Research Report

Contraction of the Abdominal Muscles Associated With Movement of the Lower Limb

Background and Purpose. Activity of the trunk muscles is essential for maintaining stability of the lumbar spine because of the unstable structure of that portion of the spine. A model involving evaluation of the response of the lumbar multifidus and abdominal muscles to leg movement was developed to evaluate this function. **Subjects.** To examine this function in healthy persons, 9 male and 6 female subjects (mean age=20.6 years, SD=2.3) with no history of low back pain were studied. **Methods.** Fine-wire and surface electromyography electrodes were used to record the activity of selected trunk muscles and the prime movers for hip flexion, abduction, and extension during hip movements in each of those directions. **Results.** Trunk muscle activity occurring prior to activity of the prime mover of the limb was associated with hip movement in each direction. The transversus abdominis (TrA) muscle was invariably the first muscle that was active. Although reaction time for the TrA and oblique abdominal muscles was consistent across movement directions, reaction time for the rectus abdominis and multifidus muscles varied with the direction of limb movement. **Conclusion and Discussion.** Results suggest that the central nervous system deals with stabilization of the spine by contraction of the abdominal and multifidus muscles in anticipation of reactive forces produced by limb movement. The TrA and oblique abdominal muscles appear to contribute to a function not related to the direction of these forces. [Hodges PW, Richardson CA. Contraction of the abdominal muscles associated with movement of the lower limb. *Phys Ther.* 1997;77:132–144.]

Key Words: *Abdominal muscles, Feedforward postural reactions, Limb movement, Motor control, Spinal stability.*

Paul W Hodges

Carolyn A Richardson

Due to the inherently unstable structure of the spine,[1] there must be contributions from the muscular system to spinal stability that must be coordinated by the central nervous system (CNS). One method for the evaluation of this mechanism is the investigation of the response of the trunk muscles to perturbation of the trunk. Evaluation of the response to external perturbations such as support-surface movement[2] or the addition of a weight, dorsally or ventrally, to the trunk[3,4] provides useful information regarding the reflex response to the perturbation. In contrast, evaluation of the muscle response to a perturbation of the spine generated by the reactive forces produced by limb movement[5] provides information regarding how the CNS deals with spinal stability in advance of perturbation. The contraction of muscles associated with movement of a limb, other than those producing the movement, have been shown to contribute to the maintenance of both the position of the center of mass over the base of support and the stability of affected joints.[5,6] Consistent with this model, several authors have identified contraction of the rectus abdominis muscle (RA) and the erector spinae muscle (ES) in advance of upper-limb flexion[5,7] and extension.[6,7] This muscle activity, occurring prior to or shortly after the onset of activity of the prime mover of the limb, is referred to as "feedforward" because it cannot be initiated by feedback from the limb movement.[7]

Recent evidence indicates that the lumbar multifidus muscle (MF)[8] and transversus abdominis muscle (TrA)[3,9] may be involved in controlling spinal stability. Importantly, Cresswell and colleagues[3] found that the TrA contracted prior to the other abdominal muscles when the trunk was loaded by applying a weight ventrally to a harness over the shoulders. Furthermore, when the subjects applied the weight themselves by dropping a weight attached by a cord to the harness, the TrA was active prior to acceptance of the load. Although there is evidence that the TrA and the MF are important for controlling the stability of the spine, little is known of how the CNS controls these muscles when stability of the spine is challenged by limb movement when the exact magnitude and time of onset of the perturbation to the spine can be predicted by the CNS. Evaluation of activation of these muscles prior to the provision of this controlled and predictable challenge to spinal stability can provide insight into the CNS strategy for controlling the spine.

Studies[5–7,10] have evaluated only the feedforward muscular response to upper-limb movement. Due to the anatomical proximity and functional interrelationship between the hip and spine,[11] however, we considered evaluation of movement of the lower limb to be more appropriate for investigation of control of the lumbar spine. Evaluation of movement of a lower limb in a

PW Hodges, BPhty(Hons), is a doctoral candidate, Department of Physiotherapy, The University of Queensland, Brisbane, Queensland, Australia 4072 (hodges@physio.therapies.uq.oz.au). Address all correspondence to Mr Hodges.

CA Richardson, PhD, BPhty(Hons), is Senior Lecturer, Department of Physiotherapy, The University of Queensland.

This research was approved by the Medical Research Ethics Committee of The University of Queensland.

This research was supported by the Menzies Foundation, the Physiotherapy Research Foundation, the Dorothy Hopkins Clinical Research Award, and the Manual Therapy Group of the Australian Physiotherapy Association.

This article was submitted October 27, 1995, and was accepted October 7, 1996.

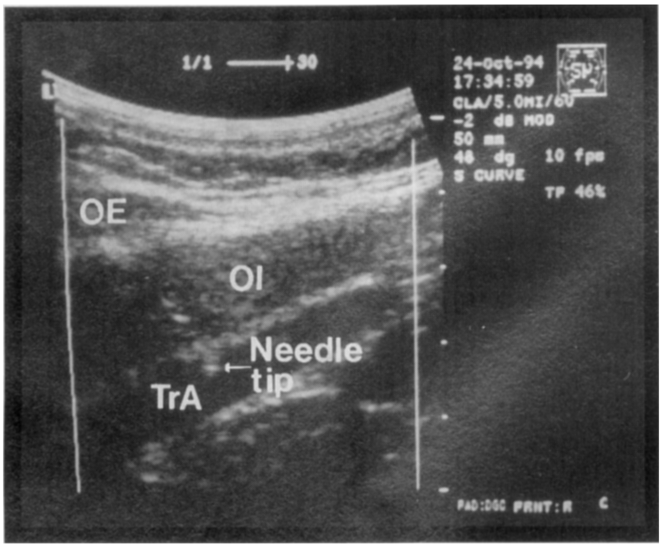

Figure 1.
Transverse ultrasound image of the abdominal wall just distal to the rib cage showing the transversus abdominis muscle (TrA), the obliquus internus abdominis muscle (OI), and the obliquus externus abdominis muscle (OE). Note the high-contrast oblique echo of the needle with the needle tip located in the muscle belly of the TrA. The origin of the needle is not observable in this image. The white lines on either side of the image are indicators of image intensity.

standing position is complex because with movement of a supporting limb, the body is required to deal with two distinct challenges to postural equilibrium. The first challenge is related to displacing the center of mass over the new base of support, and the second challenge is concerned with defending this new equilibrium position against the perturbation produced by the movement. The body deals with this challenge by shifting the weight over the nonmoving leg prior to movement of the limb.[12] To facilitate investigation of the control of the spine against the reactive forces produced by the limb movement, it is necessary to remove the weight-shift component of the task. If removal of this component is not satisfactorily achieved, then it is impossible to identify whether the muscle activity recorded is (1) related to controlling the spine against the forces produced by movement or (2) involved in the establishment of the new equilibrium position to allow the movement to be performed.

