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| Complete List of Authors: | Chiou, Shin-Yi; Imperial College London Department of Surgery and Cancer, Surgery and Cancer<br>Koutsos, Ermis; Imperial College London, Centre for Bio-Inspired Technology<br>Georgiou, Pantelis; Imperial College London, Centre for Bio-Inspired Technology<br>Strutton, Paul; Imperial College London Department of Surgery and Cancer, Surgery and Cancer |
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**Spectral characteristics of paraspinal muscles and functional disability in low back pain**

Shin-Yi Chiou, PhD[1], Ermis Koutsos, PhD[2], Pantelis Georgiou, PhD[2], Paul H Strutton, PhD[1,*].

[1] The Nick Davey Laboratory, Human Performance Group, Division of Surgery, Department of Surgery and Cancer, Faculty of Medicine, Imperial College London, Charing Cross Hospital, London W6 8RF, UK.

[2]Department of Electrical and Electronic Engineering, Centre for Bio-inspired Technology, Imperial College London, London SW7 2AZ, UK.

* Corresponding author Address: The Nick Davey Laboratory, Human Performance Group, Division of Surgery, Department of Surgery and Cancer, Faculty of Medicine, Imperial College London, W6 8RF. Tel: +44 (0)20 331 38837; fax: +44 (0)20 331 38835. Email: p.strutton@imperial.ac.uk

**Abstract**

**Objectives.** Characteristics of muscle activity, represented by surface electromyography (EMG), have revealed differences between patients with low back pain and healthy adults; how they relate to functional and clinical parameters remains unclear. The purpose of the current study was to examine the correlation between frequency characteristics of EMG (analysed using continuous wavelet transform (CWT) analysis) and patients' self-rated score of disability.

**Design and setting.** This is a case control study with fifteen patients with mechanical low back pain (LBP) without radicular symptoms. Patients were recruited from the orthopaedic clinic at Charing Cross Hospital. Ten healthy adults were recruited from the staff working in the hospital and associated university. Patients completed the Roland-Morris Disability Questionnaire (RMDQ) and bilateral EMG activity was obtained from erector spinae at vertebral levels L4 and T12. Subjects performed 3 brief maximal isometric voluntary contractions (MVCs) of the back extensors and the torque was measured using a dynamometer. CWT was applied to the EMG signals of each muscle in a 200ms window centred around the peak torque obtained during the MVCs. The ratio (low/high frequencies) of the energy, the peak power, and the frequency of the peak power were calculated for each recording site, averaged and correlated with the individual's RMDQ score.

**Results.** Patients had lower peak power (T12 and L4) and lower frequency of the peak power (at T12) than the healthy adults. Additionally, RMDQ positively correlated to the average ratio of energy at T12 (rho=0.63; p=0.012), i.e. greater self-rated disability corresponded to a dominant distribution of energy in the lower frequencies.

**Conclusion.** The current findings reveal alterations in EMG profile and its association with self-related back pain disability, suggesting that spectral characteristics of EMG reflect muscle function.

**Keywords:** trunk muscles; isometric; electromyography; wavelet transform; back pain.

**Strengths and limitations of this study**

- This study uses a computational approach to decompose the signals of surface electromyography obtained from paraspinal muscles in patients with low back pain with a view to revealing information that may not be detected from a conventional amplitude analysis.
- The methodology of combining maximal voluntary isometric contraction of paraspinal muscles and wavelet transform analysis offers the opportunity for a simple and quick assessment of function of the back muscles.
- A difference in body mass between patients and controls indicates that careful interpretation of the findings are required.

**Introduction**

Low back pain (LBP) is a common health condition with 60-80% of people in the UK reporting it at some point in their lives[1 2] . The costs of back pain alone account for 20% of the total UK's health expenditure [3] and LBP is also an important cause of work absence. It has wide ranging impact upon both biological and psychosocial aspects such as physical impairments, mental health and loss of employment [2 4]. Evidence has shown that subjects with chronic low back pain (LBP) have changes in trunk muscle control by the central nervous system [5 6], including reduced corticospinal excitability [7] and neural drive [8] in addition to anatomical changes such as in trunk muscle size and muscle fibre type which may account for observed altered activity patterns during functional tasks [9 10] and reductions in muscle strength and endurance [11 12]. Electromyographic (EMG) activity, including its temporal and spectral characteristics, has been commonly used to investigate muscle function. Changes in EMG signal amplitude are used as an indirect measure of overall muscle activity and of muscle contraction force [13 14]; however, the precise nature of the relationship between EMG amplitude and force output has not been established [15 16]. The frequency distribution of the EMG signals has been reported to be associated with the underlying muscle fibre type characteristics [17 18]. For example, fatigability of back muscles has shown to be related to the muscle fibre type area distribution in healthy subjects [18]. These observations indicate complex alterations in temporal (e.g. EMG signal amplitude) and spectral (e.g. median frequency) characteristics of muscle activity. Therefore, a simultaneous assessment of changes across these domains may provide more information on neuromuscular alterations of back muscles in patients with LBP.

Wavelet transform is a time-frequency method of signal analysis, which has been proposed to be more suitable for analysis of surface EMG since these are non-stationary[19] spikey[20] signals than short-time Fourier transform (STFT). Wavelet transform projects a signal into space comprised of functions limited in duration. This technique consists of mapping the signal in frequency and time from a series of base functions, which produces a family of ordered decompositions located in

different frequency bands. From a single basic wavelet, a so-called mother wavelet, stretching and shifting (dilating and translating) the wavelet allows for discovery of the frequency content and location in time of the signal [21].

