A new method for the noninvasive determination of abdominal muscle feedforward activity based on tissue velocity information from tissue Doppler imaging


J Appl Physiol 104: 1192–1201, 2008. —Rapid arm movements elicit anticipatory activation of the deep-lying abdominal muscles; this appears modified in back pain, but the invasive technique used for its assessment [fine-wire electromyography (EMG)] has precluded its widespread investigation. We examined whether tissue-velocity changes recorded with ultrasound (M-mode) tissue Doppler imaging (TDI) provided a viable noninvasive alternative. Fourteen healthy subjects rapidly flexed, extended, and abducted the shoulder; recordings were made of medial deltoid (MD) surface EMG and of fine-wire EMG and TDI tissue-velocity changes of the contratralateral transversus abdominis, obliquus internus, and obliquus externus. Muscle onsets were determined by blinded visual analysis of EMG and TDI data. TDI could not distinguish between the relative activation of the three muscles, so in subsequent analyses only the onset of the earliest abdominal muscle activity was used. The latter occurred <50 ms after the onset of medial deltoid EMG (i.e., was feedforward) and correlated with the corresponding EMG onsets (r = 0.47, P < 0.0001). The mean difference between methods was 20 ms and was likely explained by electromechanical delay; limits of agreement were wide (~40 to +80 ms) but no greater than those typical of repeated measurements using either technique. The between-day standard error of measurement of the TDI onsets (examined in 16 further subjects) was 16 ms. TDI yielded reliable and valid measures of the earliest onset of feedforward activity within the anterolateral abdominal muscle group. The method can be used to assess muscle dysfunction in large groups of back-pain patients and may also be suitable for the noninvasive analysis of other deep-lying or small/thin muscles.

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A new method for the noninvasive determination of abdominal muscle feedforward activity based on tissue velocity information from tissue Doppler imaging

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STABILIZATION of the osteoligamentous spine is primarily achieved by the activity of muscles that surround and span it (41). One of the muscles that has been shown to contribute to stability is the transversus abdominis (TrA) (8, 13, 22, 33, 46, 52). Fibers of TrA run transversely from the lower ribs, iliac crest, and (via the thoracolumbar fascia) transverse and spinous processes of the lumbar vertebrae to the linea alba (50, 56). Contraction of this deep-lying abdominal muscle increases tension in the thoracolumbar fascia, increases intra-abdominal pressure, and compresses the sacroiliac joints and is considered to contribute to stabilization through these mechanisms (23, 33, 44). Using fine-wire electromyography (EMG), it has been shown that, in healthy controls, TrA is active during both trunk flexion and extension movements, with almost constant activity when moving between the two (13), i.e., around the “neutral position,” where minimal resistance is offered by the passive tissues. Further, it is the first muscle to be activated under both expected and unexpected loading conditions (14). During rapid arm movements, TrA is commonly activated before the other trunk muscles and before the muscle responsible for initiation of the movement, i.e., deltoid (32, 34). Collectively, these studies suggest a role for TrA in the control of lumbar stability during movements that pose a challenge to balance.

Deficits in control of the deep trunk muscles in people in remission from low back pain (LBP) have also been reported: using fine-wire EMG it has been shown that, compared with healthy controls, the onset of TrA EMG, and to some extent also the obliquus internus (OI), is delayed during rapid limb movements, i.e., “anticipatory” or “feedforward” activity of these muscles is compromised (24, 30, 31, 33). Similar changes have also been observed during experimental acute pain (injection of hypertonic saline into the longissimus muscle at L4) (29, 38). These studies suggest a consistent dysfunction of the deep trunk muscles in LBP, although the exact nature of the relationship (cause or effect) and the underlying mechanisms of action remain unclear. The phenomenon has not been studied widely in the LBP population because of the invasive, time-consuming nature of fine-wire EMG. Hence, there is no information on the prevalence of alterations in TrA feedforward activity in LBP. Further, it is not known how well this “dysfunction” can be used to characterize patients with LBP, how well it relates to clinical symptoms (e.g., pain, disability) and functional attributes (e.g., spinal instability), or how it responds to treatment and training, although the latter has recently been addressed in two studies with small numbers of subjects (48, 49).
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To address these issues, it was considered necessary to have a tool for assessment of the onset of deep trunk muscle activity that would be comparable to the “gold standard,” EMG, in terms of its accuracy and reliability, but noninvasive and readily utilizible in the clinical environment. This study aimed to develop such a tool, based on tissue Doppler imaging (TDI). TDI is an ultrasound technology that uses modified color Doppler processing to image and quantify tissue motion and is most commonly used in the field of cardiology (37, 40). TDI was used successfully in a preliminary study of skeletal muscle function to distinguish between different modes of contraction (19). As EMG records the electrical activity associated with muscle contraction, and TDI records the resultant tissue motion, it was anticipated that the onset of EMG would precede that of TDI by a systematic amount due to electromechanical delay.