Any attempt to limit the requirement for weight shift by supporting the body is inappropriate because associated postural adjustments are greatly reduced by increasing the stability of a position.[13] Therefore, a paradigm was developed involving completion of the weight-shift component (by moving the center of mass over the nonmoving lower extremity) prior to provision of a stimulus to move the contralateral limb. Although this position is not essentially functional, use of a model such as this is necessary to identify the muscle response initiated by the CNS to counteract the perturbation to the spine produced by limb movement.

The aim of this study was to evaluate the sequence of activation of the abdominal muscles and the MF during the performance of hip movement following prior weight shift over the supporting limb. Consistent with the findings of Cresswell et al,[3] we hypothesized that the TrA would be active prior to the other trunk muscles and the prime mover of the limb. Furthermore, several directions of movement were used to determine whether the sequence of activation was influenced by the direction of the reactive forces.

Method

Subjects

Fifteen subjects (9 male, 6 female) participated in the study. The subjects had a mean age of 20.6 years (SD=2.3, range=18–25), a mean height of 1.74 m (SD=0.09, range=1.58–1.87), and a mean weight of 69 kg (SD=11, range=55–87). Subjects were excluded if they had any history of low back pain, lower-limb pathology, scoliosis producing rib elevation of greater than 8 mm or lumbar prominence of greater than 5 mm in trunk flexion as described by Vercauteren et al,[14] or leg-length discrepancy greater than 3 cm, each of which may have altered muscle recruitment. Subjects were also excluded if they had regular involvement in a competitive sport involving training of greater than three times per week, which may have produced learned patterns of muscle recruitment. The rights of the subjects were protected at all times, and all subjects gave informed consent to participate.

Electromyographic Recordings

Electromyographic (EMG) activity was recorded from the left TrA, the obliquus internus abdominis muscle (OI), the obliquus externus abdominis muscle (OE) and the posterior fibers of the gluteus medius muscle (PGM) using bipolar fine-wire electrodes, which were fabricated from 75-μm Teflon®*-coated stainless steel wire† with 1 mm of Teflon® removed. The electrodes were threaded into hypodermic needles (0.7×38 mm) and inserted under the guidance of real-time ultrasound imaging‡ using a 5-MHz sound head (Fig. 1) in order to confirm the accuracy of placement. Anesthetic EMLA cream§ was applied externally to minimize the cutaneous sensation of needle insertion. Following insertion, the

* Du Pont de Nemours & Co Inc, 1007 Market St, Wilmington, DE 19898.
† A-M Systems Inc, 1220 75th St SW, Everett, WA 98203.
‡ Advanced Technology Laboratories, 22100 Bothel Hwy SE, Bothel, WA 98041-3003.
§ Astra Pharmaceuticals Pty Ltd, 10 Khartoum Rd, North Ryde, New South Wales, Australia 2113.

needles were removed, leaving the wires in place. The technique has been described elsewhere.[9,15]

Insertion of the electrodes was supervised by an experienced medical practitioner. Sites used for the placement of the electrodes were determined in relation to bony landmarks. The electrode for the TrA was inserted 2 cm medial to the proximal end of a line projected vertically from the anterior superior iliac spine (ASIS) to the rib cage, the electrode for the EO was inserted halfway between the iliac crest and the caudal border of the rib cage in the midaxillary line, and the electrode for the OI was inserted 3 cm medial and superior to the ASIS. The electrode for the PGM was inserted 3 cm lateral and 2 cm inferior to the left posterior superior iliac spine.[16] Electrode placement was checked by ultrasound visualization of movement of the wire during gentle traction and through monitoring the EMG trace during performance of a series of maneuvers designed to preferentially activate each of the muscles.

Pairs of silver-silver chloride surface electrodes were used to record the activity of the left RA and MF and the right rectus femoris, tensor fasciae latae, and gluteus maximus muscles as the prime movers of flexion, abduction, and extension of the hip, respectively. The electrodes were positioned parallel to the muscle fibers with an interelectrode distance of 12 mm following careful skin preparation to reduce the skin impedance to below 5 kΩ. The electrode for the RA was placed midway between the umbilicus and the pubic symphysis close to the midline in a cephalolateral direction, and the electrode for the MF was located 2 cm adjacent to the spinous process at the L4–5 interspace. This location was selected for the recording of MF activity because the bulk of the MF is superficial at this level and the influence of cross talk from the ES would be reduced. The electrodes over the lower-limb muscles were placed centrally over the muscle bellies following palpation of a resisted isometric contraction. The ground electrode was placed over the right ASIS. Pilot studies were conducted to identify any difference in EMG onset detected by fine-wire and surface electrodes. No difference in EMG onset time was identified, and representative data for one muscle (tensor fasciae latae) are presented in Figure 2.

All EMG signals were sampled at 2,000 Hz and band-pass filtered between 20 and 1,000 Hz using an AMLAB workstation.[||] Data were stored on disk for later analysis.

[||] Associative Measurement Pty Ltd, Unit 5B, 112–118 Talavera Rd, North Ryde, New South Wales, Australia 2113.

