Smudging of the Motor Cortex Is Related to the Severity of Low Back Pain

ARTICLE in SPINE · APRIL 2015
Impact Factor: 2.3 · DOI: 10.1097/BRS.0000000000000938 · Source: PubMed

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Smudging of the motor cortex is related to the severity of low back pain

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The manuscript submitted does not contain information about medical device(s)/drug(s). The National Health and Medical Research Council of Australia research fellowship funds were received in support of this work. No relevant financial activities outside the submitted work.

Abstract

Study design: Cross-sectional design.

Objective: Here we aimed to determine whether motor cortical reorganisation in LBP can be identified using non-invasive surface electromyographic (EMG) recordings of back muscles.
at different lumbar levels, and whether cortical reorganisation is related to clinical features of LBP.

**Summary of background data:** Reorganisation of motor regions of the brain may contribute to altered motor control, pain and disability, in chronic LBP. However, data have been limited by the need for invasive recordings of back muscle myoelectric activity. The relationship between altered cortical organisation and clinical features of LBP remains unclear.

**Methods:** In 27 individuals with recurrent, non-specific LBP and 23 painfree controls, we mapped the motor cortical representation of the paraspinal muscles using transcranial magnetic stimulation in conjunction with non-invasive surface EMG recordings at L3 and L5 levels. Clinical measures of pain severity, location and duration were made.

**Results:** The results demonstrate a loss of discrete motor cortical organisation of the paraspinal muscles in chronic LBP that can be identified using non-invasive EMG recordings. A loss of discrete cortical organisation was clearer when surface electrodes were positioned at L3 rather than L5. A novel finding was that altered motor cortical organisation (number of discrete peaks and map volume) was associated with the severity and location of LBP.

**Conclusions:** These data suggest surface EMG positioned at L3 is appropriate for identification of changes in the motor cortex in LBP. Further, our data have implications for treatment strategies that aim to restore cortical organisation in LBP.

Key Words: chronic low back pain, Electromyography, motor Control, motor cortex reorganization, paraspinal muscles, pain severity, pain duration, Pain location, transcranial magnetic stimulation
Mini abstract: This study demonstrates that motor cortical organisation is associated with the severity and location of LPB and can be measured using non-invasive EMG recordings. This information may have implications for treatments that aim to restore cortical organisation in LBP.

Key points:

1. Motor cortical organisation is associated with the severity and location of LPB
2. Altered motor cortical organisation in LBP can be measured non-invasively using surface EMG recordings.
3. A relationship between motor cortical organisation and LBP severity and location has implications for treatments that aim to restore cortical organisation in LBP.

Introduction

Low back pain (LBP) is associated with poor rates of recovery and high rates of recurrence. Although persistence of symptoms is multifactorial, altered control of back muscles has been identified as a predictor of pain onset and recurrence. Despite this, the mechanisms that underpin adaptation of the motor system, and their relationship to pain and disability, remain poorly understood. Reorganisation of the primary motor cortex (M1) has been identified in LBP, and this may contribute to altered motor control, pain and disability. However, interpretation of these findings is limited by the use of invasive recordings that restrict the number of individuals tested. The relationship between brain...
organisation, motor control and clinical features of LBP will remain unclear until larger populations can be tested using less invasive methods.

Maps of M1 generated for two back muscles (lumbar longissimus [LL] and deep multifidius [DM]) using transcranial magnetic stimulation (TMS)) demonstrate a change from two discrete map peaks in healthy individuals to a single, overlapped peak in LBP\textsuperscript{4}. Increased overlap (‘smudging’) in the cortical representations of LL and DM may explain the loss of differentiated control of the paraspinal muscles and tendency for back muscles to be recruited \textit{en masse} in this population\textsuperscript{6,7}. A key feature of this work was the discrete recording of electromyography (EMG) from individual muscle fascicles with intramuscular fine-wire electrodes. Although fine-wire electrodes enabled resolution of the origin of the EMG signals, their invasive nature restricts the size of the participant group and thus, sample sizes have been insufficient to address the relationship between motor cortical organisation and clinical symptoms. No studies have investigated whether reorganisation of the cortical outputs to the back muscles in LBP is identifiable with non-invasive recordings. Further, motor cortical mapping has been limited to investigation of a single level of the spine and it is unclear whether changes are present across multiple spinal levels.

