

External perturbation of the trunk in standing humans differentially activates components of the medial back muscles

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During voluntary arm movements, the medial back muscles are differentially active. It is not known whether differential activity also occurs when the trunk is perturbed unpredictably, when the earliest responses are initiated by short-latency spinal mechanisms rather than voluntary commands. To assess this, in unpredictable and self-initiated conditions, a weight was dropped into a bucket that was held by the standing subject ($n = 7$). EMG activity was recorded from the deep (Deep MF), superficial (Sup MF) and lateral (Lat MF) lumbar multifidus, the thoracic erector spinae (ES) and the biceps brachii. With unpredictable perturbations, EMG activity was first noted in the biceps brachii, then the thoracic ES, followed synchronously in the components of the multifidus. During self-initiated perturbations, background EMG in the Deep MF increased two- to threefold, and the latency of the loading response decreased in six out of the seven subjects. In Sup MF and Lat MF, this increase in background EMG was not observed, and the latency of the loading response was increased. Short-latency reflex mechanisms do not cause differential action of the medial back muscles when the trunk is loaded. However, during voluntary tasks the central nervous system exerts a 'tuned response', which involves discrete activity in the deep and superficial components of the medial lumbar muscles in a way that varies according to the biomechanical action of the muscle component.

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The mechanical advantage of individual muscle fibres can vary within a muscle. Although there is debate regarding the lowest level of motor unit organization at which the central nervous system (CNS) can differentially control the activity of motor units, data from some studies of limb and trunk muscles demonstrate that this differentiation can occur within single muscles. For example, at longer muscle lengths, the biceps brachii long head is activated more than the short head (Brown *et al.* 1993) and muscle fibres in the medial and lateral components of the long head show differential activity in elbow tasks (Denier van der Gon *et al.* 1985). De Troyer and colleagues (1996) found differential activity in canine intercostal muscles, with activity being greatest in those parts of the muscle that possessed the greatest mechanical advantage. Thus, muscle components may be activated on the basis of their biomechanical contribution to the task.

Few studies have considered the functional differentiation between the different components of back muscles. Most studies of their neural control in humans rely on biomechanical models in which the extensor group is approximated as a single functional unit (e.g. Lavender *et*

al. 1993; Thomas *et al.* 1998; Krajcarski *et al.* 1999; Cholewicki *et al.* 2000). In other studies, EMG activity has been recorded with non-selective electrodes (Arendt-Nielsen *et al.* 1996; Arokoski *et al.* 1999), even though architectural and histochemical differences exist between components.

The most medial of the lumbar back muscles is the multifidus, which is composed of a series of distinct muscle groups, so that each group extends caudolaterally from the spinous processes and laminae of a particular lumbar vertebra (Macintosh *et al.* 1986). The most superficial components cross up to five vertebral segments to insert on the ilia and sacrum, while the deepest components insert two vertebral segments below (Macintosh *et al.* 1986). Each group is innervated by the adjacent nerve root (Bogduk *et al.* 1982) and by the nerve roots immediately above and below (Travlos *et al.* 1995). The deep components of multifidus have a greater proportion of type I muscle fibres than do the superficial components (Sirca & Kostevc, 1985; Jorgensen *et al.* 1993).

Differential activity in the multifidus components occurs during voluntary arm movements (Moseley *et al.* 2002), in

which preparatory postural adjustments are pre-planned by the CNS (Belen'kii *et al.* 1967; Marsden *et al.* 1981). During single voluntary arm movements, preparatory postural activity of the superficial multifidus fibres (Sup MF) was linked to the direction of arm movement, while activity of the deep multifidus fibres (Deep MF) was not affected by the direction of arm movement. This was corroborated during repetitive arm movements when for each cycle of flexion–extension of the arm, there was a single burst of EMG in the Sup MF, but two bursts of activity in the Deep MF. The differential preparatory postural activity of the Deep MF and Sup MF components can be explained by their biomechanical arrangement. As the Sup MF has a greater moment arm and is well suited to resist flexion of the lumbar spine, this component will be activated in advance of reactive forces that flex the trunk. The Deep MF has a small moment arm, is better suited to provide intervertebral compression and will be activated in advance of any reactive forces, regardless of the direction of those forces. It is unclear whether this differential activation between multifidus components occurs only in tasks that are predictable to the CNS or whether it also occurs when the muscle is perturbed unpredictably, when early responses are mediated at a spinal level.

