Reduced task-induced variations in the distribution of activity across back muscle regions in individuals with low back pain

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This study investigated change in the distribution of lumbar erector spinae muscle activity and pressure pain sensitivity across the low back in individuals with low back pain (LBP) and healthy controls. Surface electromyographic (EMG) signals were recorded from multiple locations over the lumbar erector spinae muscle with a 13 × 5 grid of electrodes from 19 people with chronic nonspecific LBP and 17 control subjects as they performed a repetitive lifting task. The EMG root mean square (RMS) was computed for each location of the grid to form a map of the EMG amplitude distribution. Pressure pain threshold (PPT) was measured before and after the lifting task over a similar area of the back. For the control subjects, the EMG RMS progressively increased more in the caudal region of the lumbar erector spinae during the repetitive task, resulting in a shift in the distribution of muscle activity. In contrast, the distribution of muscle activity remained unaltered in the LBP group despite an overall increase in EMG amplitude. PPT was lower in the LBP group after completion of the repetitive task compared to baseline. Reduced variability of muscle activity may have important implications for the provocation and recurrence of LBP due to repetitive tasks.

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1. Introduction

Low back pain (LBP) affects 50%-80% of the population at some stage of their lives [3,7]. While many individuals recover within 1 month of their first episode, most people will have recurrence of pain within 12 months [12,14]. A contributor to the persistence or recurrence of LBP is altered neuromuscular control of the trunk [13,23].

Numerous studies have shown changes in muscle activation in LBP, including reduced transversus abdominis activity during walking [48], and repetitive arm movements [24], increased erector spinae activity during the stride [1,57,63] and swing [5,31] phase of gait, and increased trunk muscle co-activation during sudden unloading of the spine [45] and during unexpected, multidirectional translation perturbations [22,28]. These studies have utilized classic bipolar electromyography (EMG). In these applications, electrodes are placed over a small portion of a muscle. The amplitude of the EMG signal can be measured to evaluate the magnitude of muscle activation, the frequency content analyzed to assess myoelectric manifestations of fatigue, or the onset of activity detected to evaluate reaction times. However, as consistently shown, the responses in patients with LBP are highly variable and may even be contradictory [25,55,60]. This is not surprising given the limited information that can be obtained from a single pair of electrodes placed over a small muscle region. In contrast, high-density, 2-dimensional surface EMG provides a measure of the electric potential distribution over a large surface area [20,65]. This method provides a topographical representation of EMG amplitude, and can identify relative adaptations in the intensity of activity within regions of a muscle/s [65]. This novel technique has been applied in healthy individuals and has revealed spatial heterogeneity in muscle activity under various conditions.

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[18,20,26], indicating a nonuniform distribution of motor units or spatial dependency in the control of motor units [27]. For example, studies in asymptomatic individuals show a change in the distribution of lumbar erector spinae muscle activity during sustained lumbar flexion [56].

Variation in the distribution of activity within the same muscle is functionally important to maintain motor output in the presence of altered afferent feedback (eg, pain or fatigue) [20]. This mechanism is potentially relevant to avoid overload of the same muscle fibers during prolonged activation and is particularly relevant for muscles commonly exposed to repetitive or sustained activation, such as the lumbar erector spinae [2]. It is unknown whether this mechanism of adaptation of muscle activity is altered in people with LBP during repetitive work. Such knowledge may have important implications for the provocation of LBP due to repetitive tasks.

We investigate the topographical distribution of EMG amplitude in the lumbar erector spinae muscle of healthy controls and people with chronic LBP during a repetitive lifting task. It was hypothesized that the mechanisms of adaptation of muscle activity across regions of the lumbar erector spinae would be altered in the presence of LBP. In addition, we obtained multiple measures of pressure pain threshold over the same area of the lower back to assess the effect of the task on pressure pain sensitivity.