Studies have shown associations between wavelet transform and muscle function. In healthy adults, changes in EMG spectral power and frequency have been observed in limb and trunk muscles during fatiguing exercise [22 23]. Previous work has demonstrated that energy distribution between low and high frequency bands from leg muscles was different in individuals with diabetic neuropathy and in postoperative total knee arthroplasty patients compared to controls [24-26]. This may be due to changes in motor unit recruitment or muscle fibre type distribution in patients [27 28]. In patients with LBP, the total power in the trunk muscles was lower and could be used to discriminate patients from controls [29]. However, whether there are changes in energy distribution between low and high frequency bands from trunk muscles and whether these changes correlate with any clinical or functional scores (i.e. pain, disability) remains unclear.

The purpose of the current study was to investigate whether time and frequency domain EMG characteristics, obtained using continuous wavelet transform (CWT), of erector spinae muscles (ES) in people with LBP are associated with levels of back pain disability and pain. We hypothesised that the EMG characteristics would be different between people with LBP and controls and that the energy distribution between low and high frequency bands would be associated with the level of disability and/or pain.

**Materials and Methods**

*Participants.*

With ethical approval (from NHS NRES Committee London – Harrow) and written informed consent, 15 patients with mechanical, non-specific low back pain (LBP group) were recruited from the orthopaedic clinic at Charing Cross Hospital and 10 healthy controls were recruited from the staff working in the hospital and associated university. Only subjects with mechanical LBP without

radicular symptoms were included; those with back pain related to rheumatologic disease, spondylolisthesis or spinal trauma or with constant severe pain were excluded. All of the subjects were asked to complete the Edinburgh Handedness Inventory, a 10-item questionnaire with a score between -100 (left handed) and 100 (right handed) [30] and a visual analogue pain scale (VAS; 0 - no pain to 10 - maximum pain); patients additionally completed a 24-item Roland-Morris Disability Questionnaire (RMDQ), a disease specific functional measure [31]; the scores range from 0, no disability to 24, maximum disability.

*Recordings.*

***Torque.*** Back extensor isometric torque was measured using a Cybex Norm Isokinetic Testing System (CSMInc., Stoughton, MA, USA) with an extendable input lever arm. The output from the Cybex was sampled at 500Hz by a data acquisition system [Power 1401 plus and Spike2 v5; Cambridge Electronic Design (CED), Cambridge, UK] connected to a personal laptop for subsequent offline analysis. ***Electromyography (EMG).*** Bilateral EMG recordings were obtained from the erector spinae (ES) muscles at vertebral levels T12 and L4. Pairs of Ag/AgCl electrodes (self-adhesive, 2cm diameter, CareFusion, UK) were positioned 3cm either side of the spinous processes, parallel to the fibre orientation of ES muscles, with an inter-electrode distance of 2cm. A ground electrode was placed over the left anterior superior iliac spine. The EMG signals were filtered (10Hz–1kHz), and amplified (1000×; Iso-DAM, World Precision Instruments, UK) before being sampled at 4kHz by the data acquisition system; both torque and EMG data were collected simultaneously.

*Experimental procedure.*

The experimental setup has been used previously [8 32]. Briefly, subjects were positioned prone on the dynamometer bench, with their ankles and hips strapped securely, to help isolate back muscle movements as well as limit the contributions of hip extensors; the arms were by the sides and the iliac crests were aligned with the pivot of the dynamometer lever arm. The lever arm was positioned over the lower edge of the scapulae (see Fig. 1); this was confirmed by a physiotherapist (SYC) who

identified the inferior angle of the scapula for each subject by palpation. Subjects had a gentle warm-up consisting of several push-ups into extension without using their arms. Following this, three brief (~3s) maximal voluntary isometric contractions (MVICs) of the trunk extensors were performed with at least 10 seconds interval between each contraction; consistent verbal encouragement was given throughout. After each contraction, subjects were asked to indicate how much effort they used on a modified Borg scale (from 0, no effort to 10, maximal effort)[33].

*Data analysis.*

The peak torque achieved during the 3 MVICs was identified and the EMG signals obtained during the MIVC from each back muscle in a 200ms window centred on the peak torque were calculated as root-mean-square amplitude (rmsEMG). They were then resolved into their respective intensities in time-frequency space using a continuous wavelet transform (CWT), processed in MATLAB R2014a (MathWorks, Natick, Massachusetts). Specifically, the Daubechies family of wavelet (in particular the db4 wavelet) was selected for CWT decomposition due to the similarity between the wavelet and the waveforms of motor unit action potentials [34 35]. Performing a CWT on a time waveform results in a matrix of normalized coefficients calculated over scale and time. Scales were tested from 5 to 300 (corresponding to 595.29Hz-9.92Hz) with regards to the common signal bandwidth of surface EMG [36 37]; the sum of the energy of the wavelet coefficient for the 200ms window was obtained for each scale (Fig 1). Parameters including peak power and its corresponding frequency were obtained. Furthermore, since the ratio of muscle fibre type I to type II in the ES has been reported to be approximately 1.8 [38], the scale splitting the energy matrix into the ratio 1.8 of lower to higher energy (low:high frequencies) for each muscle was identified from the controls. The scale was then converted into its corresponding frequency; this corresponding frequency was used to split the energy matrix obtained from the LBP group into two parts representing lower to higher energy. The ratio of these two parts from the energy matrix was then calculated for each muscle for individuals in the LBP group.

*Statistical analysis.*

Data were analysed using Statistical Program for the Social Sciences (SPSS) version 22 (IBM Corp, Armonk, NY). Demographic data and modified Borg scale scores were compared between the control group and the LBP group using independent-t tests and Chi-Square tests for scale data and for nominal data (gender), respectively. Normal distribution was tested by the Shapiro-Wilk test for spectral parameters and rmsEMG; since the variables of frequency at the peak power and the ratio were not normally distributed ($p<0.05$) and our sample sizes of two groups were not equal, non-parametric tests were applied. Wilcoxon Signed Rank tests and Mann-Whitney *U* tests were used to examine within-group and between-group differences, respectively. Within-group comparisons were made between left and right sides for rmsEMG at T12 and L4; between-group comparisons were made between rmsEMG, peak power and its corresponding frequency and the ratio of energy. Given that this ratio was based on the presumed ratio of muscle fibre type I to type II in the ES [38], Spearman correlation coefficients were performed between the scores of questionnaires (RMDQ and VAS) and the ratio of energy in the LBP group. Statistical significance was set at $p<0.05$ and Bonferroni correction was applied to allow for multiple comparisons.