The aim of the present experiment was to determine whether differential recruitment of the components of the multifidus occurs in response to an unpredictable external perturbation to posture and to a similar self-initiated (and therefore predictable) perturbation. The initial response to the load is likely to involve short-latency spinal paths, presumably those mediating the first phase of the stretch reflex. It was hypothesised that if supraspinal centres were required for differential recruitment, then differential recruitment would be absent following an unpredictable postural perturbation.

METHODS

Subjects

Five male and two female subjects, with a mean \pm s.d. age, body mass and height of 27 ± 5 years, 76 ± 10 kg and 178 ± 6 cm, respectively, participated in the study. Subjects were excluded if they had any respiratory, neurological or orthopaedic condition or had experienced low back pain in the previous 2 years. Written informed consent to participate was obtained from all subjects. All procedures were approved by the institutional research ethics committee and conformed with the Declaration of Helsinki.

Electromyography

EMG activity of three multifidus components was recorded with bipolar intramuscular electrodes fabricated from Teflon-coated stainless steel wire ($75 \mu\text{m}$ diameter). Recordings from the transversus abdominis (TrA) were also made because like the Deep MF, this muscle has been shown to respond in a non-direction-specific manner (Hodges & Richardson, 1997). The insulation was removed from a 1 mm length of the cut ends of the wire and the tips were bent back 1 and 2 mm from the end to form hooks. The electrodes were threaded into a hypodermic needle ($0.70 \text{ mm} \times 0.55 \text{ mm}$ or $0.32 \text{ mm} \times 0.50 \text{ mm}$).

With the subject in a sitting position, the morphology of the lumbar multifidus at L4 was imaged sonographically using a 5 MHz transducer (128XP/4, Acuson, Mountain View, CA, USA). Under ultrasound guidance, three electrodes were inserted into the right lumbar multifidus. The first electrode was positioned to record from the fibres 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. the Deep MF; Fig. 1A). The second electrode recorded activity from the lateral fibres of the multifidus that arise from the upper lumbar vertebrae (Lat MF; Fig. 1A). The third electrode recorded activity from the superficial fibres of multifidus adjacent to the L4 spinous process (Sup MF; Fig. 1A). After the needles were removed, gentle traction on the wires under ultrasound visualisation confirmed the position of each electrode.

Pairs of surface EMG electrodes (Ag–AgCl discs, 1 cm diameter, 2 cm interelectrode distance) were placed longitudinally, at the level of T7, ~ 5 cm lateral to the midline to record activity from the