2. Methods

2.1. Subjects

Nineteen people with chronic nonspecific LBP aged between 18 and 45 years were sought for the study through referral from physiotherapy practices, general practitioners, or through general advertising in the popular press. Patients were considered for the study if they were suffering from nonspecific episodic LBP lasting longer than 3 months, with continuous LBP over the last 3 months or periods of symptom aggravation and remission in the last 6 months. Each episode of LBP should have lasted at least 1 week, with sufficient intensity to limit function.

Seventeen age- and gender-matched healthy individuals were recruited to act as the control group. Pain-free participants were included if they had no relevant history of back or lower-limb pain or injury that limited their function and/or required treatment from a health professional. Patients and control subjects had to have the capacity to give consent at his/her own will.

Participants were excluded from both groups if they had any major circulatory, neurological, or respiratory disorders, recent or current pregnancies, previous spinal surgery, back pain radiating below the knee, current treatment for low back pain from health care providers, or participation in trunk muscle exercise in the past 12 months. Patients who reported that they were in an acute “flare up” of their LBP condition were excluded due to the nature of the task. Participants were also excluded from both groups if they were taking medication such as opioids, anticonvulsives, antidepressants, or regularly high-dosed nonsteroidal antiinflammatory drugs (NSAIDs), while NSAIDs as needed were allowed. Initial screening was accomplished by telephone, and eligible persons attended a baseline evaluation appointment. Both groups were asked not to take NSAIDs for the day of the experiment.

Ethical approval for the study was granted by the local Ethics Committee and the procedures were conducted according to the Declaration of Helsinki.

2.2. Questionnaires

A questionnaire was administered to obtain information on subject demographics, history, duration of pain, average intensity of pain, and localization of pain. Patients completed the short form of the state scale of the Spielberger State-Trait Anxiety Inventory (SF-STA). It is a 6-item questionnaire that has been shown to be a reliable and sensitive measure of anxiety [51]. The Oswestry Disability Index was used to assess pain-related disability specifically related to LBP (7 items [16]). Patients also completed the Short Form (SF)-36 Health Survey [9], a measure of the general health status of the patient, and the Tampa Scale for Kinesiophobia (TSK; 17 items [62]), a measure to assess fear-avoidance behavior and fear-avoidance beliefs. The Pain Catastrophizing Scale (PCS) was implemented to assess catastrophic thinking related to pain; in this 13-item questionnaire, respondents rate the frequency with which they experience different thoughts and feelings when in pain [43].

Finally, the patient’s activity-related pain was monitored during the repetitive task. For this, participants were asked to verbally rate their level of perceived pain intensity on an 11-point numerical rating scale anchored with “no pain” (0) and “the worst possible pain imaginable” (10) every 40 seconds during the lifting task.

2.3. Experimental procedure

Subjects were asked to repetitively move a box (40 × 20 × 30 cm) with hole-shaped handles, loaded with a weight of 5 kg, between 2 shelves placed at knee (lateral epicondyle of femur with the knee extended) and shoulder (position of the clavicle while standing) height. An absolute weight was selected, rather than a relative weight, to better represent a functional task that may be encountered by the participants. The weight was placed in the center of the box and kept in position by means of light packaging foam. Starting from the lower shelf, the subjects were instructed to lift the box to the upper shelf in one second, wait for 3 seconds (without interrupting contact with the box), move it back to the lower shelf (in one second), and wait 3 seconds before commencing the next cycle. The task was performed to the beat of an electronic metronome for a total of 25 cycles (~200 seconds). Subjects practiced the movement sequence for ~1 minute without the weight prior to data recording. The duration of the task was selected based on pilot tests, which confirmed that patients could successfully complete the task without the need to interrupt the task due to pain or excessive fatigue.

2.4. Pressure pain thresholds

Pressure pain thresholds (PPT) were measured with an electronic algometer (Somedic Production, Stockholm, Sweden) over 8 locations distributed across the lumbar region, on the side of greatest pain for the people with LBP, and on the right side for the control group (Fig. 1A). The distance between the locations was 2.5 cm each starting from L5 (detected via palpation) in the cranial direction, and 2.5 cm in the lateral direction starting from the spine.