The specific aims of this study were to examine 1) the validity of TDI-velocity measures of abdominal muscle activity, using fine-wire EMG as the gold standard, and 2) the between-day reliability of TDI-velocity measures.

METHODS

Ethical approval. The study conformed to the standards set by the latest revision of the Declaration of Helsinki and was approved by the local ethics committee. Informed consent to participate was obtained in writing from all volunteers.

Subjects. Healthy volunteers (n = 30) were recruited among staff and students of the local universities and hospitals. Exclusion criteria for both substudies included any LBP at the time of testing, a history of LBP requiring medical attention or time off work within the previous 5 years, neuromuscular or neurological disorders, uncorrected visual impairment, or pregnancy in the last 2 years. Fourteen subjects took part in the first study (validity of TDI). Their mean (SD) age, height, weight, and body mass index (BMI) were 22.3 yr (SD 1.5), 1.78 m (SD 0.07) m, 72.1 kg (SD 7.7), and 22.7 kg/m² (SD 1.6), respectively, for the men (n = 8), and 24.0 yr (SD 2.3), 1.68 m (SD 0.05), 58.8 kg (SD 7.3), and 20.8 kg/m² (SD 1.8), respectively, for the women (n = 6). Sixteen volunteers took part in the second study (reliability of TDI), and their mean (SD) age, height, weight, and BMI were 32.5 yr (SD 8.5), 1.83 m (SD 0.10), 79.0 kg (SD 14.7), and 23.4 kg/m² (SD 3.1), respectively, for the men (n = 8), and 33.9 yr (SD 13.7), 1.69 m (SD 0.05), 61.9 kg (SD 10.7), and 21.6 kg/m² (SD 3.3), respectively, for the women (n = 8).

All volunteers were habitually physically active, but the majority (29/30) had jobs with relatively low physical demands.

Ultrasound/TDI. All ultrasound acquisitions were made using an HDI-5000 ultrasound scanner with a L12–5 linear-array transducer (Philips Medical Systems, Bothell, WA). This transducer scans linearly a rectangular area with a width of 38 mm, and the central frequency of the ultrasonic pulses transmitted during tissue Doppler acquisition was 7.5 MHz.

With the subject relaxed in prone lying, the ultrasound transducer supported in a high-density custom-made foam block (10, 11) was placed perpendicular to the skin, on the lateral wall of the abdomen, midway between the costal margin and the iliac crest (36, 47). The position of the transducer was adjusted to ensure that the deepest fascial boundary of the TrA and the fascial boundaries between and the TrA, OI, and obliquus externus abdominis (OE) were approximately parallel, with the medial edge of the TrA −1 cm from the medial edge of the B-mode ultrasound image. The transducer position was marked on the skin, to direct the later placement of the intramuscular wire EMG electrodes. Once the latter were inserted (see below), a 130 × 120 × 10 mm gel stand-off pad (Somar-Aid, Alloga AG, Burgdorf, Switzerland) and transmission gel were placed between the transducer and the skin. This ensured good signal transmission and adjustment of the ultrasound foci to the abdominal muscle layers of interest, including the OE, which in slender volunteers was otherwise very superficial. The foam block was secured with Velcro straps around the pelvis, to ensure that the transducer was placed against the skin at a constant angle and with a constant pressure, and to minimize relative movement between the transducer and the abdomen that could potentially have led to onset artifacts (Fig. 1).

The ultrasound scanner was set to M-mode scanning, i.e., one scan line vs. time, and the gray-scale plus TDI data were acquired at a sampling rate of 333 Hz (machine’s maximum possible sampling rate), i.e., the M-mode line of sight was interrogated 333 times per second. The gray-scale M-mode data were used to form a depth vs. time gray-scale map displaying the position and backscattering power of the anatomic structures along the scan line. The TDI M-mode data were analyzed to estimate the moving-tissue Doppler velocities along the scan line, which were then displayed as a depth vs. time velocity color-coded map with movement toward the transducer (positive velocity) displayed in red/yellow and that away from the transducer (negative velocity) in blue (Fig. 1). The scanner, the gray-scale and tissue Doppler velocity map were superimposed on the same display by using simple motion-dependent rules (i.e., if the velocity of a pixel is above a certain threshold, display the color-coded velocity value at this pixel, or else display the gray-scale value instead). Gray-scale and tissue velocity data from the M-mode ultrasound files and event marker data from the arm-movement switch were exported in digital form using the ResearchLink option of the HDI-5000 system, and stored on computer.

The onset of muscle motion could have been appreciated by visual inspection of the gray-scale M-mode image alone; however, TDI is a more complete method in the sense that it provides direct estimation of tissue velocity and can produce high-quality tissue-velocity vs. time waveforms. Gray-scale M-mode, in contrast, records the position of major tissue interfaces and would require hand tracing of the tissue trajectory over time followed by temporal differentiation of this trajectory to get a velocity vs. time waveform (which is of much inferior quality because of the tracing and temporal-derivative operations). TDI is hence considerably more sensitive than gray-scale M-mode imaging. In the field of echocardiography, where both gray-scale M-mode and TDI-M-mode were first used, gray-scale M-mode is still being used to measure structure dimensions at specific points of the cardiac cycle (i.e., left-ventricular diameter at peak systole and end diastole), but TDI has become the gold standard for all cardiac motion-related quantification methods.