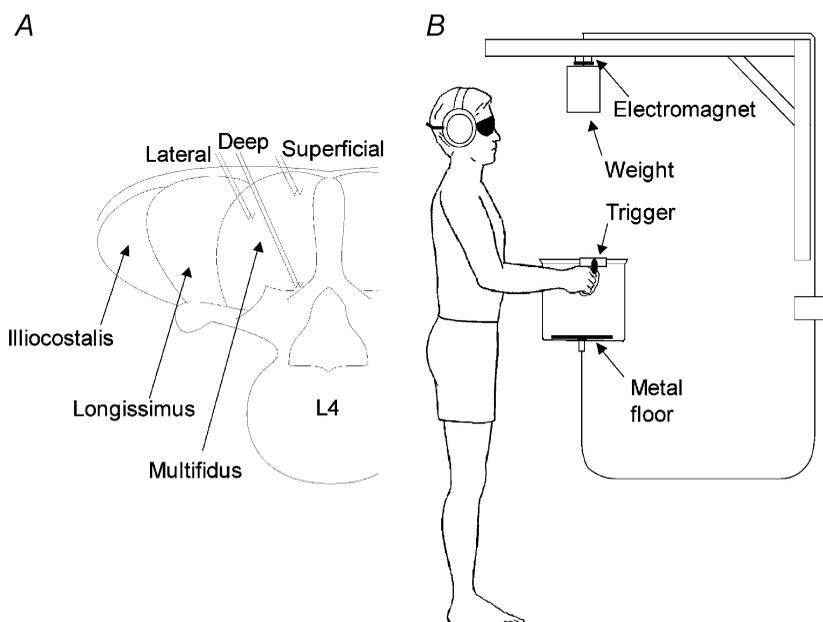


Figure 1. Experimental arrangement

A, EMG electrode positions in the deep, superficial and lateral multifidus, adjacent to the L4 lamina, as captured by ultrasonography (see Methods). B, experimental set up. When the weight is released from the electromagnet, it fell into the bucket and connected a circuit, which signalled the onset of the perturbation to the arms.

medial back muscles at the thoracic level (ES), and over the left biceps brachii. A ground electrode was placed over the right iliac crest. EMG data were differentially amplified with a gain of $\times 10\,000$ – $50\,000$, band-pass filtered between 53 Hz and 1 kHz, and sampled at 2 kHz using Signal2 software (Cambridge Electronic Design, Cambridge, UK). Data were exported for analysis with Matlab 5.1 (Mathworks, Natic, MA, USA).

Unpredictable loading

Subjects stood relaxed. They wore a blindfold and headphones and held a bucket with a metal base in both hands with their elbows flexed to 90° and their forearms horizontal (Fig. 1B). A metal weight ($\sim 1\%$ of body mass) was fixed by an electromagnet to a bracket situated approximately at eye level, directly above the bucket. At random times, and without warning, the weight was released. Subjects were instructed to hold the arms stable when the load landed in the bucket. Contact between the weight and the floor of the bucket completed a circuit so that the timing of the perturbation was recorded. Trials were rejected if the subject initiated a response prior to contact, or if the weight did not cleanly strike the floor of the bucket. More than 90% of trials were accepted, with approximately 15 trials for each subject.

Self-initiated loading

Subjects stood in a similar position to the unpredictable condition, but without the blindfold and headphones. A button that released the weight was placed on the handle of the bucket so that it was easily operated by the subject, without associated activity of the trunk muscles. Subjects were instructed to release the weight at any time and to hold the arms stable when the load landed in the bucket. Fifteen trials were recorded.

Data analysis

For each condition, both the temporal and spatial parameters of the EMG were analysed. To remove bias, EMG traces were displayed individually without reference to muscle or trial. The onset and offset of EMG activity were identified visually from the raw data as the point at which EMG activity increased above the baseline level and returned to baseline level, respectively. The time between the perturbation and the onset and offset of EMG, and the duration of the initial response, were analysed. Trials were excluded if the onset of EMG activity occurred more than 200 ms after the perturbation, and trials for the unpredictable condition were excluded if the onset of the EMG occurred prior to the perturbation (i.e. the subject anticipated the perturbation). Less than 10% of the analysed trials were excluded based on these criteria.

To assess pre-loading activity in the self-initiated condition, the magnitude of the rectified EMG signal was measured. The period 500 ms prior to the onset of the load was divided into 10 epochs of 50 ms each. The mean EMG amplitude during each epoch was calculated for each muscle. For each epoch, the mean EMG amplitude during self-initiated perturbation was expressed as a percentage of the mean EMG amplitude during the unpredicted perturbation. Data were not analysed for the period between 300 and 400 ms prior to impact due to artefacts caused by the weight release button.

Statistical analysis

For each muscle, the EMG onset latency relative to the perturbation, and the mean EMG amplitude for each epoch were averaged for all trials across the sample. Repeated measures analysis of variance (ANOVA) was used to compare the EMG onset latency between muscles for each condition. Two-way ANOVAs were used to compare: (1) the EMG onset latency for each muscle between conditions, (2) the EMG offset latency for each muscle between conditions, (3) the duration of the initial burst in EMG activity and (4) the mean rectified EMG amplitude for each epoch, for each muscle, between conditions. *Post hoc* testing of the EMG onset latency, offset latency and burst duration between muscles, between conditions, and the epoch data between conditions, was performed using Duncan's multiple range test. The level of statistical significance was set at $P < 0.05$.