This study aimed to determine whether reorganisation of M1 in LBP: i) can be identified from non-invasive surface EMG recordings of back muscles; ii) is present in individuals who have LBP at the time of testing; iii) differs between levels of the lumbar spine; and iv) is related to clinical features of mild to moderate LBP.

Materials and methods

Participants

Twenty-seven individuals with non-specific, recurrent LBP and 23 painfree individuals participated. Individuals with LBP were included if they experienced episodic
pain in their low back, sufficient to limit function, for greater than 3 months. Individuals were excluded if they presented with suspected spinal pathology, major circulatory, neurological or psychiatric conditions, previous spinal surgery or recent/current pregnancy. LBP participants indicated the region of worst pain on a body chart. From this diagram the side of worst pain was identified and participants allocated to either “upper” or “lower” lumbar pain on the basis of whether pain was indicated above or below the line representing the iliac crest. Participants rated their current pain intensity on an 11-point numerical rating scale (NRS). Participants were asked to estimate the duration of LBP as the total time since their first episode, regardless of periods of remission. Participant characteristics are provided in Table 1.

All procedures were approved by the institutional Ethics Committee and conformed to the Declaration of Helsinki.

**Electromyography**

Surface EMG was used to record activity of the paraspinal muscles at two sites: 3 cm lateral to the spinous process of L3 and 1 cm lateral to the spinous process of L5, on the side of worst pain (silver-silver chloride disposable electrodes; Noraxon USA Inc, Arizona, USA). These sites record EMG from multiple back muscles. As the purpose of this study was to determine whether multiple peaks in the TMS map could be recorded from surface electrodes it was necessary to record from multiple muscles simultaneously. EMG data were amplified 1000x, filtered 20-1000 Hz and sampled at 2000 Hz.

**Motor cortex mapping**

Single-pulse TMS (width 1ms) was delivered to M1 contralateral to the side of worst pain (figure-of-eight coil; Magstim Co. Ltd. Dyfed, UK). The vertex was determined using the 10/20 International EEG Electrode Placement system and this point registered using a Brainsight2 neuronavigation system (Rogue Resolutions Ltd, Cardiff, UK). Starting at the
cranial vertex, used as the standard reference for reporting location of TMS of the brain\textsuperscript{4,9,10}, five magnetic stimuli were delivered at 1-cm intervals on a 6 x 7 cm grid. Accurate coil placement was determined using neuronavigation. Stimuli were applied at 100% (maximum) stimulator output. During TMS mapping, participants were requested to activate the paraspinal muscles to 20% of the EMG amplitude recorded during a maximum voluntary contraction (MVC). This level of activation of the extensor muscles was based on that used in previous studies\textsuperscript{4,9} and was required for two reasons. First, activation of muscles facilitates the corticomotor pathway and thus increases MEP amplitude. This is often necessary to evoke a MEP in trunk muscles. Second, control of the intensity of contraction standardizes the facilitation of the pathway between participants. The target EMG amplitude was determined as 20% of the highest root mean square (RMS) EMG for 1 s during three, 3-s maximal trunk extension efforts performed against manual resistance in sitting. Visual feedback was provided on a computer monitor and the 20% MVC target achieved by sitting forward with the back straight\textsuperscript{11,12}. All procedures adhered to the TMS checklist for methodological quality\textsuperscript{13}.

\textit{Data analyses}

EMG was full-wave rectified and the five MEPs at each scalp site averaged. MEP onset and offset were visually identified from the averaged traces and MEP amplitude calculated as the RMS EMG amplitude between the onset and offset\textsuperscript{4,5,14-16}. Background EMG from 55 to 5 ms prior to stimulation was subtracted\textsuperscript{4,5,15}. MEP amplitudes were superimposed over the respective scalp sites to produce a topographical representation of the target paraspinal muscle and normalised to the peak amplitude for each participant. Normalised values less than 25 % of the peak response were removed and the remaining values rescaled from 0 to 100 % \textsuperscript{4}. Three parameters were calculated from motor cortical maps. First, map volume, a measure of the total excitability of the cortical representation, was
calculated as the sum of the mean normalised MEP peak-to-peak amplitude at all active sites. To be considered “active”, a scalp site was required to evoke a MEP with a normalised amplitude of equal to or greater than 25% of the peak response. Second, the centre of gravity (CoG), defined as the amplitude weighted centre of the map\textsuperscript{17,18}, was calculated for each muscle using the formula: CoG = \( \sum V_i x X_i / \sum V_i \), \( \sum V_i x Y_i / \sum V_i \); where: \( V_i \) = mean MEP amplitude at each site with the coordinates \( X_i, Y_i \). Finally, the number of discrete map peaks was determined using criteria that were derived based on inspection of data from a previous study\textsuperscript{4} and initial pilot work. Accordingly, a peak was identified if its amplitude was greater than 60% of the maximum MEP amplitude and was separated from any adjacent areas above the threshold by a reduction in MEP amplitude of at least 20%. Peaks in addition to the primary peak were only registered if they were separated from the primary peak along an anterior-posterior axis\textsuperscript{4}.