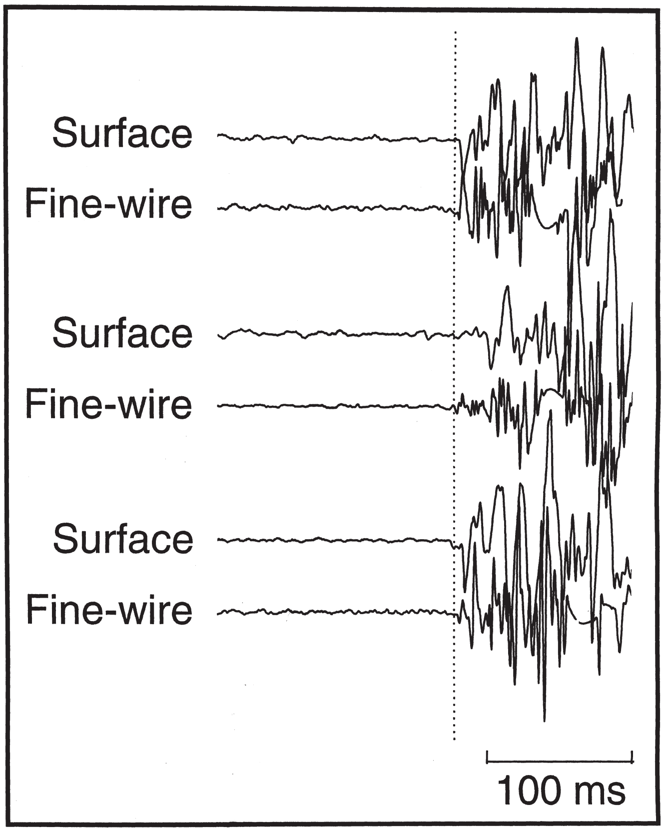

Figure 2.
Representative raw electromyographic (EMG) signals of the tensor fasciae latae muscle measured with fine-wire electrodes and surface electrodes during abduction of the hip. The time of onset of EMG activity measured with the fine-wire electrodes is marked with the dotted line. Note that no difference in onset of EMG activity is present between electrode types. For this evaluation, the fine-wire electrode was placed between the two surface electrodes. Note the difference in character of the surface and fine-wire electrodes due to the low-pass filtration of the signal detected with the surface electrodes by the subcutaneous tissues.

Procedure

The study involved the identification of the sequence of contraction of the trunk and limb muscles during hip flexion, abduction, and extension. All movements were made with the subjects in the standing position. In order to move the right lower extremity, the subjects were requested to completely shift their weight onto the left lower extremity prior to each repetition so that the right foot was free to move and was just in contact with the floor without bearing weight. Although the main criterion used to ensure complete weight shifting was the verbal report by the subject, two additional factors assured us that weight shifting was performed in a consistent manner. First, EMG activity of the left PGM was observed to increase when weight shifting was performed, although this increase did not indicate that weight shifting was complete. A further indication that weight shifting was incomplete was the identification of resting activity in the rectus femoris muscle of the right lower extremity prior to movement. Activity in this muscle suggested that weight was being supported by the lower extremity. If any factor indicating that weight shifting was incomplete was observed, the subjects were requested to shift their weight further until no weight was borne by the right lower extremity.

Subjects were trained to shift their weight by horizontally gliding their pelvis while preventing any flexion, extension, or lateral flexion of the trunk. The majority of subjects used this as their strategy for weight shifting and did not require further training. Although not measured as part of the analysis, we observed that all subjects were able to perform the weight shift in a consistent manner. The starting position of the right foot, in line with the left foot, was controlled by placing the right foot with light contact against a switch placed behind the heel using just enough force to activate the switch.

The trial took the form of a standard reaction-time task with a visual warning stimulus preceding a visual movement stimulus by a random period of between 0.5 and 4 seconds. Weight shifting occurred prior to the warning stimulus. If the examiner observed excessive activity on the EMG trace of any muscle, the subjects were asked to relax their posture while maintaining the single-leg stance position. On the stimulus to move, the subjects were instructed to respond as quickly as possible and move as fast as possible to approximately 20 degrees in the specified direction, with emphasis on the speed of movement and not the distance moved. Ten repetitions each of hip flexion, abduction, and extension were performed. The order of each set of 10 repetitions in each direction was randomized, and the sets were separated by a 5-minute break, during which the subjects were seated. Equal weight bearing was adopted between repetitions. For the performance of each movement, the subjects were instructed to isolate the movement to their hip joint without contribution of their trunk or flexion of the knee. Trials in which trunk movement was obvious or balance was compromised were excluded from the analysis, and an additional repetition was performed.

Due to the role of the TrA in respiration,[15] the stimulus to move was timed to coincide with the end of expiration. In order to achieve this timing, the examiner continually monitored the subjects' breathing cycle by observation of the chest wall and abdominal movement. The warning stimulus was given at random during the cycle, and the stimulus to move was illuminated just prior to the end of expiration. The subjects were not informed of this coordination of the stimuli and phase of respiration.

Data Analysis

The onset of EMG activity was determined by MATLAB mathematical processing software* using an algorithm adapted from Di Fabio[17] denoting the time of onset of EMG activity as the point at which the mean of 50 consecutive samples deviated more than three standard deviations from the mean baseline activity recorded for the 50 milliseconds prior to the warning stimulus. Prior to processing, the EMG signals were filtered with a 50-Hz elliptical sixth-order low-pass filter. The computer-derived onset times were all checked visually to confirm their accuracy and ensure that the onset of the EMG burst was not obscured by the appearance of an electrocardiogram signal or movement artifact.

Both the premotor reaction time (ie, time from stimulus to onset of EMG activity) and the time delay between the onset of EMG activity of the prime mover of the limb and that of the trunk muscle (ie, relative latency) were evaluated. In pilot studies, we found that the movement of the limb was delayed between 30 and 114 milliseconds after the onset of EMG activity of the prime mover of the limb. Due to the time required for nerve conduction and synaptic transmission, the earliest reflex response to the movement cannot occur less than 50 milliseconds after the onset of EMG activity of the prime mover of the limb. On this basis, we concluded that any EMG activity of the trunk muscles occurring either before the onset of EMG activity of the prime mover or less than 50 milliseconds after the onset of EMG activity of the prime mover could not be reflexly mediated and thus could be regarded as feedforward. These criteria are consistent with previous reports.[7]

The intent of the statistical analyses was to identify any differences in the timing variables between the trunk muscles for each movement independently and for each muscle between movements. The reaction time and relative latency of each of the trunk muscles and the prime mover were compared for each movement and for each muscle between movements using a one-way analysis of variance to identify any differences that existed. The specific differences were then calculated using a Duncan's multiple-range test, with the significance level set at $\alpha=.05$. All analyses were conducted using SAS statistical software.**

Results

Hip Flexion

Rapid flexion of the hip in response to a visual stimulus following completion of weight shifting resulted in the onset of EMG activity of all of the recorded muscles of

* The Math Works Inc, 24 Prime Park Way, Natick, MA 01760.
** SAS Institute Inc, PO Box 8000, Cary, NC 25711.