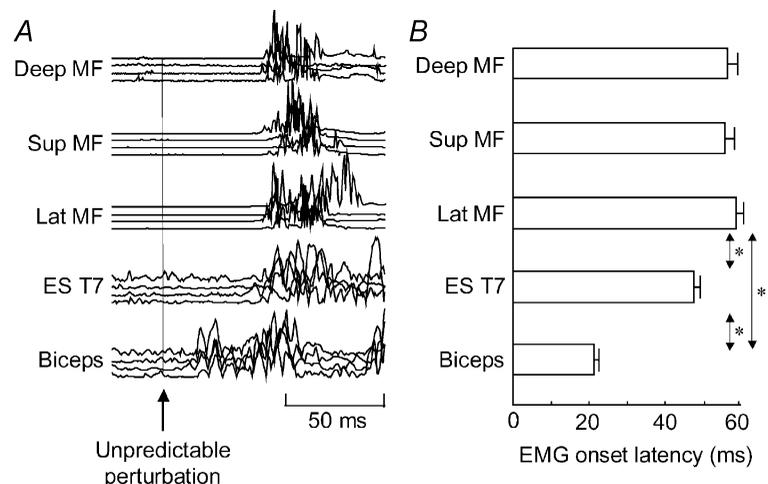
RESULTS

Unpredictable loading of the trunk

When a weight was dropped without warning into a bucket held by a standing subject, the EMG response in the biceps brachii occurred approximately 22 ± 5 ms after the instant of loading. This was earlier than the initial response in the thoracic ES (47 ± 11 ms), which was in turn earlier than the initial response in the medial back muscles of the lumbar region, which had mean onsets between 53 and 56 ms. The mean duration of the initial burst of EMG activity was between 28 and 33 ms for each of the multifidus components. There were no differences in the onset latency, offset latency or burst duration between the components of the medial back muscles ($P > 0.35$). Data from multiple trials in a representative subject and group

Figure 2. Responses to unpredictable loading of the trunk

A, single trials in a representative subject produced by unpredicted perturbation of the trunk, showing EMG activity from the deep (Deep MF), medial superficial (Sup MF) and lateral superficial (Lat MF) fibres of the multifidus muscle at the L4 level, the right erector spinae at T7 (ES T7) and the left biceps brachii (Biceps). The vertical line marks the onset of perturbation. B, group data showing the mean and S.E.M. for the latency of the EMG response to the unpredictable perturbation. The asterisks adjacent to the arrowed vertical lines indicate a significant difference in onset latency between muscles ($P < 0.05$). Note the similar latency of the EMG response in the three components of the lumbar multifidus.



data are shown in Fig. 2. TrA showed variable ongoing activity; however, in the majority of trials, the onset latency of its activity was 44 ± 19 ms, which was earlier than the lumbar back muscles.

Self-initiated loading of the trunk

Multiple trials from the same subject (Fig. 3A) and group data (Fig. 3B) show the EMG responses to loading when the weight was dropped using a button activated by the subject. The sequence in the latency of the responses to loading was similar to that observed during unpredictable loading (i.e. the EMG response to the loading occurred first in the biceps brachii, then the thoracic muscles and then the lumbar muscles). However, in contrast to the unpredicted condition, the onset and offset of the EMG response occurred ~ 10 ms earlier in the Deep MF than in the Sup MF and Lat MF ($P < 0.01$). There was no difference in burst duration between the components of the multifidus. The ongoing EMG in TrA was more marked during self-initiated loading than during unpredictable loading, and no consistent latencies could be identified for the loading response.