**Results**

*Group characteristics.*

Demographic data of the groups are shown in Table 1. The median (interquartile range) duration of back pain episode was 20 (22) months in patients with LBP. Of 15 patients with LBP, 6 had pain on the right side and 9 had bilateral pain. The MVIC torque (normalized to body mass) of patients was smaller than that of controls (mean±SD: LBP: 2.88±1.03 Nm/kg; C: 4.11±1.42Nm/kg; Z=-2.16; *p*=0.03). Further, the VAS reported by patients was 5.2±2.84; as anticipated, controls reported no pain (i.e. 0.0). All subjects completed all aspects of the protocol; no data were excluded from analyses. During the MVICs, the modified Borg scale scores reported by the subjects were not different between the groups (LBP: 8.80±1.04; C: 9.42±0.60; *p*=0.07).

*Root-mean-square (RMS) EMG.*

There was no side difference in rms EMG in the LBP group (T12: Z=-1.36; *p*=0.18; L4: Z=-1.07; *p*=0.29) or in the controls (T12: Z=-0.30; *p*=0.77; L4: Z=-0.15; *p*=0.88; Table 2). The mean rmsEMG, averaged from left and right ES, at T12 and L4 vertebral levels was significantly lower in the LBP group than in the controls (T12: Z=-2.69; *p*=0.007; L4: Z=-2.33; *p*=0.02; Table 2).

*Spectral parameters.*

The peak power (Fig 2A) and its corresponding frequency (Fig 2B) of the transformed EMG were different between the two groups. For the ES T12, the peak power and its corresponding frequency were lower in the LBP group (peak power: 0.84±0.22; frequency: 40.94±8.21Hz) than in the controls (peak power: 1.17±0.25; frequency: 49.56±10.56Hz; peak power: Z=-2.88; *p*=0.004; frequency: Z=-2.16; *p*=0.030; Fig 2). For the ES L4, the peak power was lower in the LBP group (peak power: 0.75±0.18) than in the controls (peak power: 1.13±0.29; Z=-2.99; *p*=0.003; Fig 2A), whereas its corresponding frequency (LBP group: 40.64±14.81Hz; control group: 47.97±6.16Hz) was not different between two groups (Z=-1.66; *p*=0.096; Fig 2B).

In the controls, the mean (±SD) scales splitting the energy matrix into the ratio to ~1.8 of low to high energy for T12 (the mean ratio was 1.72±0.05) and L4 (1.74±0.04) were 36.8±10.52 and 34.25±9.60, respectively; the corresponding frequencies were 87Hz for T12 and 96Hz for L4. The splitting scales used in the LBP group were therefore 37 for T12 and 34 for L4; the mean ratios (low/high) at these two scales were 3.56±2.36 for T12 (Z=-2.11; *p*=0.035, compared to the control group) and 4.32±3.19 for L4 (Z=-1.94; p=0.052) scales in the LBP group. Spearman correlation analysis showed a correlation between the ratios from ES T12 and the RMDQ scores (rho=0.63; *p*=0.012; Fig 3); however, the ratios from ES L4 did not significantly correlate with the RMDQ scores (rho=0.47; *p*=0.075). The ratios did not correlate with the VAS scores (ES T12: rho=0.09; *p*=0.76. ES L4: rho=0.01; *p*=0.96*p*>0.05).

**Discussion**

The current study used continuous wavelet transform to decompose the surface EMG signals recorded from the ES during maximal isometric back extensions performed by patients with LBP and controls. In patients with LBP, there was a lower peak power in ES T12 and L4 and the overall energy distribution in ES T12 was shifted toward lower frequencies than in the controls. Moreover, the ratios of energy between low and high frequencies, calculated from ES T12, correlated with patients' self-rated back pain disability which may highlight the potential clinical application of wavelet analysis in monitoring the progression of, or response to treatment, for back pain.

Frequency analysis has been widely applied to analyse EMG signals recorded from paraspinal muscles in patients with chronic LBP and short-time Fourier transform (STFT) has been used in the majority of studies. Mean and median frequencies were lower in patients with chronic LBP than in controls [29 39]; however, controversial results are still reported [40 41]. Although there is evidence that analysis of back muscle EMG activity using STFT and wavelet transform provides similar information [23 42 43], some studies suggest that wavelet transform could detect changes in muscle fatigue earlier and be more sensitive than the STFT [44-46]. A recent study used discrete wavelet transform on surface EMG of trunk muscles during the contraction in subjects with chronic LBP and in controls. Patients with chronic LBP had lower spectral power in the trunk muscles compared to the healthy subjects [29]; however, their study did not include any subjective measurements (e.g. pain scores, disability scores) or compare energy distribution between low and high frequency bands, which may reflect alterations in motor unit recruitment or muscle fibre type distributions. Our results show patients with LBP presented different EMG characteristics from healthy subjects, including lower peak power (both ES T12 and L4) and its corresponding frequency (ES T12), and higher ratio of energy between low and high frequencies (ES T12), in line with previous findings that patients with chronic LBP have an overall shift of energy distribution toward lower frequencies in the back muscles[47]. We further demonstrate a correlation between the energy distribution calculated from the EST12 and the

RMDQ, indicating an association between muscle function and self-rated disability. However, the reduced volume muscle at the lumbar level [38] might explain the differences in the findings between ES T12 and L4 levels. Together with previous work showing that EMG variables recorded from ES may identify people at increased risk of developing low back pain in two years [48], we suggest that the EMG characteristics could be useful in clinics to monitor progression of back pain as well as the effectiveness of therapeutic interventions.