EMG. Bipolar fine-wire electrodes were fabricated from 75-µm diameter Teflon-coated stainless steel wire (SS-3T/A, Science Products, Hofheim, Germany) with 1 mm of Teflon insulation removed at the end and inserted into a hypodermic needle (Sterican, Braun Melsungen, Germany) (0.70 × 40 mm or 0.70 × 60 mm). The exposed ends were bent back 1 mm and 2 mm to separate the receptive areas (7). Using a sterile technique, needles were inserted sequentially under ultrasound guidance into the TrA, OI, and OE muscles. Needle insertion began (TrA) −15 mm medial to the medial edge of the markings that indicated the location of the ultrasound transducer and continued with −5 mm lateral separation between the subsequent two insertion points; angles of insertion ranged from −45° to the horizontal (for TrA) to −20° (for OE). Needles were guided laterally with 0.1 mm, pulse repetition rate of 3 Hz, and amplitude of up to 100 mA (individually determined). Muscle twitches were observed as visible movements with B-mode ultrasound imaging.
During stimulation, movement was sometimes observed in more than one muscle (due to their close proximity and interconnecting fascia), and hence 100% accurate placement could not be guaranteed; however, careful observation on ultrasound of the insertion procedure (needle tip progression) and subsequent stimulation represented the best and only possible means of attempting to verify electrode placement.

For surface EMG recordings of medial deltoid (MD), the skin was prepared by gentle abrasion and cleaning with alcohol (with shaving of hair if necessary) and pairs of disposable Ag/AgCl surface electrodes (15 mm × 20 mm recording area, Biotrace-HR 1212 Ag/AgCl ECG electrodes; MSB, Ramsbury, UK) were placed over the muscle bulk of the MD, with an interelectrode distance of 20 mm. Electrode placement was in accordance with the European recommendations for surface electromyography (20). A reference electrode was placed over the ASIS of the contralateral side. Our pilot studies had shown that MD was suitable as a reference for all arm movement directions and that there was no advantage to be gained from recording from the separate heads of the deltoid (in an ANOVA there was no significant interaction between “deltoid head” and “movement direction” for the muscles’ motor times, perhaps due to the synergistic actions of the different heads of the muscle in the directions in which they were not prime mover, e.g., medial deltoid is the prime mover in abduction, but also a synergist [probably in a stabilizing role] in shoulder flexion and extension).

EMG data were differentially amplified (Dantec Keypoint system, Medtronic Functional Diagnostics A/S, Skovlunde, Denmark), band-pass filtered between 20 and 1,000 Hz, sampled at 5 kHz, analog-to-digital converted (16-bit resolution), and stored on computer.

**Test procedure.** The test set-up was similar to that previously described by Hodges and Richardson (33), in which trunk muscle activity was assessed during rapid movements of the contralateral arm. The volunteers stood barefoot on a thin rubber mat, upright but in a relaxed posture, with the feet approximately shoulder-width apart. To standardize the position, foot placement was drawn on the mat.

After initial instructions regarding the task, subjects performed several practice movements. In response to a visual stimulus that indicated the direction of movement to be undertaken (randomized order), the subject performed shoulder flexion (∼60°), abduction (∼60°), or extension (∼40°), as quickly as possible. Emphasis was placed on speed of arm movement rather than the angular distance moved. The output of a customized contact switch attached to the thigh indicated the onset of arm movement, and this was recorded on the ECG input of the ultrasound machine, a channel of the EMG system, and the computer delivering the cue signal, to synchronize the data. Ten arm movements were made in each direction. Movements were performed during expiration, as judged by visual inspection of the participant’s breathing pattern, to avoid any possible changes in abdominal muscle activity associated with respiration (15, 28, 36). Subjects rested in standing for ∼1 min between individual arm movement trials.

For the TDI-validity study, the test procedure was performed for the right and left sides each on a separate day [mean 4 days (SD 2) apart]. For the TDI-reliability study (without abdominal EMG), both sides were tested on each of 2 days, −1−2 wk apart [mean 8 days (SD 2)].