The algometer probe tip (1 cm²) was applied to the skin at a rate of 30 kPa/second and the participant was instructed to depress a handheld switch at their first perception of pain, at which point the application of pressure ceased. An explanation of the PPT measurement procedure, followed by a demonstration on the patient’s forearm or thigh, was performed prior to 2 consecutive PPT measures at each location in a randomized order. The mean of the 2 PPT measures at each location was used for further analysis. Topographical maps of the PPT were generated from the mean values (Fig. 1B). The same researcher performed the PPT measurements in all subjects before and after the repetitive lifting task.

2.5. Motion analysis

Tridimensional tracking of body movement was achieved by means of an 8-camera stereo-photogrammetry system (Oqus}

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300+, Qualisys Gothenburg, Sweden). Retro-reflective markers were placed bilaterally on the subject’s skin overlying the following landmarks (in craniocaudal order): 7th cervical vertebra (C7), left and right acromion process (LSHO, RSHO), 1st and 5th lumbar vertebrae (L1 and L5, respectively), left and right lateral epicondyle of the humerus (LELB, RELB), left and right greater trochanter (LHIP, RHIP), left and right lateral condyle of the femur (LKNEE and RKNEE, respectively), left and right lateral malleolus (LAND, RANK), and left and right 5th metatarsal (L5MT, R5MT). Landmarks were identified via palpation. Four markers were placed in a non-specific asymmetric position on the box (BOX1, 2, 3, 4) to track its average position and speed (see below). Cameras captured the movement of the subject at 64 frames per second. One of the EMG channels after amplification (see below) was mirrored on the analog board of the motion capture system (sampled at 500 Hz) by a factor of 2000, sampled at 2048 Hz, and converted to digital form by a 12-bit analog-to-digital converter.

Surface EMG signals were detected with a semi-disposable adhesive grid of electrodes (OT Bioelettronica, Torino, Italy). The grid consisted of 13 rows and 5 columns of electrodes (1-mm diameter, 8-mm interelectrode distance in both directions), with one electrode absent from the upper right corner (Fig. 2A). The position corresponding to the missing electrode was used as the origin of the coordinate system to define the electrode location. The subject’s skin was prepared by gentle local abrasion using abrasive paste (Medic-Every, Parma, Italy) and cleaned with water. The grid was located ~2 cm lateral to the lumbar spinous process midpoint, and covered the low back from the level of L5 to approximately L2 (Fig. 2B). The electrode grid was placed on the right side for healthy controls and on the most painful side (right = 14) for the people with LBP. Thirty microliters of conductive gel was inserted into each cavity of the grid to provide electrode-skin contact. A reference electrode was placed over the 6th thoracic vertebra. The bipolar EMG signals were amplified (128-channel surface EMG amplifier, OT Bioelettronica; –3 dB bandwidth 10-500 Hz) by a factor of 2000, sampled at 2048 Hz, and converted to digital form by a 12-bit analog-to-digital converter.

Fifty-nine bipolar EMG signals were obtained from the grid (12 longitudinal bipolar recordings in each column except the far right, which had 11 electrode pairs). Mean power spectral frequency (MF) and root mean square (RMS) values were computed from each bipolar recording from adjacent, nonoverlapping signal epochs of 1-second duration, as described previously [38]. For graphical representation, the 59 values were interpolated by a factor of 8, but only the original values were used for data processing and statistical analysis (Fig. 2C). To characterize the spatial distribution of muscle activity, the following variables were extracted from the 59 bipolar signals: RMS and MF averaged over the 59 signals and the 2 coordinates of the centroid of the RMS map (x- and y-axis coordinates for the medial-lateral and cranial-caudal direction, respectively) [20].