Comparison between the two loading conditions

The group data for mean EMG amplitude during each epoch prior to the self-initiated perturbation, normalised to the unpredicted condition, for Deep MF, Sup MF and Lat MF are shown in Fig. 4. Artefacts caused by release of the weight meant that analysis of the period 300–400 ms prior to the perturbation was not possible (see Methods), but this did not obscure the main result. The amplitude and timing of the responses to the perturbation were different between the components of the medial back muscles. From 450 ms prior to the main response to the perturbation, the mean amplitude of the Deep MF EMG increased two- to threefold (2.7 ± 2.5 ; $P < 0.05$). In contrast to the Deep MF, there was no pre-perturbation increase in Sup MF EMG activity ($P > 0.2$), and a limited increase in Lat MF EMG activity in one epoch (1.4 ± 1.1 ; $P < 0.05$). The pre-perturbation activity in Deep MF was similar to that observed in biceps brachii, which also

increased two- to threefold from 450 ms pre-perturbation (2.4 ± 1.9 ; $P < 0.05$).

Comparison of the latency of the loading response between conditions revealed that during self-initiated perturbation, there was a reduced latency of the onset of the loading response for Deep MF of ~ 5 ms in six of the seven subjects, but the group data were not significantly different (4 ± 5 ms; $P = 0.07$). There was a reduced latency of the response from the biceps brachii of 6 ± 4 ms ($P < 0.001$). In contrast, for the Sup MF and Lat MF, there was an increase in the latency of the loading response (Sup MF 7 ± 5 ms, Lat MF 6 ± 5 ms; both $P < 0.001$). In the self-initiated condition, the latency of the offset of the EMG response was 10–20 ms less, and the duration of the EMG response was 10–15 ms less, for all three components of the multifidus.

DISCUSSION

This study shows that when an individual can control the timing of a known external perturbation, the CNS exerts differential control over activity in the components of the medial back muscles. This does not occur when a similar perturbation is delivered unexpectedly. In addition, when the perturbation was self-initiated, there was increased baseline activity prior to loading and an earlier loading response in the Deep MF in six out of the seven subjects. This response was also observed in the biceps brachii, in which it is considered to limit the impact of the disturbance by effecting a general increase in the stiffness of the arm (Biryukova *et al.* 1999). In contrast to the Deep MF, when the perturbation was initiated by the subject, the Sup MF exhibited no increase in background activity and the onset of the response was delayed. These data support the hypothesis that there is a functional differentiation among the components of the multifidus, which operates during voluntary tasks.

Our data from the biceps brachii are consistent with previous studies of similar tasks. In response to

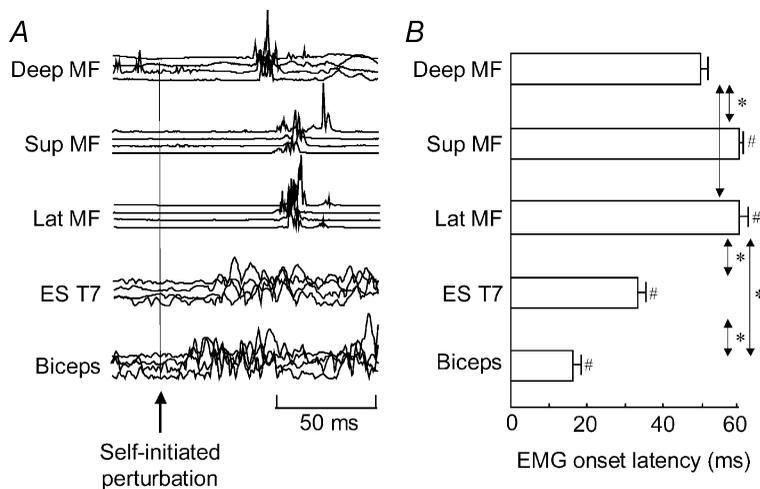


Figure 3. Responses to self-initiated loading of the trunk

A, data from single trials of self-initiated perturbation of the trunk, obtained from the same subject as Fig. 2A. The vertical line marks the onset of perturbation. Note the reduced duration of the response compared to that obtained with unpredicted perturbation. B, group data showing the mean and S.E.M. for the latency of EMG response to predicted perturbation. The hash to the right of the bar denotes a significant difference in the latency of the response between conditions (compare with Fig. 2B) and the asterisks adjacent to the arrowed vertical lines indicate a significant difference in the latency of the response between muscles ($P < 0.05$).