**Data processing.** The gray-scale, TDI velocity, and switch data from the M-mode ultrasound files were exported to MATLAB (Student version 7.1; The Mathworks, Natick, MA) for identification of the region of interest for each muscle (Fig. 2). The data were encoded as a matrix of ∼2,500 horizontal pixels, depending on the precise duration of the data recorded (with each column of pixels representing a period of 3 ms) × 384 vertical pixels using an eight-bit color scale. The region either side of the movement switch was marked for each of the three abdominal muscles. For each column of pixels, the numerical value of the color-coded tissue velocity within the boundary of each muscle was averaged and exported as text data. For detection of onset of EMG activity and change in tissue velocity, the experimenter was blinded to the subject, muscle, test condition, and its relationship to any mechanical event. One person performed all analyses. TDI data were plotted as raw velocity data. EMG data were high-pass filtered with a 50-Hz second-order Butterworth filter and...
plotted as both unrectified (Fig. 3) and rectified data. Trials were displayed individually, and in random order. Onsets were identified visually as the earliest consistent rise in tissue velocity or EMG amplitude above the baseline level. This could be clearly detected in most cases but was sometimes difficult for EMG data when there was high baseline activity or the data were noisy or contaminated by ECG signals. If no onset could be determined, this was indicated in the output file. Although automated methods for determination of onsets are available, most are not ideal, as they cannot distinguish between artifact and EMG, and they detect systematically later onsets when baseline activity is high or when EMG activity increases slowly (1, 25). Measurement error for the blinded determination of onsets was assessed on 81 sets of MD surface EMG and abdominal muscle output file. Although automated methods for determination of onsets are available, most are not ideal, as they cannot distinguish between artifact and EMG, and they detect systematically later onsets when baseline activity is high or when EMG activity increases slowly (1, 25). Measurement error for the blinded determination of onsets was assessed on 81 sets of MD surface EMG and abdominal muscle.

The difference in the onset of each abdominal muscle (TrA, OI, and OE) in relation to the onset of MD EMG was calculated for each trial and each method (EMG and TDI). The earliest EMG and TDI-velocity onsets of the three abdominal muscles were also determined. Trials were excluded if the onset of trunk muscle EMG or TDI-velocity change occurred >200 ms before or after that of MD since activity during this period is unlikely to be related to the task (3, 38). MD reaction time was calculated as the latency between the visual cue and onset of MD EMG. Data from the 10 repetitions were averaged before further analysis, but data from the right and left sides were treated separately, such that (potentially, assuming no exclusions) 14 × 2 datasets contributed to the mean value for each movement direction and method.

To verify the accuracy of the mean trunk muscle EMG onsets, the data were also analyzed in relation to the EMG amplitude for each trunk muscle during 10-ms epochs around the onset of MD EMG (29). The latter was identified from the raw data (as described above), and the root mean squared (RMS) EMG amplitude for 35 × 10 ms epochs was then calculated. Data were averaged across the group for a given movement direction to visualize the “average” pattern for each trunk muscle for the given task. No attempt was made to compare the epoch analyses with the onset analyses on an individual basis.

Statistical analyses. Descriptive statistics are presented as means ± SD. EMG and TDI-velocity onsets and reaction times were compared between movement directions using repeated-measures ANOVA. The relationship between the two methods (EMG and TDI) was examined using the Pearson product-moment correlation coefficient. The level of agreement between the two methods was determined using the Bland and Altman method (9); the differences between values obtained using the two methods (TDI-velocity minus EMG) was plotted against the mean of the two values for each data pair. Agreement between the two methods was given by the mean and SD of the differences; a nonzero value suggests a systematic error or bias, and positive values indicate later onsets for the TDI method. The boundaries at 2 SD from the mean are referred to as the “limits of agreement.”

For the assessment of between-day reliability of the TDI-velocity data, the following statistics were determined from the output of a repeated-measures ANOVA: mean (SD) values; the significance of the difference between mean values; the intraclass correlation coefficient [ICC (3,1); 2-way, mixed-effects, with results reported for single-day reliability of the mean of 10 trials for a given arm direction and body side]; the SEM [square root of the within-subjects residual mean squares error, and also referred to as the “within-subjects SD” or “typical error of measurement” (35)].

Statistical significance was set at $P < 0.05$.

RESULTS

Exclusion of data files. For one volunteer, the data from one body side had to be discarded due to technical problems with
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Table 1. Time of onset of intramuscular EMG for each of the abdominal muscles relative to the onset of medial deltoid

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Shoulder Flexion, ms</th>
<th>Shoulder Abduction, ms</th>
<th>Shoulder Extension, ms</th>
<th>P Value (Across Directions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TrA</td>
<td>$-8.3^\circ$ (60.8)</td>
<td>10.2 (27.5)</td>
<td>15.5 (26.7)</td>
<td>0.03</td>
</tr>
<tr>
<td>OI</td>
<td>19.9 (55.1)</td>
<td>10.8 (28.9)</td>
<td>19.1 (20.5)</td>
<td>0.26</td>
</tr>
<tr>
<td>OE</td>
<td>18.5 (30.0)</td>
<td>11.7 (15.2)</td>
<td>18.5 (18.2)</td>
<td>0.39</td>
</tr>
</tbody>
</table>

Values are means (SD). Negative value indicates onset of abdominal muscle before that of medial deltoid (MD); positive values indicate onset of abdominal muscle after that of MD. TrA, transversus abdominis; OI obliquus internus; OE obliquus externus. *Significantly different from other values in column and row.