Changes in spectral energy from leg and thigh muscles have been found in individuals with diabetic neuropathy and are suggested to be related to alterations in muscle recruitment strategies due to the loss of type I fibres in this population [25]. Studies have shown that instantaneous spectra derived from wavelet decomposition of EMG signals are associated with activity from different muscle fibre types using a range of approaches including electrical nerve stimulation [28] and voluntary contractions [49]. In addition, previous findings using conventional Fourier transformation demonstrated a correlation between the change in median frequency in ES during fatiguing exercise and the relative area of the muscle occupied by type I fibres in healthy subjects [18]. Anatomical evidence from biopsy studies is equivocal, with some studies demonstrating differences in muscle fibre-type proportions in paraspinal muscles between patients with LBP and healthy subjects [50 51], whilst others show no differences [52 53]. Nevertheless, studies using twitch interpolation to assess central neural drive to muscles suggest that decreases in time-to-peak amplitude of superimposed twitches at increasing levels of voluntary contraction reflect the recruitment of different types of motor units [32 54-56]. Further, given patients with chronic CLBP patients have been shown to exhibit longer time-to-peak amplitudes of twitches during MVICs, this supports the view that these patients have alterations in muscle fibre-type composition [8]. In the current study, the spectra obtained from the patients with LBP had a shift in the peak power towards the lower frequencies; this might reflect alterations in motor control or in muscle fibre-type proportions.

The approach used in the current study may provide a valuable tool for clinical assessment. Surface EMG recordings are easy to use in clinics and the task is feasible for people with chronic LBP as all of our patients were able to perform the 3 maximal isometric back extensions. While factors such as fear avoidance or pain inhibition likely affect muscle activity, our subjects were asked to report pain levels during the MVICs and also to give an indication (on a modified Borg scale) of the degree of effort used to perform the MVICs. Patients reported no increase in pain, and levels of effort comparable to the controls. Wavelet transform is a robust approach for the surface EMG signal and could reveal extra features which may be useful to monitor subtle changes in muscle function during rehabilitation. A further study to test whether the wavelet approach is able to detect the therapeutic effect on muscle function is therefore warranted.

In conclusion, the patients with LBP recruited in the current study had lower maximal force of the back extensors and smaller ES muscle activity during the MVICs. The wavelet transform further revealed alterations in EMG profile and its association with the self-related back pain disability, indicating that spectral characteristics of EMG reflect muscle function.

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**Competing interests:** None declared.

**Author's contributions:** SYC and PHS conceived and designed the study. SYC and PHS conducted the experiment. SYC, EK and PHS analysed the data and interpreted the data. PG provided guidance on the data analysis. All authors drafted the manuscript and read, edited and approved the final version of the manuscript. All authors had full access to all of the data in the study and can take responsibility for the integrity of the data and the accuracy of the data analysis.

**Data sharing statement:** No additional data are available.

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**Figure Captions**

**Figure 1.** Experimental setup (top left) and peak torque and EMG activity recorded from left and right erector spinae at T12 (L ES and R ES) from a representative subject during one maximal voluntary isometric contraction (MVIC, top right). A representative 3 dimensional matrix of power, scale (frequency) and time calculated from a continuous wavelet transform analysis of the EMG data centred around the peak torque (bottom right). The bottom left figure represents the sum of the power collapsed across the time-window. The area under the curve has been split according to the ratio 1.8 (see data analysis) and the corresponding scale was used to split the curve derived from each patient dataset.

**Figure 2.** Group mean (±SEM) data showing (A) peak power and (B) its corresponding frequency from erector spinae muscles at vertebral levels T12 (ES T12) and L4 (ES L4) in the controls and in patients with LBP. *p<0.05, between-group comparison.

**Figure 3.** Correlation between the ratio of energy at low to high (low:high) frequencies and Roland-Morris Disability Questionnaire (RMDQ) in subjects with LBP.

Table 1. Demographic data.

| Characteristics | Controls (n = 10) | LBP (n = 15) | P value |
|---|---|---|---|
| Age (years) | 44.6 ± 7.9 | 43.5 ± 6.3 | 0.72 |
| Gender | 5Male; 5Female | 6Male; 9Female | 0.70 |
| Body stature (m) | 1.70 ± 0.09 | 1.70 ± 0.07 | 0.95 |
| Body mass (kg) | 72.37 ± 10.32 | 87.67 ± 24.39 | 0.04 |
| Edinburgh Handedness Inventory | 64.44 ± 54.34 | 79.00 ± 33.21 | 0.51 |
| Roland-Morris Disability Questionnaire (0-24) | 0.0 ± 0.0 | 10.27 ± 6.45 | < 0.001 |
| VAS (0-10) | 0.0 ± 0.0 | 5.20±2.84 | < 0.001 |

Data are presented as mean ± standard deviation. LBP: low back pain; VAS: visual analogue pain scale. For the Edinburgh Handedness Inventory, -100 indicates left handed whereas 100 indicates right handed; for the VAS, 0 means no pain at all and 10 means maximum pain imaginable; for the Roland-Morris Disability Questionnaire, the scores range from 0, no disability to 24, maximum disability.

Table 2. Root-mean-square EMG (mV) during maximal isometric back extension.

| | ES T12 | | | ES L4 | | |
|---|---|---|---|---|---|---|
| | Left | Right | Average | Left | Right | Average |
| Control | 0.21±0.08 | 0.20±0.07 | 0.21±0.07 | 0.22±0.10 | 0.22±0.10 | 0.22±0.09 |
| LBP | 0.13±0.07 | 0.12±0.08 | 0.12±0.07* | 0.12±0.12 | 0.14±0.07 | 0.13±0.12* |

Data are presented as mean ± standard deviation. LBP: low back pain. *p<0.05 between the LBP group and the control group.