Table.
Mean Premotor Reaction Times (RT) and Relative Latencies (LAT) for All Muscles and *F* Values for Analysis of Variance Comparing the Reaction Times of All Muscles for Each Movement

	Flexion		Abduction		Extension	
Muscle[a]	**RT**	**LAT**	**RT**	**LAT**	**RT**	**LAT**
PM						
$\bar{X}$	225		172		218	
SEM	8		10		49	
Range	165–284		120–261		135–297	
TrA						
$\bar{X}$	112	−113	103	−70	120	−97
SEM	6	7	7	8	25	10
Range	71–148	−188–87	69–153	−131–29	87–165	−191–25
OI						
$\bar{X}$	154	−75	131	−43	155	−64
SEM	10	12	9	10	61	17
Range	107–214	−131–16	83–307	−115–28	97–360	−199–104
OE						
$\bar{X}$	215	−11	174	0	186	−32
SEM	16	17	19	22	61	17
Range	139–379	−93–138	82–327	−109–181	83–279	−165–85
RA						
$\bar{X}$	184	−41	144	−27	150	−69
SEM	11	11	7	7	53	14
Range	118–279	−92–67	91–188	−99–14	92–266	−179–65
MF						
$\bar{X}$	158	−67	176	4	216	−2
SEM	13	14	13	11	49	10
Range	107–275	−134–65	118–307	−60–91	155–311	−95–54
F^b	18.38	19.21	10.82	11.14	15.33	15.25

[a] PM=prime mover, TrA=transversus abdominis muscle, OI=obliquus internus abdominis muscle, OE=obliquus externus abdominis muscle, RA=rectus abdominis muscle, MF=multifidus muscle, SEM=standard error of the mean.
[b] df=14,5; P<.001.

the trunk, except the OE, prior to the onset of rectus femoris muscle EMG activity (Table). Representative subject data are presented in Figures 3 and 4. The TrA was invariably the first muscle that was active, and its onset of EMG activity was earlier than that of each of the other trunk muscles, preceding the onset of EMG activity of those muscles by 42 to 104 milliseconds. No differences in reaction time or relative latency existed between the OI, MF, and RA or between the RA and OE. Because the onset of EMG activity of each of the muscles occurred either before or less than 50 milliseconds after the onset of EMG activity of the rectus femoris muscle, the relative latency of each of the muscles was within our criteria for feedforward activation.

Hip Abduction

When the hip was abducted, only the onset of EMG activity of the TrA and the OI was earlier than that of the prime mover (the tensor fasciae latae muscle) (Table, Figs. 3 and 4). The differences between the onset of EMG activity of the tensor fasciae latae muscle and that of the remaining trunk muscles (RA, OE, and MF) were not significant. The relative latency of all of the trunk muscles was within our criteria for feedforward activation. The TrA was active earlier than all other trunk muscles, except the OI, by 40 to 72 milliseconds. There were no differences in reaction time or relative latency between the OI and RA, the RA and OE, or the MF and OE.

Hip Extension

Hip extension was associated with onset of EMG activity of the TrA, RA, and OI prior to that of the gluteus maximus muscle (Table, Figs. 3 and 4). The reaction time of the OE and MF was not different from that of the gluteus maximus muscle. All muscles were active within our criteria for feedforward activation. No difference in relative latency or reaction time occurred between the TrA and RA or among the RA, OI, and OE. The onset of EMG activity of the TrA preceded that of the OI, OE, and MF by 35 to 96 milliseconds.

Comparison Among Movements

With movement of the hip, the reaction time and relative latency of several muscles were found to vary among directions. The reaction time of the prime mover of the lower limb varied among movement directions (F=12.57; df=14,2; P<.001). The reaction time of the prime mover was faster during hip abduction than during either hip flexion or hip extension. There was no difference between the two sagittal-plane movements.

Of the trunk muscles, only the RA (F=4.41; df=14,2; P<.02) and the MF (F=5.78; df=14,2; P<.01) were different among movement directions. The RA had a shorter reaction time associated with hip extension compared with the other directions of movement. In contrast, the trunk extensor, the MF had a longer reaction time associated with hip extension compared with the other two directions of movement. The reaction times of the TrA (F=2.28; df=14,2; P=.12), the OI (F=1.38; df=14,2; P=.27), and the OE (F=1.74; df=14,2; P=.19) failed to vary among movements in different directions. This consistency of reaction time across movement directions of the TrA, OI, and OE was apparent for all subjects.

Because the reaction time of the prime mover was different among movement directions, it was important to determine whether the relationship between the trunk muscles and the prime mover remained constant among limb movement directions, that is, whether the relative latency remained constant among movement directions. The relationship between the prime mover and the trunk muscles was not consistent for the TrA (F=8.06; df=14,2; P<.002), the RA (F=3.54; df=14,2; P<.05), or the MF (F=10.75; df=14,2; P<.001) (Fig. 5). The TrA had a shorter relative latency for hip abduction than for the other directions of movement. The relative latency for the MF was longer for hip flexion than for the other movements, and the relative latency for the RA was longer for hip extension than for the other two movements. The relative latency for the other muscles was not different among movements: OE (F=0.76; df=14,2; P=.48), OI (F=1.55; df=14,2; P=.23) (Fig. 5).

Discussion

Feedforward Abdominal Activation With Movement of a Lower Limb

The results of the study confirm the hypothesis that the TrA is invariably the first muscle that is active during movement of a lower limb following contralateral weight shifting. This finding is consistent with the results of the previously mentioned trunk loading study of Cresswell and colleagues.[3] Because the contraction of this muscle occurs prior to movement of the limb, the TrA can be considered to be involved in the preparation of the body for the disturbance produced by the movement. In association with the contraction of the TrA, feedforward activation of each of the other abdominal muscles and the MF was recorded for movement in each direction. Although no studies have evaluated trunk muscle response to lower-limb movement, the previously mentioned studies indicating ES and RA contraction with upper-limb movement[5–7,10] are consistent with this finding. Evaluation of the OE with upper-limb movement has been limited to movements performed in a seated position.[18] This position resulted in the OE being active after the prime mover in the majority of trials, in contrast to the results of our study.