Fig. 3. A: full-wave high-pass-filtered EMG signals. B: raw TDI tissue velocity data. In A and B, the bottom plot is a temporally expanded view of part of the signal around the time of the onset. Individual traces were presented randomly to the investigator; the onset (thick vertical dotted lines in bottom view of A and B) was identified by visual examination as the earliest rise above baseline.

the surface EMG data and hence loss of the reference measure (MD onset). In the remaining datasets, for 7% of traces (13% fine-wire EMG, 3% TDI, 4% surface EMG), no onset could be determined as it was either unclear whether there was an onset or it was too difficult to identify; for 1.5% individual trials (2% fine-wire EMG, 1% TDI), the onset in relation to MD was outside the acceptable range. These individual trials were excluded from further consideration (see methods). This missing data meant that for the Bland-Altman analysis, 6 of 84 (2 sides × 14 subjects × 3 directions) (7%) data pairs (EMG and TDI) were excluded, and for the repeated-measures ANOVA (due to case-wise deletion of missing data in any of the 3 directions), 3 of 28 (2 sides × 14 subjects) (11%) whole datasets were excluded.

MD reaction time. The MD reaction time was 275 ms (SD 102) in flexion, 248 ms (SD 92) in abduction, and 248 ms (SD 98) in extension (flexion vs. abduction and extension, P < 0.05).

EMG onsets. Mean onsets of abdominal muscle activity (relative to onset of MD EMG) determined with fine-wire EMG are shown in Table 1. All mean values were <20 ms after onset of MD EMG and therefore fulfilled the criteria for feedforward activity, i.e., <50 ms after onset of MD EMG (4). Examination of the EMG onsets across muscles for a given movement direction indicated that, with shoulder flexion, the TrA EMG onset occurred ~8 ms before that of MD and was significantly earlier than the EMG onsets for OI and OE (~19–20 ms after MD) (P = 0.02). In abduction, the EMG onsets of all three abdominal muscles occurred at a similar time (P = 0.94), ~10–12 ms after that of MD. Similarly, for extension, the three abdominal muscles were activated at approximately the same time (P = 0.97), approximately 16–19 ms after MD.

Examination of the EMG onsets across movement directions for a given muscle indicated that TrA had a significantly earlier onset in flexion than in abduction or extension (P = 0.03). There was a tendency for OI and OE to have earlier onsets in abduction compared with the other movement directions but this failed to reach significance. Individual values showed considerable variability in relation to the mean patterns of activity (Fig. 4).

The group mean EMG epoch analyses confirmed the aforementioned sequence of timing of muscle onsets across muscles and movement directions: in flexion there was an early rise of TrA EMG activity, with OI and OE following ~50 ms (3 epochs) later, whereas for the other arm movement directions there was a more synchronous pattern of amplitude increase for all three abdominal muscles alike (Fig. 5).

Comparison EMG and TDI-velocity onsets. The mean TDI-velocity onsets for all three abdominal muscles gave the appearance of being systematically later than those of the corresponding EMG onsets by ~15–25 ms for extension and abduction (Fig. 6). However, when the data for flexion was examined, it was clear that the differential sequence of TrA, OI, and OE EMG onsets (TrA onset significantly earlier than OI or OE; see Table 1 and Fig. 6) was not reflected in similar differences in TDI-determined onsets, and this indicated that TDI could not distinguish between the onsets of the individual abdominal muscles. Instead, the TDI velocity change, for any
given movement direction, was dependent on the earliest EMG-recorded activation in any one of the three muscles. Hence, only the onsets for the “earliest abdominal muscle activity” (or “first on”) were used for subsequent analyses.

Agreement between EMG and TDI-velocity onset methods. The results of the Bland-Altman analyses for the earliest abdominal muscle onset times are shown in Fig. 7. There was a mean difference of 20 ms (SD 30) between the two methods, and the 95% limits of agreement were -40 to 80 ms (or ±60 ms). Removal of an extreme outlier (see Fig. 7) resulted in a mean difference of 22 ms (SD 25), and limits of agreement -28 to 72 ms (or ±50 ms). There was a significant correlation between the onsets determined with EMG and with TDI for the earliest abdominal muscle activity \( r = 0.47, P < 0.0001 \), increasing to \( r = 0.63 \) with the exclusion of the extreme outlier).

Between-day reliability of TDI-velocity onsets. The mean onset times for the earliest abdominal muscle activity (relative

**Fig. 4.** Individual datasets for the onset of abdominal muscle EMG activity, relative to the onset of medial deltoid (MD), for movement in each direction. Each point indicates the mean onset time averaged over the 10 repeated trials for a given individual for a given movement direction on a given body side. For each muscle, the dashed line at zero indicates the onset of MD activity. Positive values indicate abdominal muscle onset after MD; negative values, before MD. “Earliest active” is the onset of the first of the three abdominal muscles to be activated. Note the high individual variability, especially in flexion, leading to the large SDs around the mean shown in Fig. 6.