unpredicted lengthening of biceps brachii, the EMG increased with a latency of ~22 ms, which is similar to that reported by others (e.g. Bennis *et al.* 1996; Nakazawa *et al.* 1997, 1998). This reflects the onset of a short-latency spinal reflex. We observed two main differences in biceps brachii EMG when the perturbation was initiated by the subject. First, the background EMG was increased and second there was a decreased latency of the short-latency response to loading. Elevated background EMG during self-initiated loading has been reported previously for the biceps brachii (Bennis *et al.* 1996). The small reduction in latency is probably due to the additional activation of higher threshold motoneurons with faster conducting axons (Burke, 1981).

We observed a sequential onset of the response in the biceps brachii, followed by the thoracic muscles and then the lumbar muscles. This is probably due to the proximity of these segments to the load and the delay in transmission of the load to distant regions (Hodges *et al.* 2001). Among the components of the multifidus, there was no difference in onset latency of the response to the unpredicted perturbation, which is in contrast to the response associated with rapid voluntary arm movement (Moseley *et al.* 2002). This finding suggests that short-latency spinal reflex mechanisms are not sufficient to cause differential activation of the medial lumbar muscles and that input from higher centres is required. This study does not reveal the specific descending pathways that are involved. However, it is likely that corticofugal paths contribute by presetting spinal circuitry. It is more difficult to determine

whether such paths directly mediate the onset of the responses at 45–50 ms (Gandevia & Plassman, 1988). Given the minimal latencies involved (to and from the cortex), the delay in transmission of the perturbation to the spine and the relatively long central conduction time for the projection of truncal afferents to the cortex (Macefield & Gandevia, 1992), it is more likely that the responses are modified by cortical output rather than being initiated through them. The latencies in the lumbar multifidus for the response to loading are comparable with previous values. During unpredicted perturbation, the latency of ~55 ms in each of the medial lumbar muscles is consistent with previous reports of an ES onset latency of 60 ms (Radebold *et al.* 2000) or 65 ms (Carlson *et al.* 1981; Cresswell *et al.* 1994; Stokes *et al.* 2000).

Similar to the biceps brachii, increased background EMG activity was observed for the Deep MF prior to self-initiated loading (see also Marras *et al.* 1987; Cresswell, 1993; Lavender *et al.* 1993; Thomas *et al.* 1998). Such activation of motoneurons may account for the decreased latency of the main response observed in the Deep MF and biceps brachii. Lavender and colleagues (1993) found variability in the preparatory strategy adopted for self-initiated loading, but reported that every response involved an increase in background EMG of the trunk extensors. It has been proposed that during unpredicted perturbations to the spine, the trunk muscles are activated to an amplitude in excess of that assumed to be required to overcome the perturbation (i.e. 'overshoot'), but when preparation for the perturbation is possible, increased