Direct comparison between our findings for the developed lower-limb movement model and those of previous upper-limb studies is limited to the response of the RA. The period between the onset of EMG activity of the RA and that of the prime mover was greater in our study than has been reported previously for the upper limb (10–30 milliseconds).[6,7,10] Increased limb speed,[19] increased limb mass,[20] and decreased postural stability[13] have been shown to increase the latency between the onset of EMG activity of the postural muscles and that of the prime mover. The larger mass of the lower limb and the reduced base of support when a lower limb is moved may explain the difference between the results of our study and those of previous studies of upper-limb movements.

Direction-Specific Changes in Timing of Onset of Electromyographic Activity

Changes in the direction of movement of the limb result in corresponding changes in the direction of associated reactive forces. Flexion of the upper limb produces forces acting on the center of mass in an inferior and posterior direction.[21] Although the biomechanical effect of the limb movement on the trunk was not evaluated, we would expect the forces associated with lower-limb flexion to be equal to and opposite in direction to the forces producing the movement. These forces would result in movement of the center of mass of the body in a superior and posterior direction, potentially causing the trunk to flex and to rotate toward the moving limb. The earlier contraction of the MF (a trunk extensor) in flexion compared with extension is consistent with the need to control the trunk flexion moment and to maintain the position of the center of mass within the base of support. Conversely, the reaction of the RA is faster with hip extension than with hip flexion. This finding is consistent with the need to control the imposed trunk extension moment.

The failure of the reaction time of the TrA, OE, and OI to change with movement direction indicates that the contraction of these muscles is not influenced by the direction of the reactive forces. Although contraction of the OE and OI may control extension and rotation of the trunk and it has been suggested that the TrA contributes to the production of rotation,[9] the failure of

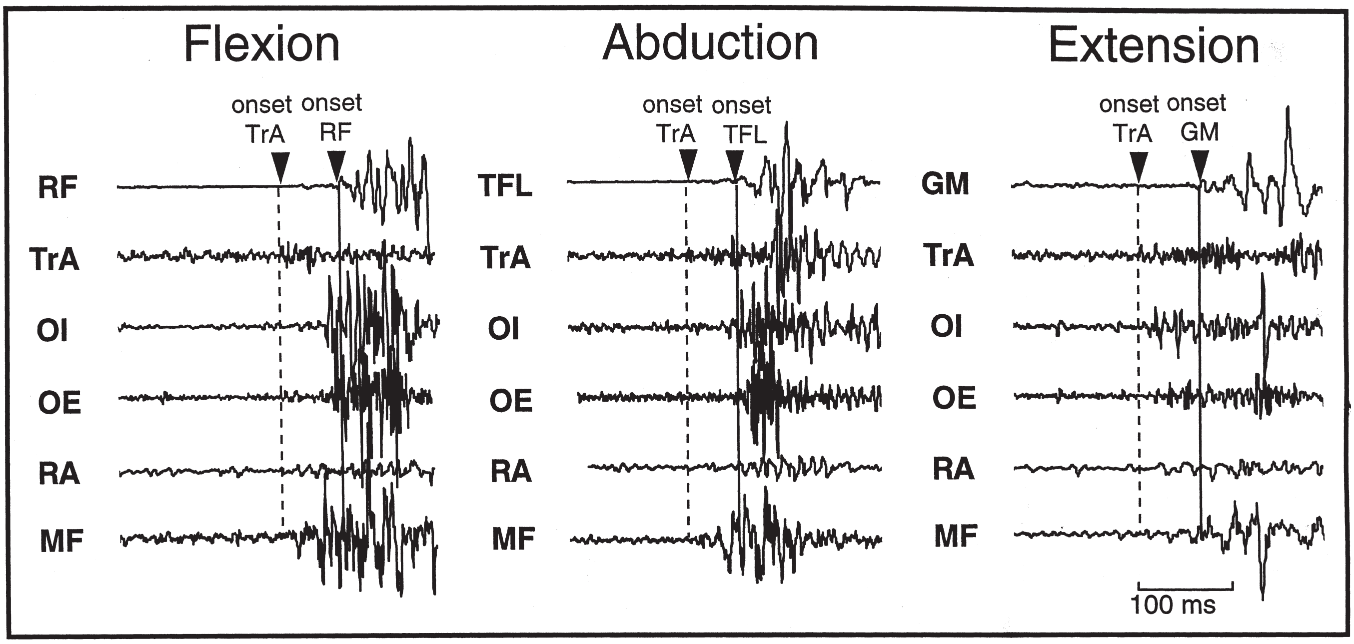

Figure 3.
Electromyographic data of a single trial of a representative subject for all muscles for lower-limb movement in different directions. The time of alignment of the traces at the onset of electromyographic (EMG) activity of the prime mover is noted by the solid vertical line. The onset of EMG activity of the transversus abdominis muscle (TrA) is noted by the dashed vertical line. Note the onset of EMG activity of the TrA prior to that of the prime mover and the other trunk muscles. Note also the change in sequence of activity of the rectus abdominis muscle (RA) and the multifidus muscle (MF) as a function of limb movement direction. Electromyographic activity is expressed in arbitrary units. RF=rectus femoris muscle, OI=obliquus internus abdominis muscle, OE=obliquus externus abdominis muscle, GM=gluteus maximus muscle.