**Fig. 5.** EMG signal amplitude for each abdominal muscle for each of 35 × 10 ms epochs during the rapid arm movements (top, flexion; middle, extension; bottom, abduction). The onset of MD activity occurred between the 10th and 11th epoch.

**Fig. 6.** Comparison of mean (±SD) abdominal muscle onset times recorded with EMG and TDI tissue velocity changes for each muscle (TrA, OI, OE) and for the earliest muscle to be activated (“first on”) for each movement direction. The TDI onsets do not follow those of the EMG onsets for each individual muscle but are instead dependent on the earliest EMG-recorded activation in any of the 3 muscles for the given movement direction: for abduction (Abd) and extension (Ext) there is a more or less concurrent activation of all 3 muscles seen with EMG, leading the TDI onsets to give the appearance of “following the timing” of the EMG onsets for the respective muscles; however, in flexion (Flex), the TrA is activated considerably earlier than the other 2 muscles and this then highlights the true mismatch in EMG and TDI-determined onsets on an individual-muscle basis. When both TDI and EMG onsets are expressed in relation to the earliest activation of any muscle (first on), a relatively systematic difference between the mean TDI and EMG-determined onsets is revealed.
to the movement switch) for all movement directions and body sides were $-91.0$ ms (SD $24.0$) on day 1 and $-94.4$ ms (SD $25.0$) on day 2 ($P = 0.14$). The corresponding ICC, SEM, mean difference (± limits of agreement) were 0.58, 15.8 ms, and $-3 ± 44$ ms, respectively.

**DISCUSSION**

**Feedforward activity of the abdominal muscles as recorded with EMG.** The present study examined whether TDI provides a viable noninvasive method to measure feedforward activity of the abdominal muscles during rapid arm movements by comparison with the “gold standard,” intramuscular EMG. Although not without its own limitations (7), intramuscular EMG is currently the only method available to accurately identify the onset of activity within deep-lying or small/thin muscles. The test setting employed in the present study was similar to that used in the original studies of Hodges et al. (32, 33), with the exception that the arm movements were performed in a choice reaction time task, with the task direction randomized, rather than a simple reaction time task where the movement direction is predictable. The additional decision making lengthens the response time of the prime mover (38, 43), explaining the longer time from the cue signal to the onset of deltoid activity in the present study (average $257$ ms) compared with previous studies (176 ms) (32, 33), and prevents any postural preparation before the cue to move. Equivalent and muscle-dependent findings have been reported for the effect on the timing of anticipatory postural adjustments of introducing choice into the response task (4, 24, 43).

The methods used for determination of EMG onset, i.e., visual examination, were consistent with the more recent studies by Hodges et al. (29, 38, 39) but differed from those in their earlier series of experiments, in which automated techniques were used (24, 30, 32, 34). The accuracy of the onsets determined in the present study by visual inspection was verified by the consistent results obtained for the epoch analyses with respect to the relative onsets of the three abdominal muscles.

Notwithstanding the slight differences in methodology, the results for the abdominal muscle EMG onsets recorded in the present study were expected to replicate those previously reported for healthy volunteers, at least in terms of trends across muscles and movement directions (32–34). In the present study, the mean EMG onset for the three abdominal muscles suggested feedforward activation, i.e., EMG onset was ± 50 ms after the onset of deltoid EMG in all movement directions (4). This is commensurate with most of the previous data (32–34), except that in earlier studies the onset of OE EMG was 60 ms after MD in shoulder flexion, which is just outside the range considered to be feedforward (32, 34). Further, we confirmed the significantly earlier onsets for TrA compared with OI/OE during shoulder flexion, and lack of significant difference between the three muscles for their onsets in shoulder abduction and extension (32, 33). In each case, our absolute mean values for the onset of each muscle differed from those of Hodges et al. (32, 33), although this may have arisen, in part, as a result of the methodological factors described earlier, or the interindividual variability typically observed for these parameters, both here (see Fig. 4) and in previous studies (33, 32).

The previously reported influence of arm movement direction on OI and OE EMG onsets, with shoulder abduction resulting in significantly earlier onsets than shoulder flexion (32, 33), could not be replicated in the present study, although nonsignificant tendencies consistent with the previous reports were observed. Earlier activity of OE and OI is commonly reported during shoulder extension and abduction movements to prepare for the reactive flexion and lateral flexion moments, respectively, at the trunk and control the shift in center of mass of the body (2, 3, 27). However, since all movements were made unilaterally, coupled axial rotation and/or lateral flexion moments would have accompanied each of the primary movements (27), perhaps explaining the less clear-cut directional specificity. It has been reported that the possible postural function of a muscle cannot be based exclusively on its apparent function (e.g., a flexor, an extensor, an abductor, etc.) and that the postural control system may at times employ counterintuitive strategies of muscle activation (3). Possibly, this is more marked in choice reaction tasks (less preplanning possible), accounting for the differences between the present and previous studies in the extent of the directional specificity observed. Other explanations include the variation in strategy adopted by individual subjects (highlighted in Fig. 4), either as an innate characteristic, or in relation to the test set-up itself, e.g., due to the presence of the EMG wires or the attachment around the abdomen of the transducer-block and Velcro straps.
potentially adding lumbar support/stabilization and altering the “normal” motor control strategy, etc.

