3. Belen'kii V, Gurfinkel VS, Paltsev Y. Elements of control of voluntary movements. Biofizika 1967;12:135–41.
4. Bogduk N. Clinical Anatomy of the Lumbar Spine and Sacrum. Edinburgh: Churchill Livingstone, 1997:105.
5. Bogduk N, Macintosh JE, Pearcy MJ. A universal model of the lumbar back muscles in the upright position. Spine 1992;17:897–913.
6. Bouisset S, Zattara M. Biomechanical study of the programming of anticipatory postural adjustments associated with voluntary movement. J Biomech 1987;20:735–42.
7. Cholewicki J, Panjabi MM, Khachatryan A. Stabilizing function of trunk flexor-extensor muscles around a neutral spine posture. Spine 1997;22:2207–12.
8. Cordo PJ, Nashner LM. Properties of postural adjustments associated with rapid arm movements. J Neurophysiol 1982;47:287–302.
9. Crisco JJ, Panjabi MM. The intersegmental and multisegmental muscles of

the lumbar spine: a biomechanical model comparing lateral stabilizing potential. Spine 1991;16:793–9.

10. Donisch EW, Basmajian JV. Electromyography of deep back muscles in man. Am J Anat 1972;133:15–36.
11. Floyd WF, Silver PHS. Function of the erector spinae in flexion of the trunk. Lancet 1951;133–4.
12. Henneman E, Somjen G, Carpenter DO. Excitability and inhibitability of motoneurons of different sizes. J Neurophysiol 1965;28:599–620.
13. Hides JA, Richardson CA, Jull GA. Multifidus muscle recovery is not automatic after resolution of acute, first-episode low back pain. Spine 1996;21: 2763–9.
14. Hodges PW, Butler JE, McKenzie DK, et al. Contraction of the human diaphragm during rapid postural adjustments. J Physiol (Lond) 1997;505: 539–48.
15. Hodges PW, Richardson CA. Contraction of the abdominal muscles associated with movement of the lower limb. Phys Ther 1997;77:132–42, discussion 142–4.
16. Hodges PW, Richardson CA. Delayed postural contraction of transversus abdominis in low back pain associated with movement of the lower limb. J Spinal Disord 1998;11:46–56.
17. Hodges PW, Richardson CA. Feedforward contraction of transversus abdominis is not influenced by the direction of arm movement. Exp Brain Res 1997;114:362–70.
18. Hodges PW, Richardson CA. Inefficient muscular stabilization of the lumbar spine associated with low back pain: a motor control evaluation of transversus abdominis. Spine 1996;21:2640–50.
19. Hodges PW, Richardson CA. Relationship between limb movement speed and associated contraction of the trunk muscles. Ergonomics 1997;40: 1220–30.
20. Hodges PW, Richardson CA. Transversus abdominis and the superficial abdominal muscles are controlled independently in a postural task. Neurosci lett 1999;265:91–4.
21. Jorgensen K, Nicholaisen T, Kato M. Muscle fiber distribution, capillary density, and enzymatic activities in the lumbar paravertebral muscles of young men: significance for isometric endurance. Spine 1993;18:1439–50.
22. Joseph J, McColl I. Electromyography of muscles of posture: posterior vertebral muscles in males. J Physiol (Lond) 1961;157:33–7.
23. Kaigle AM, Holm SH, Hansson TH. Experimental instability in the lumbar spine. Spine 1995;20:421–30.
24. Lewin T, Moffett B, Viidik A. The morphology of the lumbar synovial joints. Acta Morphol Neerlanco Scand 1962;4:299–319.
25. Lindgren KA, Sihvonen T, Leino E, et al. Exercise therapy effects on functional radiographic findings and segmental electromyographic activity in lumbar spine instability. Arch Phys Med Rehabil 1993;74:933–9.
26. Macintosh JE, Bogduk N. The biomechanics of the lumbar multifidus. Clin Biomech 1986;1:205–13.
27. Macintosh JE, Valencia F, Bogduk N, et al. The morphology of the human lumbar multifidus. Clin Biomech 1986;1:196–204.
28. Massion J. Postural changes accompanying voluntary movements: normal and pathological aspects. Hum Neurobiol 1984;2:261–7.
29. McGill SM. Kinetic potential of the lumbar trunk musculature about three orthogonal orthopaedic axes in extreme postures. Spine 1991;16:809–15.
30. Morris J, Brenner F, Lucas D. An electromyographic study of the intrinsic muscles of the back in man. J Anat 1962;96:509–20.
31. Panjabi M, Abumi K, Duranceau J, et al. Spinal stability and intesegmental muscle forces: a biomechanical model. Spine 1989;14:194–200.
32. Pauly JE. An electromyographic analysis of certain movement and exercises: some deep muscles of the back. Anat Rec 1966;155:223–34.
33. Rantanen J, Hurme M, Falck B, et al. The lumbar multifidus muscle five years after surgery for a lumbar intervertebral disc herniation. Spine 1993;18: 568–74.
34. Richardson C, Jull G, Hodges P, et al. Therapeutic Exercise for Spinal Segmental Stabilization in Low Back Pain. London: Churchill Livingstone, 1999.
35. Sihvonen T. Flexion relaxation of the hamstring muscles during lumbar-pelvic rhythm. Arch Phys Med Rehabil 1997;78:486–90.
36. Sirca A, Kostevc V. The fibre type composition of thoracic and lumbar paravertebral muscles in man. J Anat 1985;141:131–7.
37. Travlos A, Trueman S, Eisen A. Monopolar needle evaluation of paraspinal musculature in the cervical, thoracic, and lumbar regions and the effects of aging. Muscle Nerve 1995;18:196–200.
38. Valencia FP, Munro RR. An electromyographic study of the lumbar multifidus in man. Electromyogr Clin Neurophysiol 1985;25:205–21.
39. Wilke HJ, Wolf S, Claes LE, et al. Stability increase of the lumbar spine with different muscle groups: a biomechanical *in vitro* study. Spine 1995;20: 192–8.
40. Wolf SL, Wolf LB, Segal RL. The relationship of extraneous movements to lumbar paraspinal muscle activity: implications for EMG biofeedback training applications to low back pain patients. Biofeedback Self Regul 1989;14: 63–74.

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