Figure 1

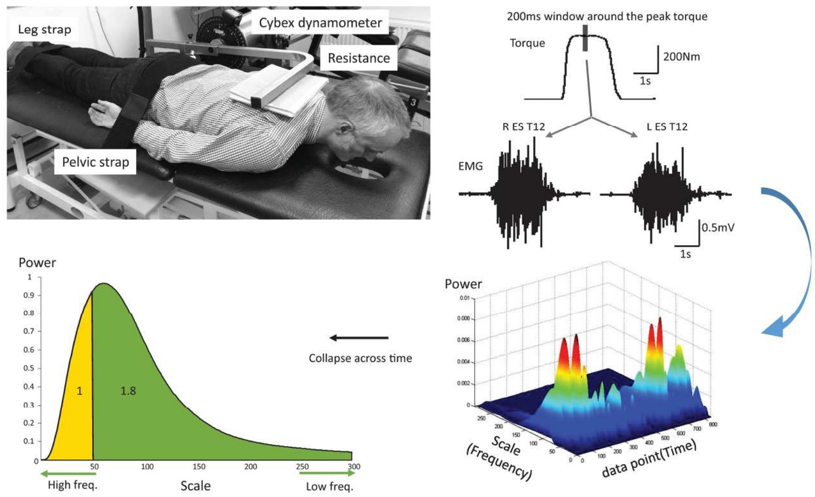


Figure 1. Experimental setup (top left) and peak torque and EMG activity recorded from left and right erector spinae at T12 (L ES and R ES) from a representative subject during one maximal voluntary isometric contraction (MVIC, top right). A representative 3 dimensional matrix of power, scale (frequency) and time calculated from a continuous wavelet transform analysis of the EMG data centred around the peak torque (bottom right). The bottom left figure represents the sum of the power collapsed across the time-window. The area under the curve has been split according to the ratio 1.8 (see data analysis) and the corresponding scale was used to split the curve derived from each patient dataset.

190x107mm (300 x 300 DPI)

Figure 2

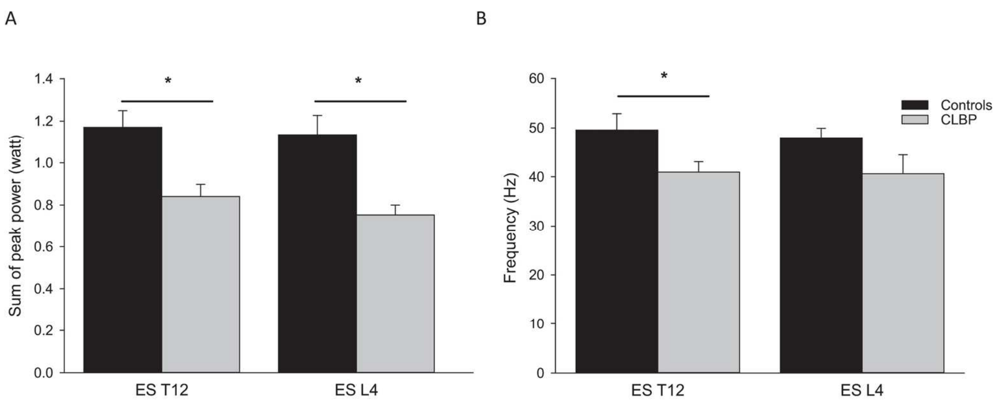


Figure 2. Group mean (±SEM) data showing (A) peak power and (B) its corresponding frequency from erector spinae muscles at vertebral levels T12 (ES T12) and L4 (ES L4) in the controls and in patients with LBP. *$p<0.05$, between-group comparison.

147x81mm (300 x 300 DPI)

Figure 3

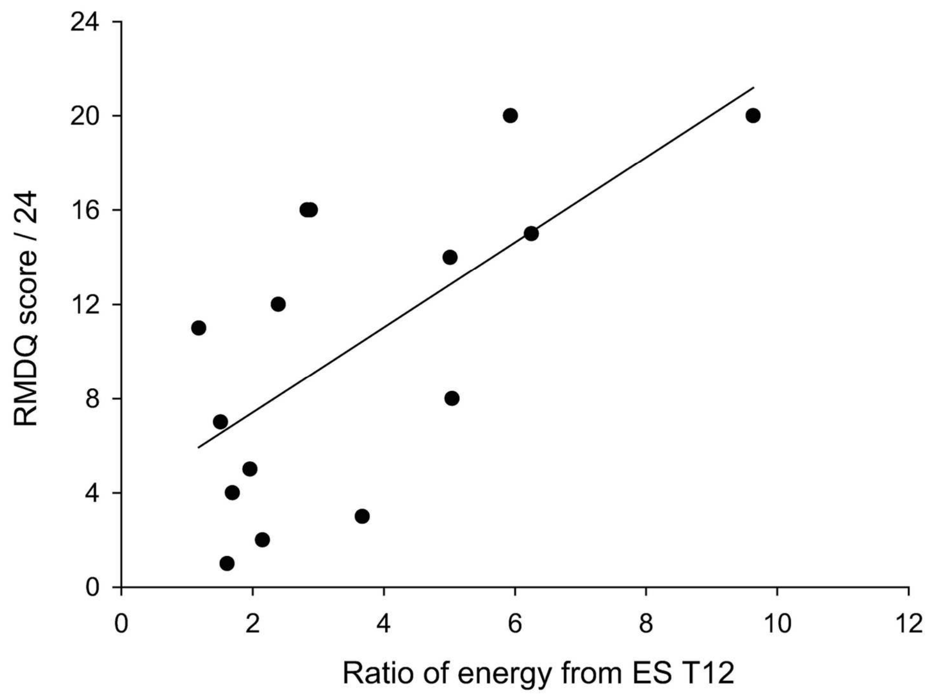


Figure 3. Correlation between the ratio of energy at low to high (low:high) frequencies and Roland-Morris Disability Questionnaire (RMDQ) in subjects with LBP.