The significantly earlier activation of TrA with shoulder flexion compared with the other movement directions also requires consideration. While the present data support the earlier conclusion that this muscle is active in a feedforward manner regardless of movement direction, the earlier onset in flexion differs from previous data that show variable timing of onset of TrA EMG between movement directions (32). Earlier TrA EMG onset during shoulder flexion is consistent with a contribution of TrA to control of the associated trunk flexion moment, i.e., to generation of a trunk extension moment. Such an extension moment has been shown in modeling (16) and in human experimental studies (26) and is thought to occur either via increases in intra-abdominal pressure (IAP) (6) or via tensioning of the thoracolumbar fascia (5, 46). Although in vivo measures suggest that the extension moment generated by TrA is small, it cannot be excluded that this explained the earlier activation of TrA during shoulder flexion. In earlier studies of bilateral upper limb movement, which induces greater reactive forces, differences in TrA EMG onset between directions of movement have been reported in some subjects (21). Furthermore, differential activity of TrA has been recorded during tasks with high rotary moments (51). Thus specific mechanical demands appear to be able to drive differential activation of TrA between movement directions. As discussed above for the case of OE/OI, the response characteristics of TrA also may vary between individuals, emphasizing the need for much larger studies of deep trunk muscle control.

Comparison of feedforward activity of abdominal muscles measured with TDI tissue velocity changes and with EMG. Comparison of the mean TDI-velocity and EMG onset values across movement directions (Fig. 6) indicated that TDI was unable to distinguish between activity of the three abdominal muscles: the onset of TrA EMG earlier than OE/OI in shoulder flexion was not reflected in corresponding differences in TDI onsets. The lack of differentiation between the muscles may have been due to “cross-motion” between them, due to tethering or compression effects, as a result of their contiguous nature. This has been observed in relation to attempts to record selective activation of superficial and deep portions of the multifidus muscle using M-mode ultrasound measures of tissue deformation (54). The latter authors suggested that TDI may provide the solution to the problem; however, it appears that, even though TDI can be used to measure the tissue velocity for well-defined regions, contraction in one muscle can still result in movement and velocity changes in apposing muscles. In future studies, consideration of the actual tissue velocity reached for each muscle, rather than just its onset of change, may assist in defining the muscle that initiates the movement, since passive movements yield considerably lower velocities compared with active movements (19). Further, measures of strain rate rather than velocity may be better able to distinguish between active and passive motion, as seen in the assessment of myocardial dysfunction (18). In the meantime, however, we still consider assessment of the earliest muscle active to be adequate for use in future clinical studies in this area. Where delays in feedforward activity have been observed in groups of patients with LBP (24, 30, 31, 33) or experimental pain (29, 38), all abdominals tended to be affected to a certain extent. Further, although the TrA was often affected most, no obvious compensation strategy involving earlier onsets of the other abdominal muscles was seen, at least on a group-data basis (few studies examined the potential for individual variations in timing). Several recent studies suggest increased activity of more superficial muscles during arm movements (29) and changes in timing (albeit in a different task) (42), although different strategies of increased activity were used by each individual. In this sense, examination of the first muscle active may convey certain advantages, by reflecting individual activation strategies that are otherwise obscured by averaging group data for a given muscle.

The TDI recordings of the earliest onset of activity within the lateral abdominal muscle group showed a moderate but significant correlation with the corresponding variable measured with EMG. However, a systematic difference was found between paired values recorded with each method, with EMG onsets preceding those of TDI by, on average, ~20 ms. Part of this may be accounted for by the internal time delay inherent in ultrasound systems (55). Based on timing information embedded in the TDI M-mode data and switch signals exported by the ResearchLink option of the HDI-5000 scanner, we established that the switch samples preceded the corresponding TDI M-mode columns by a time interval varying from 6.8 to 8.2 ms. A further systematic difference between the two methods can be expected due to the electromechanical delay (EMD) between the onset of muscle activity and the development of tension (12, 57). Although it is not known whether the TDI-velocity changes reflect the initial stages of movement in the contractile elements of the muscle or the whole muscle shortening/thickening on stretching of the series elastic components, the onset of tissue motion would be expected to lie somewhere within the interval of the EMD. The literature reports EMDs ranging from as short as 17 ms (57) up to 137 ms (53). A systematic (biological) difference between the EMG and TDI onsets of ~12 ms (~20 ms minus ~8 ms machine delay) is hence feasible. This value also compares favorably with the previously reported systematic differences of ~16 ms between multifidus muscle onsets measured with EMG and ultrasound tissue deformation (54).