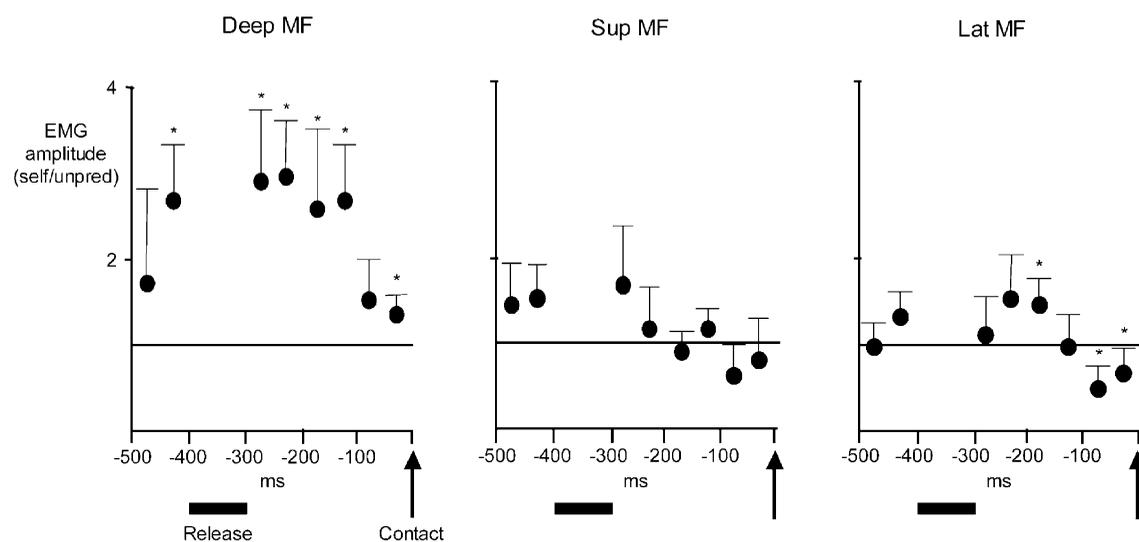


Figure 4. Pre-loading activity associated with self-initiated loading of the trunk

EMG amplitude (mean \pm S.E.M.) during self-initiated perturbations (self) as a proportion of the mean EMG amplitude during unpredicted perturbations (unpred), for each 50 ms epoch from 500 ms before the perturbation to the time of perturbation (vertical arrow) for the Deep MF, Sup MF and Lat MF. The horizontal line represents the identical mean amplitude for the self-initiated and unpredicted conditions. Asterisks denote a significant difference in mean EMG amplitude between the self-initiated and unpredicted conditions ($P < 0.05$).

background EMG activity reduces the magnitude of the required response (Lavender *et al.* 1993). This hypothesis underlies the proposal that the large muscle contractions associated with unpredicted perturbations place spinal structures at risk, and preparatory activation reduces that risk. The duration of the EMG bursts found in this study are consistent with that proposal: there was a reduction of 10–15 ms in the duration of the response when the perturbation was initiated by the subject. This 'tuned' response involves discrete activity in different components of the medial back muscles, which suggests a functional distinction between them.

The results of the present study may be related to histological differentiation between the deep and superficial back muscles. Reports suggest that there is a slightly greater proportion (~7%) of type I muscle fibres in the Deep MF than in the Sup MF (Sirca & Kostevc, 1985; Jorgensen *et al.* 1993) and thus a certain level of central drive might preferentially activate low-threshold motoneurons. If this was the case, we would expect the duration of the EMG burst to be longer, and the offset of the response to occur later in the Deep MF than in the Sup MF or Lat MF. However, there was no difference in burst duration between the muscles, and the offset of the EMG response occurred earlier in the Deep MF than in the Sup MF and Lat MF. These findings suggest that the differentiation in activity is not easily explained by differences in fibre type distribution between deep and superficial fibres. An alternative explanation may be that the response to self-initiated perturbations involved the additional activation of higher threshold motoneurons with faster conducting axons (Burke, 1981).

The response of the Deep MF to self-initiated loading was similar to that observed in the biceps brachii, in which the response is considered to limit the disturbance via a general increase in the stiffness of the arm (Biryukova *et al.* 1999). Because the deep fibres of the multifidus cross only two segments and are close to the centre of rotation of the vertebral segments, they are suited biomechanically to exert a focal increase in spinal stiffness. The superficial multifidus fibres are less well-suited to this role because although increased trunk muscle stiffness associated with elevated baseline activity can prevent lumbar spine buckling (Bergmark, 1989; Gardner-Morse *et al.* 1995), co-activation of the superficial muscles is associated with increased compressive loading of spinal structures (Granata & Marras, 1995; Gardner-Morse & Stokes, 1998). Differential control of the deep and superficial multifidus fibres may serve to limit the impact of the perturbation at both a focal and more general level without imparting excessive compressive loading to spinal structures.

In summary, our data demonstrate differential activity in the medial back muscles in response to an external perturbation, but only when the CNS can predict the

timing of the load. These results suggest that voluntary commands can drive individual components of the lumbar musculature in a way that varies according to the biomechanical action of the muscle component.

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