Values of RMS, MF, and x- and y-axis coordinates of the centroid were obtained over a 1-second window centered around the maximum lifting and maximum lowering speed of each cycle of the task. Since maximum speed of movement was not different between groups (see Results below), this allowed comparison of the data. Data were extracted for the beginning (average across cycles 2–4), mid (average across cycles 12–14), and end (average across cycles 22–24) of the task to monitor changes in each surface EMG variable as a function of time. To allow comparisons between groups, the RMS and MF were expressed as a percentage relative to the initial value (first cycle of the task).

2.6. Electromyography

Surface EMG signals were detected with a semi-disposable adhesive grid of electrodes (OT Bioelettronica, Torino, Italy). The grid consisted of 13 rows and 5 columns of electrodes (1-mm diameter, 8-mm interelectrode distance in both directions), with one electrode absent from the upper right corner (Fig. 2A). The position corresponding to the missing electrode was used as the origin of the coordinate system to define the electrode location. The subject’s skin was prepared by gentle local abrasion using abrasive paste (Medic-Every, Parma, Italy) and cleaned with water. The grid was located ~2 cm lateral to the lumbar spinous process midpoint, and covered the low back from the level of L5 to approximately L2 (Fig. 2B). The electrode grid was placed on the right side for healthy controls and on the most painful side (right = 14) for the people with LBP. Thirty microliters of conductive gel was inserted into each cavity of the grid to provide electrode-skin contact. A reference electrode was placed over the 6th thoracic vertebra. The bipolar EMG signals were amplified (128-channel surface EMG amplifier, OT Bioelettronica; –3 dB bandwidth 10-500 Hz) by a factor of 2000, sampled at 2048 Hz, and converted to digital form by a 12-bit analog-to-digital converter.

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2.7. Statistical analysis

An analysis of variance (ANOVA) was applied to patients’ self-reported pain intensity levels with time (baseline, and 40, 80, 120, and 160 seconds during the task, and 3 minutes after completion of the task) as a factor. Pearson’s correlation coefficients were conducted to evaluate the relationship between the maximum
pain intensity experienced by the LBP group during the task and initial pain intensity, average pain intensity over the last 4 weeks, duration of their pain, and scores on the Oswestry Disability Index, SF-36, TSK, PCS, and STAI.

A 3-way ANOVA was applied to values of the PPT with group (LBP, controls), time (pre, post), and location (8 locations distributed over the lumbar region unilaterally) as factors. ANOVAs were used to compare differences in the angle of the spine, hip, knee, and ankle across the duration of the lifting task, with group (LBP, controls) and stage of the cycle (10% increments in time over the duration of the cycle) as factors. ANOVAs were used to evaluate difference in EMG variables (RMS, MF, y- and x-coordinate of the centroid) during both the lifting and lowering phase of the task with group (LBP, controls) and phase of the task (start, mid, end) as factors. Significant differences revealed by ANOVA were followed by post hoc Student-Newman-Keuls (SNK) pair-wise comparisons.

Pearson’s correlation coefficient was assessed to analyze the relationship between the amount of electrophysiological fatigue (MF) and the change in PPT. Furthermore, Pearson’s correlation coefficients were evaluated to assess the association between the shift of the centroid of the EMG map and the range of C7-L5 angle and y-coordinate of the centroid during both the lifting and lowering phase of the task. This was achieved by comparing the RMS, MF, and range of hip angle across the task in the LBP group. Results are reported as mean and SD in the text and SE in the figures. Statistical significance was set at $P < 0.05$.

3. Results

3.1. Pain intensity

Baseline characteristics of the patient and control groups are presented in Table 1. At the beginning of the experiment, the patients rated their current LBP intensity as $1.8 \pm 1.5$. Pain increased during performance of the repetitive task ($F = 5.1$, $P < 0.001$) by 120 seconds and 160 seconds relative to baseline, however, current pain intensity had returned to baseline values 3 minutes after completion of the task (Fig. 3A). The maximum intensity of pain reported by the LBP patients during the task was positively correlated with their initial pain intensity ($R = 0.87$; $P < 0.0001$; Fig. 3B) and average pain intensity over the last 4 weeks ($R = 0.46$; $P < 0.05$; Fig. 3B), but not to the duration of their pain, or scores on the Oswestry Disability Index, SF-36, TSK, PCS, or STAI. Control subjects reported no pain at rest or throughout the repetitive lifting task.