While the average EMD contributes to the systematic difference in group mean values between the two methods, on an individual basis there were much wider differences between pairs of values recorded using the two techniques. Individual differences in EMD, arising due to differences in the myosin heavy chain type distribution of the muscle (45), may explain some of this variability. However, the limits of agreement for the two methods were wide (~60 ms, or ~50 ms on the removal of an outlier), and on occasion the TDI onsets even preceded those recorded with EMG. Since it is physiologically impossible for the mechanical response to precede the electrical signal, this raises the possibility that false TDI onsets were at times recorded, perhaps related to increases in abdominal pressure or motion artefact before the true feedforward activation, or that recordings made with the two methods actually emanated from different populations of motor units. The wire electrodes were placed directly below the ultrasound transducer, such that the signals collected should have been generated from one and the same anatomic structure; however, the pick-up area associated with fine-wire EMG is more localized than that of TDI. At such low levels of muscle activity, this
could have yielded differences in the timing of activity detected by the two recording devices. Nonetheless, this might have been expected to lead to consistent differences between methods for a given individual, yet this was not always the case.

Some differences between the methods may be attributable to the different characteristics of the two biological signals: compared with EMG, TDI-velocity traces had a steadier baseline, leading to easier onset determination. Further, for TDI-velocity measures, samples were recorded at 333 Hz (highest possible rate), providing a resolution of 3 ms, whereas EMG data were sampled at 5 kHz, providing a resolution of 0.2 ms. Hence, TDI data were smoothed to a greater extent than EMG data. The sensitivity to detect change from baseline will have been affected by these two issues; indeed, a greater proportion of EMG than TDI trials showed no clear onset (EMG 13% vs. TDI 3%), and more EMG than TDI onsets were out of the physiological range for inclusion (EMG 2% vs. TDI 1%). Previous EMG studies have also reported exclusion of up to 15% of trials during onset analyses (38).

In examining the between-methods differences for a given trial, the random error associated with onset determination for each method must also be considered. The SEM for muscle onsets (TDI or EMG), determined twice on a given dataset, were ~9–12 ms (same observer) and 15–24 ms (different observers). Thus the error of measurement, per se, likely explains a sizeable proportion of the difference between methods.

The limits of agreement between two methods are usually used to make decisions as to whether a new method of measurement represents an adequate alternative for the existing “gold standard” (9). In the present study, the limits of agreement were wide (see Fig. 7), although not dissimilar to those previously reported for the agreement between EMG and another ultrasound-based method (~43 ms for which pairs of data were even “preselected” for analysis on a basis that increased the likelihood of agreement (54). The wide limits would tend to imply that, even after adjustment for the systematic difference, the ultrasound-based and EMG methods cannot be considered comparable/interchangeable; however, since the error associated with onset determination per se is similar for each method and accounts for a large proportion of the between-methods error, we believe that one method cannot necessarily be considered superior to the other. Instead, it would appear that they are comparable methods for determination of the onset of earliest muscle activity, based on different phenomena that are nonetheless part of the same physiological process, with a physiologically plausible systematic difference between their values, and being associated with a similar amount of measurement error. However, if the three abdominal muscles are to be considered separately, EMG is superior.

Possible advantages of TDI for assessment of activity in other small or deep-lying muscles, in addition to its noninvasive nature, include the visual control of the recording area. Furthermore, since TDI records from the whole depth of the muscle, taking average values by means of an image “slice” through its depth, it may characterize whole muscle activity better than either fine-wire EMG (localized recording area) or surface EMG (variable and unpredictable recording area, affected by subcutaneous fat, interelectrode distance, and distance between electrodes and the active muscle) (17).

Between-day reliability for measurement of onset of muscle activity with TDI. To be able to recommend TDI for use in future studies of feedforward activity of the lateral abdominal muscles, it was considered important to assess the between-day error of measurement of this physiological phenomenon. This was quantified as the SEM or “typical error” (35), incorporating individual day-to-day biological variation as well as the “technical error” inherent in all stages of the measurement process. To our knowledge, there are no comparable data available in the literature for TDI or any other ultrasound-based methods. For EMG, there are only unpublished data, and these indicate a between-day SEM for the visually determined EMG onsets of ~18 ms and ~12 ms for the average of 5 and 10 trials, respectively (G. L. Moseley and P. W. Hodges, unpublished observations). The SEMs recorded in the present study for the TDI onsets (up to 10 trials averaged on each day) were of a comparable magnitude (~16 ms), and no greater than the error associated with the simple onset-determination procedure itself (see earlier).

In summary, we conclude that, although TDI is unable to distinguish between the onsets of the individual lateral abdominal muscles, it represents a valid and reliable noninvasive alternative to EMG for determining the earliest onset of activity of the muscle group during rapid arm movements. Future studies will identify whether it can be used to distinguish between patients with chronic LBP and healthy controls in their motor control patterns and whether the latter are responsive to change after exercise interventions. The method might also find application in other areas of musculoskeletal research in which the onset of activity of small, deep-lying, or inaccessable (to wire EMG) muscles is to be examined.

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