Statistical analyses

Map volume, CoG position and the number of discrete map peaks were compared between groups (LBP/control) using one-way analyses of variance (ANOVA). Post-hoc tests were performed using Holm-Sidak tests for multiple comparisons. Possible relationships between clinical features and properties of the cortical map were investigated in two ways. First, linear relationships between continuous measures of map volume and measures of pain severity and duration were examined using Pearson’s coefficients. Second, the relationship between clinical features and ordinal data (i.e. number of discrete map peaks) was compared between individuals based on pain duration (long – duration \( \geq 60 \) months; short – duration < 60 months; based on group median duration of 60 months), location (upper or lower [above or below the iliac crest] and pain severity (moderate to severe - LBP > 5 on the NRS; mild - LBP \( \leq 5 \) on the NRS; based on recommendation of NRS of 5 as an optimum cut-off to
Results

**Altered cortical organisation can be identified using surface EMG**

Figure 1 shows normalised TMS maps. The number of discrete peaks was less in the L3 map for the LBP (1.3±0.5, p=0.009; Figure 1a) than painfree participants (1.7±0.5; Figure 1c). At the L3 recording site, 70% of painfree controls, and only 33% of individuals with LBP, displayed two discrete map peaks. Although there was no significant difference in the number of discrete peaks in the L5 map between individuals with (1.4±0.5; Figure 1b) and without LBP (1.7±0.5, p=0.15; Figure 1d), 65% of painfree controls, and only 44% of individuals with LBP, displayed two discrete peaks. The map generated from averaging data for the group show two separate peaks when EMG is recorded with the electrodes at L3, but only one site when EMG was recorded at L5.

The CoG was located more anteriorly for both the L3 and L5 maps in individuals with LBP (L3: LBP 1.4±0.61, painfree 0.8±0.77 p=0.006; L5: LBP 1.5±0.7, painfree 1.0±0.8 p=0.02, Figure 3).

Map volume did not differ between LBP and painfree participants at either the L3 (LBP 9.8±5.1, controls 10.5±5.1, p=0.65) or L5 recording sites (LBP 10.1±5.5, painfree 10.5±5.0, p=0.81) regardless of the location of pain (L3 p=0.87; L5 p=0.93).

**Altered cortical organisation is related to clinical features of LBP**

All individuals with moderate-severe LBP (>5 on the NRS n=8) displayed a single discrete peak in the topographical map of L3 (moderate-severe LBP 1±0; Figure 2a) whereas this was apparent for only 53% of participants with mild LBP (≤ 5 on the NRS; n=19; 1.5±0.5, p=0.016, Figure 2c) and 30% of painfree controls (1.7±0.5; Figure 2e). The number
of discrete peaks in the L5 map was not related to pain severity (moderate-severe LBP 1.6±0.5 peaks; Figure 2b; mild LBP 1.4±0.5 peaks; Figure 2d; painfree controls 1.7±0.5 peaks; Figure 2f; p=0.24). The number of discrete peaks did not differ based on pain duration (L3: p=0.82; L5: p=0.8) or location (L3: p=0.79; L5: p=0.41).

Although map volume did not differ between LBP and control subjects, our data revealed a relationship between map volume and pain severity that was dependent on the location of pain. In individuals with upper LBP (n=11), a smaller map volume at both L3 and L5 was related to higher pain severity (L3: r=0.73, p=0.01, Figure 4a; L5: r=0.69, p = 0.01, Figure 4b). There was no such relationship for individuals with lower LBP (n=16; L3: r=0.16, p=0.53, Figure 4c; L5: r=0.14, p = 0.59, Figure 4d). Although not significant, there was a tendency for an association between map volume at L3 and pain duration in those with upper LBP (i.e. maps tended to be larger the longer the pain duration; r=0.54, p=0.08). Similar trends were not present when L5 map volume was considered in relation to pain duration (upper pain: r=0.27, p=0.41; lower pain: r=0.22, p=0.41).