3.2. Pressure pain thresholds

Fig. 4 presents topographical maps of the PPT measured at 8 locations distributed across the lumbar region unilaterally for all patients and all controls. The PPT was dependent on the interaction between group and location ($F = 4.2$; $P < 0.001$). PPT was lower at all locations in the LBP group compared to the control group except for locations 6 and 7 (refer to Fig. 1), where no difference was observed between groups. PPT was also dependent on the interaction between group and time ($F = 3.9$; $P < 0.05$). PPT was significantly lower in the LBP group after completion of the repetitive task, compared to baseline values (average across all locations: pre: $268.0 \pm 165.9$ kPa; post: $242.0 \pm 166.7$ kPa), whereas no change in PPT over time was observed for the control group (average across all locations: pre: $320.1 \pm 162.1$ kPa; post: $322.0 \pm 179.5$ kPa; Fig. 4). The percent reduction in PPT was dependent on group ($F = 4.0$; $P < 0.05$) but not location ($F = 1.6$; $P = 0.12$). That is, a larger reduction in PPT was observed across all locations for the LBP group compared to the control group (Fig. 4).

Table 1 Baseline characteristics of the LBP and control groups.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>LBP</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>$32.2 \pm 9.5$</td>
<td>$29.4 \pm 7.4$</td>
</tr>
<tr>
<td>Gender (% male)</td>
<td>42</td>
<td>53</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>$177.0 \pm 9.4$</td>
<td>$176.1 \pm 9.7$</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>$73.8 \pm 12.5$</td>
<td>$70.2 \pm 13.8$</td>
</tr>
<tr>
<td>Duration of pain (months)</td>
<td>$31.6 \pm 26.2$</td>
<td>$31.6 \pm 26.2$</td>
</tr>
<tr>
<td>Average pain intensity (VAS)</td>
<td>$3.1 \pm 2.0$</td>
<td>$3.1 \pm 2.0$</td>
</tr>
<tr>
<td>Oswestry Disability Score (%)</td>
<td>$13.8 \pm 7.0$</td>
<td>$13.8 \pm 7.0$</td>
</tr>
<tr>
<td>SF-36 (Total)</td>
<td>$67.6 \pm 11.8$</td>
<td>$86.5 \pm 5.8$</td>
</tr>
<tr>
<td>Physical</td>
<td>$61.3 \pm 13.9$</td>
<td>$88.4 \pm 5.2$</td>
</tr>
<tr>
<td>Mental</td>
<td>$68.3 \pm 13.7$</td>
<td>$83.2 \pm 9.0$</td>
</tr>
<tr>
<td>TSK</td>
<td>$32.1 \pm 6.8$</td>
<td>$32.1 \pm 6.8$</td>
</tr>
<tr>
<td>PCS</td>
<td>$14.5 \pm 8.7$</td>
<td>$14.5 \pm 8.7$</td>
</tr>
<tr>
<td>STAI</td>
<td>$40.1 \pm 7.2$</td>
<td>$40.1 \pm 7.2$</td>
</tr>
</tbody>
</table>

LBP, low back pain; VAS, visual analogue scale; SF-36, Short-Form-36 Health Survey; TSK, Tampa Scale for Kinesiophobia; PCS, Pain Catastrophizing Scale; STAI, State-Trait Anxiety Inventory. Values are presented as mean (SD).

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Fig. 3. (A) Pain intensity recorded at rest, every 40 seconds during the repetitive lifting task and 3 minutes after completion of the task. Significant differences between time points: *$P < 0.05$; **$P < 0.01$. (B) Correlations between maximum pain intensity experienced during the repetitive task and initial pain and average pain intensity over the last 4 weeks. Note that some patients had the same maximum pain intensity during the task and initial/average pain intensity which accounts for the reduced data points (points overlapping) e.g. four patients rated their initial pain as 0 and maximum pain during the task as 0.