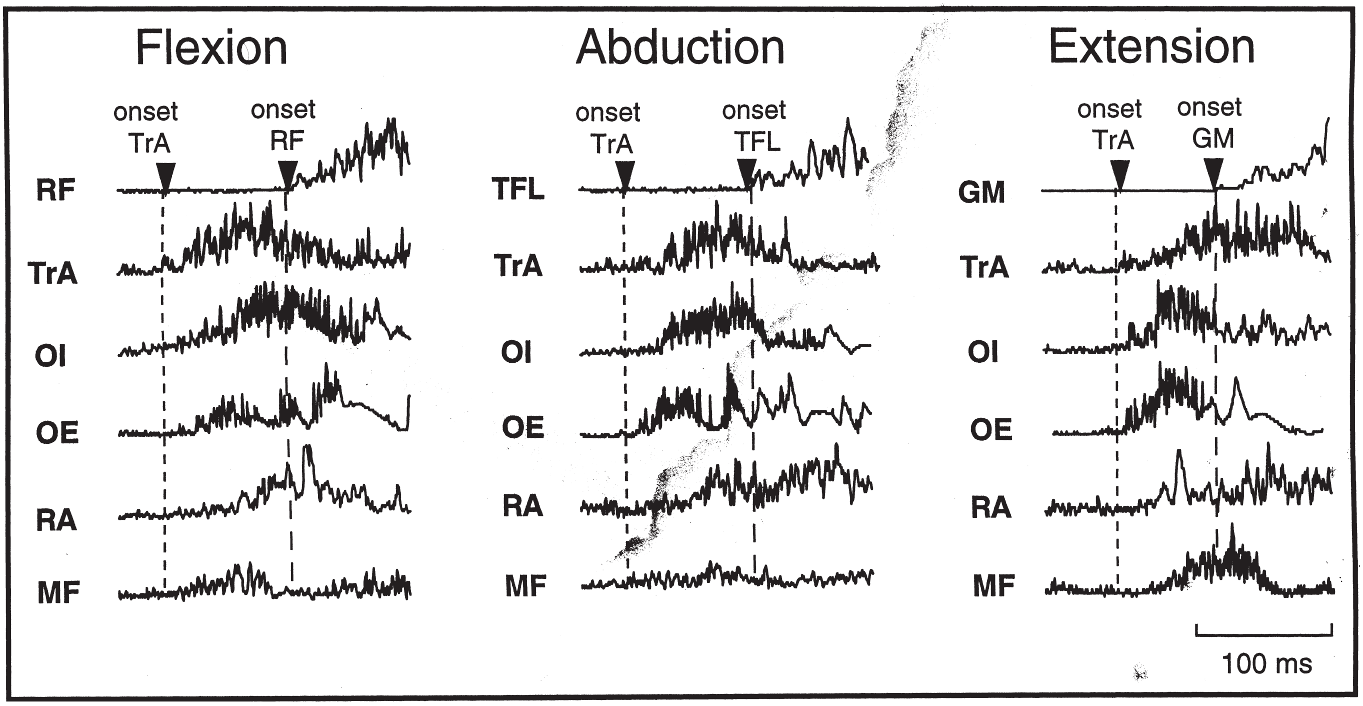

Figure 4.
Electromyographic (EMG) data of a representative subject (different subject than subject represented in Fig. 3) for all muscles averaged over 10 repetitions of shoulder movements in different directions. The time of alignment of the traces at the onset of EMG activity of the prime mover is noted by the heavy dashed vertical line. The onset of EMG activity of the transversus abdominis muscle (TrA) is noted by the light dashed vertical line. Note the onset of EMG activity of the TrA prior to that of the prime mover and the other trunk muscles. Note also the change in sequence of activity of the rectus abdominis muscle (RA) and the multifidus muscle (MF) among movement directions. The early activity of obliquus externus abdominis muscle (OE), RA, and MF in this subject with hip abduction is not representative of the subject group. Electromyographic activity is expressed in arbitrary units. RF=rectus femoris muscle, OI=obliquus internus abdominis muscle, GM=gluteus maximus muscle.

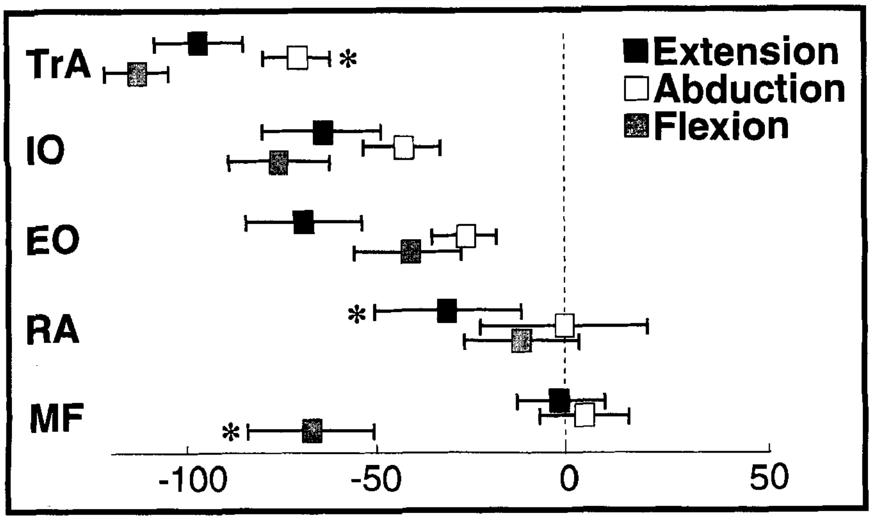

Figure 5.
Mean time of onset of electromyographic (EMG) activity of each of the trunk muscles relative to that of the prime mover for all subjects (N=15) for movement in each direction. All bars are aligned to the onset of EMG activity of the prime mover at zero. The midpoint of each box indicates the group mean time of onset of EMG activity of the muscles of the trunk. Standard errors of the mean are indicated. Note the high variability and the different onsets of EMG activity of the rectus abdominis muscle (RA), the multifidus muscle (MF), and the transversus abdominis muscle (TrA) among movement directions. Asterisk (*) indicates $P<.05$. OI=obliquus internus abdominis muscle, OE=obliquus externus abdominis muscle.

vary between movement directions, however, may be due to the high demands associated with the experimental model, which would greatly challenge the stability of the spine. Further investigation is needed to determine whether this is the case for all types of movement. Interestingly, the onset of EMG activity of the TrA relative to that of the prime mover of the limb was different between limb movement directions. This difference, however, was due to changes in the reaction time of the prime mover and not the TrA.

Methodological Considerations

The main consideration of methodology of our study is the validity of the division of the movement of a supporting limb into the weight-shifting and movement phases. Techniques such as completion of the weight-shifting component prior to provision of the stimulus to move have not been required in the past because the majority of research has focused on the initial weight-shifting component.[12,19,24–28] Recently, Béraud and Gahéry[29] attempted to evaluate the movement phase. These reseachers, however, considered the postural adjustments associated with weight shifting and limb movement together. Isolation of the components of the movement, such as that performed in our study, is essential to investigate the response to a perturbation generated by movement of the lower limb.