135x115mm (300 x 300 DPI)

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# Association between spectral characteristics of paraspinal muscles and functional disability in low back pain patients: a cohort study.

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**Association between spectral characteristics of paraspinal muscles and functional disability in low back pain patients: a cohort study.**

Shin-Yi Chiou, PhD[1], Ermis Koutsos, PhD[2], Pantelis Georgiou, PhD[2], Paul H Strutton, PhD[1,*].

[1] The Nick Davey Laboratory, Human Performance Group, Division of Surgery, Department of Surgery and Cancer, Faculty of Medicine, Imperial College London, Charing Cross Hospital, London W6 8RF, UK.

[2]Department of Electrical and Electronic Engineering, Centre for Bio-inspired Technology, Imperial College London, London SW7 2AZ, UK.

* Corresponding author Address: The Nick Davey Laboratory, Human Performance Group, Division of Surgery, Department of Surgery and Cancer, Faculty of Medicine, Imperial College London, W6 8RF. Tel: +44 (0)20 331 38837; fax: +44 (0)20 331 38835. Email: p.strutton@imperial.ac.uk

**Abstract**

**Objectives.** Characteristics of muscle activity, represented by surface electromyography (EMG), have revealed differences between patients with low back pain and healthy adults; how they relate to functional and clinical parameters remains unclear. The purpose of the current study was to examine the correlation between frequency characteristics of EMG (analysed using continuous wavelet transform (CWT) analysis) and patients' self-rated score of disability.

**Design and setting.** This is a case control study with fifteen patients with mechanical low back pain (LBP) without radicular symptoms. Patients were recruited from the orthopaedic clinic at Charing Cross Hospital. Ten healthy adults were recruited from the staff working in the hospital and associated university. Patients completed the Roland-Morris Disability Questionnaire (RMDQ) and bilateral EMG activity was obtained from erector spinae at vertebral levels L4 and T12. Subjects performed 3 brief maximal isometric voluntary contractions (MVCs) of the back extensors and the torque was measured using a dynamometer. CWT was applied to the EMG signals of each muscle in a 200ms window centred around the peak torque obtained during the MVCs. The ratio (low/high frequencies) of the energy, the peak power, and the frequency of the peak power were calculated for each recording site, averaged and correlated with the individual's RMDQ score.

**Results.** Patients had lower peak power (T12 and L4) and lower frequency of the peak power (at T12) than the healthy adults. Additionally, RMDQ positively correlated to the average ratio of energy at T12 (rho=0.63; p=0.012), i.e. greater self-rated disability corresponded to a dominant distribution of energy in the lower frequencies.

**Conclusion.** The current findings reveal alterations in EMG profile and its association with self-related back pain disability, suggesting that spectral characteristics of EMG reflect muscle function.

**Keywords:** trunk muscles; isometric; electromyography; wavelet transform; back pain.

**Strengths and limitations of this study**

- This study uses a computational approach to decompose the signals of surface electromyography obtained from paraspinal muscles in patients with low back pain with a view to revealing information that may not be detected from a conventional amplitude analysis.
- The methodology of combining maximal voluntary isometric contraction of paraspinal muscles and wavelet transform analysis offers the opportunity for a simple and quick assessment of function of the back muscles.
- A difference in body mass between patients and controls indicates that careful interpretation of the findings are required.

**Introduction**

Low back pain (LBP) is a common health condition with 60-80% of people in the UK reporting it at some point in their lives[1 2] . The costs of back pain alone account for 20% of the total UK's health expenditure [3] and LBP is also an important cause of work absence. It has wide ranging impact upon both biological and psychosocial aspects such as physical impairments, mental health and loss of employment [2 4]. Evidence has shown that subjects with chronic low back pain (LBP) have changes in trunk muscle control by the central nervous system [5 6], including reduced corticospinal excitability [7] and neural drive [8] in addition to anatomical changes such as in trunk muscle size and muscle fibre type which may account for observed altered activity patterns during functional tasks [9 10] and reductions in muscle strength and endurance [11 12]. Electromyographic (EMG) activity, including its temporal and spectral characteristics, has been commonly used to investigate muscle function. Changes in EMG signal amplitude are used as an indirect measure of overall muscle activity and of muscle contraction force [13 14]; however, the precise nature of the relationship between EMG amplitude and force output has not been established [15 16]. The frequency distribution of the EMG signals has been reported to be associated with the underlying muscle fibre type characteristics [17 18]. For example, fatigability of back muscles has shown to be related to the muscle fibre type area distribution in healthy subjects [18]. These observations indicate complex alterations in temporal (e.g. EMG signal amplitude) and spectral (e.g. median frequency) characteristics of muscle activity. Therefore, a simultaneous assessment of changes across these domains may provide more information on neuromuscular alterations of back muscles in patients with LBP.

Wavelet transform is a time-frequency method of signal analysis, which has been proposed to be more suitable for analysis of surface EMG since these are non-stationary[19] spikey[20] signals than short-time Fourier transform (STFT). Wavelet transform projects a signal into space comprised of functions limited in duration. This technique consists of mapping the signal in frequency and time from a series of base functions, which produces a family of ordered decompositions located in

different frequency bands. From a single basic wavelet, a so-called mother wavelet, stretching and shifting (dilating and translating) the wavelet allows for discovery of the frequency content and location in time of the signal [21].

Studies have shown associations between wavelet transform and muscle function. In healthy adults, changes in EMG spectral power and frequency have been observed in limb and trunk muscles during fatiguing exercise [22 23]. Previous work has demonstrated that energy distribution between low and high frequency bands from leg muscles was different in individuals with diabetic neuropathy and in postoperative total knee arthroplasty patients compared to controls [24-26]. This may be due to changes in motor unit recruitment or muscle fibre type distribution in patients [27 28]. In patients with LBP, the total power in the trunk muscles was lower and could be used to discriminate patients from controls [29]. However, whether there are changes in energy distribution between low and high frequency bands from trunk muscles and whether these changes correlate with any clinical or functional scores (i.e. pain, disability) remains unclear.