Fig. 4. Topographical maps of pressure pain thresholds (PPT) recorded from 8 sites distributed over the lumbar region unilaterally for the low back pain group and control subjects measured before and after the repetitive lifting task and topographical maps of the percent change in PPT for each group.
3.3. Motion analysis

The maximum velocity of movement was not different between controls and patients (1344.3 ± 259.4 mm/second and 1285.6 ± 275.5 mm/second, respectively). The angle formed between C7 and L5 was significantly dependent on the interaction between group and cycle stage \((F = 4.6, P < 0.0001)\). As seen in Fig. 5, the spine angle (averaged across the duration of the task) was lower in the stages equivalent to 40%-80% of the lifting cycle \((SNK: P < 0.001)\), indicating reduced range of spinal movement in the LBP group in the lifting phase of the task. A significant interaction between group and stage was also observed for the hip angle \((F = 2.3, P < 0.05)\). The LBP group displayed differences in hip angle compared to the control group in the lifting phase of the task \((stages 30%-80% of the cycle; SNK: P < 0.001)\), indicating a greater range of hip angle during this phase of the cycle \((Fig. 6)\). No differences between groups were observed for the knee or ankle angles \((P > 0.05; Fig. 6)\).

3.4. Electromyography

The average RMS (averaged across the entire grid of electrodes) was dependent on the interaction between group and cycle phase during both the lifting \((F = 3.4, P < 0.05)\) and lowering phases of the task \((F = 3.2, P < 0.05)\). As seen in Fig. 7A, significantly higher values of EMG amplitude were observed at the end of the task for the LBP group during both lifting \((SNK: P < 0.01)\) and lowering \((SNK: P < 0.05)\).

The MF was also dependent on the interaction between group and cycle phase during the lowering phase of the task \((F = 3.1, P < 0.05)\), with the LBP group demonstrating lower values of MF toward the end of the task \((SNK: P < 0.05; Fig. 7B)\). MF was not significantly different between groups for the lifting phase, however, a trend \((P = 0.08)\) was present to suggest lower values of MF at all 3 time points for the patient group. There was no significant correlation between PPT and MF extracted during maximum lifting \((R = 0.13, P > 0.05)\) or maximum lowering \((R = -0.08, P > 0.05)\) of the box.

Representative topographical maps of the EMG RMS value recorded for a control subject and a patient with LBP for the start, mid, and end of the repetitive lifting task are presented in Fig. 8. Note the shift of activity in the caudal direction for the control subject across the duration of the task. On the contrary, the patient with LBP displays increased EMG amplitude over time, with minimal change in the distribution of activity across the muscle. Accordingly, the \(y\)-coordinate of the centroid was dependent on the interaction between group and cycle phase for both the lifting \((F = 3.2, P < 0.05)\) and lowering phase of the task \((F = 3.8, P < 0.05)\), with the control group demonstrating higher values of the \(y\)-coordinate toward the end of the task \((SNK: P < 0.05, Fig. 9A)\). An increase in values of the \(y\)-coordinate over time indicates a shift of activity toward the caudal region of the lumbar spine. Thus, on average, the LBP group did not show a significant shift of the EMG amplitude distribution toward the caudal region of the lumbar spine during the repetitive task. Individual data were examined to determine the proportion of subjects per group, which demonstrated a shift of the \(y\)-coordinate of the centroid in the caudal direction. In order to determine the percentage of patients showing a shift of the \(y\)-coordinate of the centroid by a relevant amount, we arbitrarily chose for both groups a threshold of 1.5 mm, as this has been shown previously to be a significant shift in the presence of fatigue of the low back muscles \([56]\). Based on this threshold, 71% of the controls and 26% of the LBP patients showed a relevant shift of the centroid of the RMS map in the caudal direction for the data extracted during maximum lowering. For the data extracted during maximum lifting, 59% of controls and 36% of LBP patients demonstrated a relevant caudal shift of the centroid of the RMS map.