Discussion

Our findings show that loss of discrete motor cortical organisation of the paraspinal muscles can be identified using non-invasive EMG in individuals with persistent LBP who have symptoms at the time of testing. Cortical reorganisation in the LBP group most closely resembles that obtained using fine-wire recordings when surface EMG electrodes are positioned at the level of L3. A new finding is that features of altered motor cortical organisation are associated with the severity and location of LBP.

Organisation of M1 can be measured with non-invasive EMG
A key finding is that organisation of cortical networks with outputs to the paraspinal muscles can be evaluated in humans with, and without, LBP using non-invasive surface EMG. Previous work using invasive fine-wire EMG positioned at L4 revealed several characteristics of the “motor brain” that differed between healthy individuals and those with LBP: i) a shift from two discrete peaks in the topographical representation of the paraspinal muscles in healthy individuals to a single peak in LBP; ii) smaller map volume in LBP than healthy controls; and iii) a CoG that was located more posteriorly in LBP. We show similar changes in the number of discrete peaks between LBP and controls using non-invasive EMG at L3 (70 % of controls and 33 % of LBP displayed two peaks). Some differentiation of discrete map peaks between the healthy and LBP groups at L5 was also present, although less clear (65 % controls and 44 % of LBP with two peaks). Surface electrodes have a broad detection area and include contribution from muscles across multiple spinal levels. However, our finding that differentiation of cortical representations was clearer when surface EMG was recorded at L3 could be considered surprising given that LBP is more common in lower regions and multifidus wasting is also more common at lower sites. Differences in the relationship between the paraspinal muscles and the surface EMG recordings at the two sites, for example as a result of differences in relative muscle bulk of deep short and long superficial muscles, may influence the sensitivity to detect differences in cortical representations for these muscles at different lumbar regions.

Our data are the first to determine the proportion of LBP and painfree individuals who display a single map peak in the cortical representation of the paraspinal muscles. A reduction in map volume was also observed using surface EMG at L3 and L5, but only in individuals with more severe pain in the upper lumbar spine. In contrast to previous findings, the CoG was located more anteriorly for both the L3 and L5 maps in LBP than for controls. Extrapolation of previous CoG findings in LBP is limited by the use of non-
invasive recordings in our data, where the cortical representation of both LES and DM contribute to the total map. This contrasts invasive fine wire recordings that allow the CoG for LES and DM to be determined separately\(^4\). Calculation of the CoG for separate paraspinal muscles is one limitation of non-invasive surface EMG recordings, but does not limit the utility of these recordings to interpret overall organisation of the M1 map.

*Reorganisation is related to clinical features of LBP*

Our data provide evidence of a relationship between organisation of M1 in LBP and pain severity, duration and location. A unique finding is that greater smudging of the cortical representation at L3 (single map peak) was more consistently present in individuals with higher pain severity, whereas individuals with lower severity exhibit a pattern of cortical organisation that is more similar, on average, to that of controls. A loss of discrete organisation of the cortical networks that control paraspinal muscles has potential functional consequences. Individuals with focal dystonia, a condition characterised by excessive and inappropriate muscle activity during skilled motor tasks, have a reduced ability to independently contract involved muscles and move fingers independently. This motor dysfunction is associated with greater overlap of the cortical representations of the hand muscles compared with healthy individuals\(^{10,22}\). Taken together with the observation of reduced discrete activation of the paraspinal muscles in LBP\(^4,6,7\), smudging of cortical areas could explain compromised activation of discrete muscles in LBP. Impaired control of individual back muscles in the presence of pain may represent adoption of a new movement strategy to contract the muscles *en masse* in order to protect a painful body region\(^{23-25}\). If correct, this mechanism may explain our finding of a more pronounced reorganisation with more severe pain.
Reduced map volume at the L3 and L5 recording sites was associated with higher pain severity, but only in those who reported upper LBP. Smaller map volume suggests reduced excitability of corticomotor projections to paraspinal muscles and/or a smaller cortical territory devoted to control of these muscles. This is consistent with previous reports of cortical reorganisation in LBP\(^4\). It is unclear why the relationship between map volume and pain was only identified for those with upper LBP. One possibility is that, for anatomical reasons, surface electrodes can more adequately detect reduced map volume in upper lumbar regions. For instance, the muscles that are altered when pain is in the upper low back are likely to be those located in the more cranial regions of the lumbar spine (greater relative mass of the long superficial to short deep muscles) and these may be reflected differently in the surface recordings than when more caudal regions (with bias towards greater mass of deep short muscle bulk) are affected.