The limb movement used in our study was not performed in a functional manner. The results of our study, however, provide important information regarding the activity of the abdominal muscles in response to a perturbation produced by movement of a limb. During normal functional limb movement (eg, during gait), the reactive forces from the limb movement would also act on the trunk. The strategy for control of these forces, however, would be influenced by other factors such as the requirement for motion of the trunk in gait, variation in the speed of movement, and variation in the accuracy of foot placement. In terms of upper-limb movement, variation in the sequence of muscle activity has been reported to occur with influences such as the amount of practice,[30] behavioral factors,[31] and the speed of limb movement.[20] Clearly, evaluation of functional activities is required to evaluate how the mechanism identified using our model is modified in different situations.

these muscles to vary their onset of EMG activity in line with the variation in direction of the reactive forces and movement of the center of mass relative to the base of support suggests that these muscles may be involved in the control of some other variable that is not direction specific. Previous researchers have suggested that the TrA and OI, particularly the lower fibers that have a horizontal orientation, may contribute to the enhancement of the stability of the spine, either through their role in the production of intra-abdominal pressure[9] or via increasing the tension in the thoracolumbar fascia[22] through which these muscles are attached to the lumbar vertebrae.[23] Each of these mechanisms has the potential to enhance the stiffness of the spine in a general manner and not specific to any direction. The results of our study are consistent with this hypothesis.

The OE, although less efficient than the TrA and OI,[9] may contribute to the production of intra-abdominal pressure and thus the stability of the spine. We believe that the effect of these muscles would be optimal if the contraction were bilateral to prevent rotation produced by these muscles and to assist with the production of intra-abdominal pressure and fascial tension. Further studies are needed to evaluate the response of the abdominal muscles bilaterally. The contraction of the OE and OI was not influenced by movement direction, which was an unexpected finding because these muscles have a major role in the production of trunk flexion and rotation. This failure of contraction of the OE and OI to

A limitation of the study was that maintenance of the stability of the position and consistency of movement performance were not measured. For the performance of our study, importance was placed on clear instructions to the subjects, thus ensuring that the objective of each component of the task was understood. Furthermore, subjects were trained to perform weight shifting and movements in a consistent manner, the evaluation of which was assisted by evaluation of indirect measures such as the detection of activity of the PGM and identification of activity of the rectus femoris muscle for recognition of incomplete weight shifting. Analysis of ground reaction forces and three-dimensional movement analysis would have enhanced the detection of slight variations that may have occurred undetected with the current methodology. Despite this concern, however, the sequence of muscle activity reported was largely consistent for all subjects tested.

Conclusion

This study provides evidence that the CNS initiates contraction of the abdominal muscles and the MF in a feedforward manner in advance of the prime mover of the lower limb. The TrA, a muscle largely ignored in the literature, was invariably the first muscle that was active. Furthermore, the onset of EMG activity of the TrA, OI, and OE was not influenced by the direction of movement of the limb and, therefore, the associated reactive forces. We propose that the contraction of these muscles is linked with the control of stability of the spine against the perturbation produced by the movement of the limb. Therapists should consider the function of these deep muscles, particularly the TrA, when attempting to train patients to control trunk stability. Finally, the developed model has provided a controlled evaluation of the strategy used by the CNS to prepare the spine for a challenge to stability produced by the movement of a limb for which the time of onset and magnitude of the perturbation are known to the CNS. This model provides a means to evaluate one component of the motor control of trunk stability in people who have low back pain.

Acknowledgments

We thank Dr David Cooper for the assistance with the development of the fine-wire electrode insertion technique, Dr Kieran Frawley and Dr Adam Toneki for supervising the needle insertion, Professor Simon Gandevia for useful discussion and revision of the article, Associate Professor Gwendolen Jull for discussion of ideas, Mr Bang Bui for technical assistance and development of the timing analysis program, and Mr Ivor Horton for statistical advice.

References

1 Panjabi MM. The stabilizing system of the spine, part I: function, dysfunction, adaptation, and enhancement. *J Spinal Disord.* 1992;5:383–389.

2 Allum JHJ, Honegger F, Platz CR. The role of stretch and vestibulospinal reflexes in the generation of human equilibrating reactions: afferent control of posture and locomotion. In: Allum JHJ, Hulliger M, eds. *Progress in Brain Research.* Amsterdam, the Netherlands: Elsevier Science Publishers BV: 1989:399–409.

3 Cresswell AG, Oddsson L, Thorstensson A. The influence of sudden perturbations on trunk muscle activity and intra-abdominal pressure while standing. *Exp Brain Res.* 1994;98:336–341.

4 Lavender SA, Tsuang YH, Andersson GBJ. Trunk muscle activation and co-contraction while resisting applied movements in a twisted posture. *Ergonomics.* 1993;36:1145–1157.

5 Bouisset S, Zattara M. A sequence of postural adjustments precedes voluntary movement. *Neurosci Lett.* 1981;22:263–270.

6 Friedli WG, Hallet M, Simon SR. Postural adjustments associated with rapid voluntary arm movements, 1: electromyographic data. *J Neurol Neurosurg Psychiatry.* 1984;47:611–622.

7 Aruin AS, Latash ML. Directional specificity of postural muscles in feed-forward postural reactions during fast voluntary arm movements. *Exp Brain Res.* 1995;103:323–332.

8 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;20:192–198.

9 Cresswell AG, Grundstrom H, Thorstensson A. Observations on intra-abdominal pressure and patterns of abdominal intra-muscular activity in man. *Acta Physiol Scand.* 1992;144:409–418.

10 Belen'kii V, Gurfinkel VS, Paltsev Y. Elements of control of voluntary movements. *Biofizika.* 1967;12:135–141.

11 Paquet N, Malouin F, Richards CL. Hip-spine movement interaction and muscle activation patterns during sagittal trunk movements in low back pain patients. *Spine.* 1994;19:596–603.