No significant correlations were identified between the shift of the \(y\)-coordinate of the centroid of the RMS map from the beginning to the end of the repetitive task and the range of C7-L5 angle \((maximum lifting: R = -0.29; maximum lowering: R = -0.29; both P > 0.05)\) or range of hip angle \((maximum lifting: R = 0.31; maximum lowering: R = 0.16; both P > 0.05)\) across the task.

The \(x\)-coordinate, which indicates a shift of activity in the mediolateral direction was not dependent on group or cycle phase \((both P > 0.05, Fig. 9B)\).

4. Discussion

A change in the distribution of activity to different regions of the lumbar erector spinae was observed when pain-free individuals performed a repetitive lifting task. On the contrary, individuals with LBP performed the task with the same region of the muscle activated over time. This lack of variability in the distribution of muscle activity observed for the participants with LBP occurred concomitantly with an increase in LBP, reduced lumbar movement, and was associated with increased pressure pain sensitivity of the lumbar region. Reduced variability of muscle activity may have important implications for the provocation and recurrence of LBP due to repetitive tasks.

Persons with chronic LBP display a variety of biomechanical disturbances, including reduced acceleration of movement, decreased trunk velocity, and restricted range of motion \([36,49,50]\). The velocity of movement did not differ between groups in this study, likely because the lifting task was regulated to the beat of a metronome. However, the participants with LBP did display reduced range of spinal movement in the lifting phase of the task, compared to the control subjects, which occurred concomitantly with increased hip range of motion. The current results confirm previous work showing that individuals with LBP adopt alternative movement strategies and avoid motion of the lumbar spine when performing common reaching movements \([54]\). Reduced spinal movement may be a strategy to stiffen the spine in an attempt to protect the spine \([58]\). However, an altered movement strategy may place the spine at risk of damage, potentially contributing to the recurrence of back pain.

The participants with LBP reported an increase in their pain intensity from 1.8 at rest to 2.6 toward the end of the task, which
Fig. 6. Mean (±SE) of the hip, knee, and ankle angle displayed at percentages of the lifting and lowering cycle of the repetitive task (averaged across the duration of the task). Note that the low back pain group displayed differences in hip angle compared to the control group in the lifting phase of the task (stages 30%-80% of the cycle; *P < 0.001), indicating a greater range of hip angle during this phase of the cycle.

Fig. 7. Mean (±SE) of the average root mean square (RMS) (A) and average mean power spectral frequency (MF) (B) estimated during the lifting and lowering phases of the task. Data were extracted for the start (average across cycles 2-4), mid (average across cycles 12-14), and end (average across cycles 22-24) of the task to monitor changes in each surface EMG variable as a function of time. To allow comparisons between groups, the RMS and MF were expressed as a percentage relative to the initial value (first cycle of the task). Significant difference between groups: *P < 0.05.
represents a 38% increase in pain. A 30% increase in pain is considered to be clinically meaningful [44]. In this study, the task duration was limited to ~3 minutes only. It is very likely that larger increases of pain would occur, with extended periods of repetitive activity common to many occupational activities [53].

Participants with LBP demonstrated a reduction of the mean frequency of the EMG signal across the duration of the task, whereas the mean frequency remained stable over time for the control subjects. Relative changes in mean frequency over time are associated with the changes in the intracellular action potential induced by fatigue [38]. The spectral shift from high to low frequencies is caused by changes in intracellular action potential shape and propagation velocity [15,33,34,52]. A greater reduction in mean frequency over time can occur as a result of a greater accumulation of metabolic by-products, including potassium and lactic acid [10]. As discussed previously [53], prostaglandins, bradykinin, and hydrogen ions are released during intense exercise [4], but can also build up during less intense tasks [41]. Accumulation of these
chemicals in the muscle can lead to increasing pain sensation through direct and prolonged stimulation of nociceptors and can contribute to muscle fatigue [41]. Additionally, sustained or repetitive activities can lead to muscle ischemia, which hampers the wash-out of metabolic by-products of muscle contraction, further contributing to the provocation of muscle pain and fatigue [39]. A strategy to compensate for altered fiber properties is an increase in excitatory drive to the muscles [11], resulting in increased EMG amplitude [6], as previously observed for the lumbar erector spinae in studies utilizing bipolar EMG [59], and as confirmed in this study.