Apart from the requirement to satisfy general criteria (pain for longer than 3 months; sufficient pain to cause functional limitation; no spine surgery), no attempt was made to select LBP participants with a specific pathology or from a specific subgroup. This decision was based on an earlier study using intramuscular EMG that identified changes in organisation of M1 in people with non-specific LBP\(^4\). The present data suggest that on average, there is a difference in M1 organisation in people with non-specific LBP, but there was variation between participants. Future work should consider whether these changes depend on individual features of LBP such as movement behaviour or specific pathology.

**Clinical implications**

Our data suggest that moderate to severe LBP is more likely to be associated with cortical reorganisation, characterised by smudging (one map peak) and smaller map volume, than mild LBP. Altered map volume may also be influenced by the location of pain. This has
implications for treatment strategies that aim to restore normal cortical organisation. Although the optimum method to restore cortical organisation in LBP is yet to be established, studies in focal hand dystonia suggest motor retraining using isolated movements\textsuperscript{22,26} or asynchronous electrical stimulation\textsuperscript{10} restore cortical representations and improve pain. Further, interventions such as voluntary motor training\textsuperscript{15} and combined non-invasive brain and peripheral stimulation\textsuperscript{9} have been shown to restore cortical representations and this is associated with improved symptoms in LBP. Our data suggest those with moderate to severe LBP may derive more benefit from motor skill training than those with milder symptoms. This requires further investigation.

References


**Figure 1.** Normalised motor cortex maps aligned to the maximum motor evoked potential (MEP) for each participant obtained for EMG electrodes placed at the level of L3 in low back pain (A) and painfree controls (C) and at the level of L5 in low back pain (B) and painfree controls (D). The coloured scale represents the proportion of the maximum MEP amplitude. Note the L3 motor cortical map in the control participants demonstrates two discrete peaks, whereas maps obtained at L5 in healthy controls and at both recording sites in those with low back pain demonstrate only one discrete peak.
Figure 2. Normalised motor cortex maps obtained at the L3 (top panels) and L5 (bottom panels) EMG recording sites from representative individuals with severe low back pain (LBP, A and B), mild LBP (C and D) and no history of LBP (E and F). The vertex is co-ordinate 0,0. Note the single discrete peak in the L3 map of the individual with severe pain, but the two peaks observed in the L5 map, in the individual with mild pain and the painfree control participant.

Figure 3. Individual data for the centre of gravity (CoG) of the motor cortex maps obtained at the L3 and L5 EMG recording sites in those with low back pain and in painfree controls. The coordinate (0,0) denotes the vertex. Note the distribution of locations of the CoG is more anterior at both sites in those with low back pain than painfree participants.
Figure 4. Relationship between L3 map volume (sum of normalised map volume) and pain severity in individuals with upper (A) and lower (C) low back pain and between L5 map volume and pain severity in individuals with upper (B) and lower (D) low back pain. Smaller L3 and L5 map volume was associated with greater pain severity in those with upper low back pain. The same pattern was not present for those with lower back pain.

Table 1. Participant characteristics (mean ± standard deviation)

<table>
<thead>
<tr>
<th></th>
<th>Pain free controls (n=23)</th>
<th>Low back pain (n=27)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>27 ± 5</td>
<td>30 ± 9</td>
</tr>
<tr>
<td>Gender (male:female)</td>
<td>12:11</td>
<td>13:14</td>
</tr>
<tr>
<td>Pain (NRS)</td>
<td>...</td>
<td>4.6 ± 1.9</td>
</tr>
<tr>
<td>Pain duration (yrs)</td>
<td>...</td>
<td>5.3 ± 4.0</td>
</tr>
<tr>
<td>Side of worst pain (right:left)</td>
<td>...</td>
<td>18:9</td>
</tr>
<tr>
<td>Site of worst pain (upper:lower)</td>
<td>...</td>
<td>11:16</td>
</tr>
</tbody>
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Pain - current pain intensity rated on a numerical rating scale (NRS).

Pain duration - total time that participants had experienced recurrent LBP including periods of aggravation and remission.