The purpose of the current study was to investigate whether time and frequency domain EMG characteristics, obtained using continuous wavelet transform (CWT), of erector spinae muscles (ES) in people with LBP are associated with levels of back pain disability and pain. We hypothesised that the EMG characteristics would be different between people with LBP and controls and that the energy distribution between low and high frequency bands would be associated with the level of disability and/or pain.

**Materials and Methods**

*Participants.*

With ethical approval (07/Q0410/5 - NHS NRES Committee London – Harrow) and written informed consent, 15 patients with mechanical, non-specific low back pain (LBP group) were recruited from the orthopaedic clinic at Charing Cross Hospital and 10 healthy controls were recruited from the staff working in the hospital and associated university. Only subjects with mechanical LBP without

radicular symptoms were included; those with back pain related to rheumatologic disease, spondylolisthesis or spinal trauma or with constant severe pain were excluded. All of the subjects were asked to complete the Edinburgh Handedness Inventory, a 10-item questionnaire with a score between -100 (left handed) and 100 (right handed) [30] and a visual analogue pain scale (VAS; 0 - no pain to 10 - maximum pain); patients additionally completed a 24-item Roland-Morris Disability Questionnaire (RMDQ), a disease specific functional measure [31]; the scores range from 0, no disability to 24, maximum disability.

*Recordings.*

***Torque.*** Back extensor isometric torque was measured using a Cybex Norm Isokinetic Testing System (CSMInc., Stoughton, MA, USA) with an extendable input lever arm. The output from the Cybex was sampled at 500Hz by a data acquisition system [Power 1401 plus and Spike2 v5; Cambridge Electronic Design (CED), Cambridge, UK] connected to a personal laptop for subsequent offline analysis. ***Electromyography (EMG).*** Bilateral EMG recordings were obtained from the erector spinae (ES) muscles at vertebral levels T12 and L4. Pairs of Ag/AgCl electrodes (self-adhesive, 2cm diameter, CareFusion, UK) were positioned 3cm either side of the spinous processes, parallel to the fibre orientation of ES muscles, with an inter-electrode distance of 2cm. A ground electrode was placed over the left anterior superior iliac spine. The EMG signals were filtered (10Hz–1kHz), and amplified (1000×; Iso-DAM, World Precision Instruments, UK) before being sampled at 4kHz by the data acquisition system; both torque and EMG data were collected simultaneously.

*Experimental procedure.*

The experimental setup has been used previously [8 32]. Briefly, subjects were positioned prone on the dynamometer bench, with their ankles and hips strapped securely, to help isolate back muscle movements as well as limit the contributions of hip extensors; the arms were by the sides and the iliac crests were aligned with the pivot of the dynamometer lever arm. The lever arm was positioned over the lower edge of the scapulae (see Fig. 1); this was confirmed by a physiotherapist (SYC) who

identified the inferior angle of the scapula for each subject by palpation. Subjects had a gentle warm-up consisting of several push-ups into extension without using their arms. Following this, three brief (~3s) maximal voluntary isometric contractions (MVICs) of the trunk extensors were performed with at least 10 seconds interval between each contraction; consistent verbal encouragement was given throughout. After each contraction, subjects were asked to indicate how much effort they used on a modified Borg scale (from 0, no effort to 10, maximal effort)[33].

*Data analysis.*

The peak torque achieved during the 3 MVICs was identified and the EMG signals obtained during the MIVC from each back muscle in a 200ms window centred on the peak torque were calculated as root-mean-square amplitude (rmsEMG). They were then resolved into their respective intensities in time-frequency space using a continuous wavelet transform (CWT), processed in MATLAB R2014a (MathWorks, Natick, Massachusetts). Specifically, the Daubechies family of wavelet (in particular the db4 wavelet) was selected for CWT decomposition due to the similarity between the wavelet and the waveforms of motor unit action potentials [34 35]. Performing a CWT on a time waveform results in a matrix of normalized coefficients calculated over scale and time. Scales were tested from 5 to 300 (corresponding to 595.29Hz-9.92Hz) with regards to the common signal bandwidth of surface EMG [36 37]; the sum of the energy of the wavelet coefficient for the 200ms window was obtained for each scale (Fig 1). The scales were then converted into their corresponding frequencies for further analyses. Parameters including peak power and its corresponding frequency were obtained. Furthermore, since the ratio of muscle fibre type I to type II in the ES has been reported to be approximately 1.8 [38], the scale splitting the energy matrix into the ratio 1.8 of lower to higher energy (low:high frequencies) for each muscle was identified from the controls. The scale was then used to split the energy matrix obtained from the LBP group into two parts representing lower to higher energy. The ratio of these two parts from the energy matrix was then calculated for each muscle for individuals in the LBP group.

*Statistical analysis.*

Data were analysed using Statistical Program for the Social Sciences (SPSS) version 22 (IBM Corp, Armonk, NY). Demographic data and modified Borg scale scores were compared between the control group and the LBP group using independent-t tests and Chi-Square tests for scale data and for nominal data (gender), respectively. Normal distribution was tested by the Shapiro-Wilk test for spectral parameters and rmsEMG; since the variables of frequency at the peak power and the ratio were not normally distributed ($p<0.05$) and our sample sizes of two groups were not equal, non-parametric tests were applied. Wilcoxon Signed Rank tests and Mann-Whitney *U* tests were used to examine within-group and between-group differences, respectively. Within-group comparisons were made between left and right sides for rmsEMG at T12 and L4; between-group comparisons were made between rmsEMG, peak power and its corresponding frequency and the ratio of energy. Given that this ratio was based on the presumed ratio of muscle fibre type I to type II in the ES [38], Spearman correlation coefficients were performed between the scores of questionnaires (RMDQ and VAS) and the ratio of energy in the LBP group. Statistical significance was set at $p<0.05$ and Bonferroni correction was applied to allow for multiple comparisons.