Changes in the topographical map of EMG amplitude indicate relative adaptations in the intensity of activity within muscle regions during a contraction and may be attributed to variation in peripheral properties or in the control of motor units within a muscle. A constant position of the centroid of the EMG amplitude map indicates a stable distribution of activity across the muscle regions covered by the electrode grid. In the pain-free participants, a displacement of the centroid of the EMG amplitude map occurred in the presence of a constant average EMG amplitude throughout the repetitive task. This finding indicates that there was a preferential increase in the activation in some regions of the erector spinae and decreased activity in other regions. The change in EMG amplitude distribution during the repetitive task may be due to inhomogeneous modification of the fiber membrane properties over time. For example, heterogeneous changes in membrane properties may be due to a different distribution of fiber types in different regions of the lumbar erector spinae [46]. However, more likely, motor unit recruitment or the discharge rate of the active motor units varied within the different regions of the erector spinae [17].

During the task, the shift in the distribution of EMG activity was in the caudal direction. This finding supports previous work that showed an increase in EMG amplitude in lower lumbar muscles compared to upper lumbar muscles following both repetitive lifting [8] and isometric [61] tasks that induced fatigue. This observation confirms that muscles of the lumbar erector spinae group adapt over time to a repetitive activity in a nonuniform manner. The change in relative muscle activity during repetitive or sustained contractions may reflect an efficient strategy to maintain motor output by distributing the activity across different regions of the muscle rather than overloading a specific muscle region. This mechanism has the functional importance of prolonging the endurance time [20] and is considered beneficial for the muscle due to reduced overload of the muscle regions active at the beginning of the task. On the contrary, changes in the relative activation of regions of the lumbar erector spinae were impaired in patients with LBP. The patients performed the repetitive task by maintaining the same type of activation of the muscle across the duration of the task. The long-term consequence of this strategy may be an overload of some muscle fibers and, as a further consequence, possibly a perpetuation or recurrence of LBP. Repetitive tasks are indeed considered an important risk factor for initiation, maintenance, and recurrence of LBP [64]. The altered neuromuscular control of the spine observed in this study in patients with LBP during repetitive work likely contributes to this increased risk.

Patients with LBP had significantly lower PPTs than control subjects at baseline. This result is in accordance with previous observations [19,42]. Exercise can induce a hypoalgesic response in pain-free individuals [29,40]. However, in the present study, the PPT did not change in the control group following the repetitive task, thus, it is likely that the task was not intense enough to activate endogenous pain inhibitory mechanisms. In contrast, the PPT was further reduced in the LBP after completion of the repetitive lifting activity. Exercise-induced hyperalgesia has been observed previously in LBP [53] and other chronic pain conditions, including fibromyalgia [30]. It has been suggested that proinflammatory responses to muscle activation might be one of the processes that underlies exercise-induced hyperalgesia in individuals with chronic pain [47]. It has also been suggested that central processing of nociceptive stimuli from the muscles might be upregulated in patients with chronic pain [21,32].

4.1. Methodological considerations

Due to technical limitations, EMG recordings were performed only on the most painful side for the LBP subjects and on the right side for controls. It was preferred to have more channels on one side (the painful side) in order to generate a larger mapping of back muscle activity rather than having a reduced number of electrodes spread bilaterally, since previous studies have shown larger changes in muscle activation ipsilateral to the side of greatest pain [35,37]. Pressure algometry was performed on the same side for consistency with the EMG measurements.

Conflict of interest statement

The authors declare no conflicts of interest.

References