12 Mouchnino L, Autrey R, Massion J, Pedotti A. Coordination between equilibrium and head-trunk orientation during leg movement: a new strategy built up by training. *J Neurophysiol.* 1992;67:1587–1598.

13 Cordo PJ, Nashner LM. Properties of postural adjustments associated with rapid arm movements. *J Neurophysiol.* 1982;47:287–308.

14 Vercauteren M, VanBeneden M, Verplaetse P, et al. Trunk asymmetries in a Belgian school population. *Spine.* 1982;7:555–562.

15 DeTroyer A, Estenne M, Ninane V, et al. Transversus abdominis muscle function in humans. *J Appl Physiol.* 1990;68:1010–1016.

16 Hodges PW, Kippers V, Richardson CA. Validation of a technique for accurate fine-wire electrode placement into posterior gluteus medius using real-time ultrasound guidance. *Electromyogr Clin Neurophysiol.* In press.

17 Di Fabio RP. Reliability of computerized surface electromyography for determining the onset of muscle activity. *Phys Ther.* 1987;67:43–48.

18 Moore S, Brunt D, Nesbitt ML, Juarez T. Investigation of evidence for anticipatory postural adjustments in seated subjects who performed a reaching task. *Phys Ther.* 1992;72:335–343.

19 Rogers MW, Pai YC. Dynamic transitions in stance support accompanying leg flexion movements in man. *Exp Brain Res.* 1990;81:398–402.

20 Horak FB, Esselman P, Anderson ME, Lynch MK. The effects of movement velocity, mass displaced, and task certainty on associated postural adjustments made by normal and hemiplegic individuals. *J Neurol Neurosurg Psychiatry.* 1984;47:1020–1028.

21 Bouisset S, Zattara M. Biomechanical study of the programming of anticipatory postural adjustments associated with voluntary movement. *J Biomech.* 1987;20:735–742.

22 Tesh KM, ShawDunn J, Evans JH. The abdominal muscles and vertebral stability. *Spine.* 1987;12:501–508.

23 Macintosh JE, Bogduk N, Gracovetsky S. The biomechanics of the thoracolumbar fascia. *Clin Biomech.* 1987;2:78–83.

24 Nashner LM, Cordo PJ. Relation of automatic postural responses and reaction-time voluntary movements of human leg muscles. *Exp Brain Res.* 1981;43:395–405.

25 Nardone A, Schieppati M. Postural adjustments associated with voluntary contraction of leg muscles in standing man. *Exp Brain Res.* 1988;69:469–480.

26 Kasai T, Kazutake K. Quantitative EMG analysis of anticipatory postural adjustments of voluntary contraction of leg muscles in standing man. *Electroencephalogr Clin Neurophysiol.* 1994;93:184–187.

27 Dufosse M, Macpherson J, Massion J. Biomechanical and electromyographical comparison of two postural supporting mechanisms in the cat. *Exp Brain Res.* 1982;45:38–44.

28 Coulmance M, Gahéry Y, Massion J, Swett JE. The placing reaction in the standing cat: a model for the study of posture and movement. *Exp Brain Res.* 1979;37:265–281.

29 Béraud P, Gahéry Y. Relationships between the force of voluntary leg movements and the associated postural adjustments. *Neurosci Lett.* 1995;194:177–180.

30 Lee WA. Anticipatory control of postural and task muscles during rapid arm flexion. *Journal of Motor Behavior.* 1980;12:185–196.

31 Lee WA, Buchanan TS, Rogers MW. Effects of arm acceleration and behavioral conditions on the organization of postural adjustments during arm flexion. *Exp Brain Res.* 1987;66:257–270.Hasan

Invited Commentary

At least two different approaches can be adopted for the interpretation of electromyographic (EMG) signals recorded simultaneously from several muscles. In one approach, guided by neural control questions, any differences in the times of onset of activity of different muscles are regarded as salient because they shed light on the strategy of the nervous system. The other approach, guided by biomechanics, treats EMG recordings as a poor person's way of getting a handle on the muscle forces. From this latter perspective, given the large inertias of the skeletal segments, an onset timing difference of a few tens of milliseconds would not appear to be of much kinematic consequence. Hodges and Richardson ably adopt the former approach to interpret the EMG data that they obtained with their impressive—indeed virtuoso—experimental technique. I would like, however, to first make some general comments from the biomechanical perspective.

When a subject thrusts a limb forward, the force of reaction on the rest of the body initially pushes the body backward. This backward push, according to widespread belief, is countered by appropriate muscle activity commencing prior to the contraction of the prime movers of the limb; this constitutes an anticipatory postural adjustment (APA). Attention is seldom paid, however, to the fact that the forward-thrusting limb must eventually decelerate, which would result in a forward reaction force on the rest of the body. Given the brief periods of application of the backward force followed by the forward force, and given the large inertia of the body, the net backward movement of the body cannot be more than a small fraction of the forward movement of the limb. Speaking teleologically, this backward movement of the body may not be such a bad thing, because it would help keep the center of mass from going too far forward. Nevertheless, the received wisdom holds that when a limb is moved, the rest of the body must try to stay still, and all nonfocal muscle activity is usually interpreted within this framework.

Does the body stay still when a limb is moved? Simple recordings of trunk displacement show that it does not. ("Eppur si muove," Galileo might have said.) When a person raises an arm to point to a target in front of him or her, the backward movement of the trunk, amounting to several centimeters, commences even before the arm movement,[1] contrary to the notion that the APA would act to push the body forward. Clearly, however, the movement of the trunk is not simply a passive consequence of the movement of the arm. There is indeed activity of nonfocal muscles prior to that of the prime movers. Could it be, then, that the activity of the axial musculature is not of the precise magnitude to prevent trunk movement, but is at least qualitatively right? The results of a study by Tyler and Hasan,[2] albeit for arm movements from a sitting posture, indicate that for some directions of arm movement, the trunk muscle activity is not even qualitatively correct for keeping the trunk from moving.

What role the nonfocal, anticipatory muscle activity plays is an open question. The APA ideology of "try to not let the trunk move," although perhaps useful in some instances, can be quite literally a straitjacket. From a biomechanical perspective, looking at the multifidus muscle activity in Figure 4, for example, one is struck by its much larger magnitude in the case of hip extension compared with flexion, in both cases commencing before the respective prime movers become active. Yet,