**Results**

*Group characteristics.*

Demographic data of the groups are shown in Table 1. The median (interquartile range) duration of back pain episode was 20 (22) months in patients with LBP. Of 15 patients with LBP, 6 had pain on the right side and 9 had bilateral pain. The MVIC torque (normalized to body mass) of patients was smaller than that of controls (mean±SD: LBP: 2.88±1.03 Nm/kg; C: 4.11±1.42Nm/kg; Z=-2.16; *p*=0.03). Further, the VAS reported by patients was 5.2±2.84; as anticipated, controls reported no pain (i.e. 0.0). All subjects completed all aspects of the protocol; no data were excluded from analyses. During the MVICs, the modified Borg scale scores reported by the subjects were not different between the groups (LBP: 8.80±1.04; C: 9.42±0.60; *p*=0.07).

*Root-mean-square (RMS) EMG.*

There was no side difference in rms EMG in the LBP group (T12: Z=-1.36; *p*=0.18; L4: Z=-1.07; *p*=0.29) or in the controls (T12: Z=-0.30; *p*=0.77; L4: Z=-0.15; *p*=0.88; Table 2). The mean rmsEMG, averaged from left and right ES, at T12 and L4 vertebral levels was significantly lower in the LBP group than in the controls (T12: Z=-2.69; *p*=0.007; L4: Z=-2.33; *p*=0.02; Table 2).

*Spectral parameters.*

The peak power (Fig 2A) and its corresponding frequency (Fig 2B) of the transformed EMG were different between the two groups. For the ES T12, the peak power and its corresponding frequency were lower in the LBP group (peak power: 0.84±0.22; frequency: 40.94±8.21Hz) than in the controls (peak power: 1.17±0.25; frequency: 49.56±10.56Hz; peak power: Z=-2.88; *p*=0.004; frequency: Z=-2.16; *p*=0.030; Fig 2). For the ES L4, the peak power was lower in the LBP group (peak power: 0.75±0.18) than in the controls (peak power: 1.13±0.29; Z=-2.99; *p*=0.003; Fig 2A), whereas its corresponding frequency (LBP group: 40.64±14.81Hz; control group: 47.97±6.16Hz) was not different between two groups (Z=-1.66; *p*=0.096; Fig 2B).

In the controls, the mean (±SD) scales splitting the energy matrix into the ratio to ~1.8 of low to high energy for T12 (the mean ratio was 1.72±0.05) and L4 (1.74±0.04) were 36.8±10.52 and 34.25±9.60, respectively; the corresponding frequencies were 87Hz for T12 and 96Hz for L4. The splitting scales used in the LBP group were therefore 37 for T12 and 34 for L4; the mean ratios (low/high) at these two scales were 3.56±2.36 for T12 (Z=-2.11; *p*=0.035, compared to the control group) and 4.32±3.19 for L4 (Z=-1.94; p=0.052) scales in the LBP group. Spearman correlation analysis showed a correlation between the ratios from ES T12 and the RMDQ scores (rho=0.63; *p*=0.012; Fig 3); however, the ratios from ES L4 did not significantly correlate with the RMDQ scores (rho=0.47; *p*=0.075). The ratios did not correlate with the VAS scores (ES T12: rho=0.09; *p*=0.76. ES L4: rho=0.01; *p*=0.96*p*>0.05).

## Discussion

The current study used continuous wavelet transform to decompose the surface EMG signals recorded from the ES during maximal isometric back extensions performed by patients with LBP and controls. In patients with LBP, there was a lower peak power in ES T12 and L4 and the overall energy distribution in ES T12 was shifted toward lower frequencies than in the controls. Moreover, the ratios of energy between low and high frequencies, calculated from ES T12, correlated with patients' self-rated back pain disability which may highlight the potential clinical application of wavelet analysis in monitoring the progression of, or response to treatment, for back pain.

Frequency analysis has been widely applied to analyse EMG signals recorded from paraspinal muscles in patients with chronic LBP and short-time Fourier transform (STFT) has been used in the majority of studies. Mean and median frequencies were lower in patients with chronic LBP than in controls [29 39]; however, controversial results are still reported [40 41]. Although there is evidence that analysis of back muscle EMG activity using STFT and wavelet transform provides similar information [23 42 43], some studies suggest that wavelet transform could detect changes in muscle fatigue earlier and be more sensitive than the STFT [44-46]. A recent study used discrete wavelet transform on surface EMG of trunk muscles during the contraction in subjects with chronic LBP and in controls. Patients with chronic LBP had lower spectral power in the trunk muscles compared to the healthy subjects [29]; however, their study did not include any subjective measurements (e.g. pain scores, disability scores) or compare energy distribution between low and high frequency bands, which may reflect alterations in motor unit recruitment or muscle fibre type distributions. Our results show patients with LBP presented different EMG characteristics from healthy subjects, including lower peak power (both ES T12 and L4) and its corresponding frequency (ES T12), and higher ratio of energy between low and high frequencies (ES T12), in line with previous findings that patients with chronic LBP have an overall shift of energy distribution toward lower frequencies in the back muscles[47]. We further demonstrate a correlation between the energy distribution calculated from the EST12 and the

RMDQ, indicating an association between muscle function and self-rated disability. However, the reduced volume muscle at the lumbar level [38] might explain the differences in the findings between ES T12 and L4 levels. Together with previous work showing that EMG variables recorded from ES may identify people at increased risk of developing low back pain in two years [48], we suggest that the EMG characteristics could be useful in clinics to monitor progression of back pain as well as the effectiveness of therapeutic interventions.

Changes in spectral energy from leg and thigh muscles have been found in individuals with diabetic neuropathy and are suggested to be related to alterations in muscle recruitment strategies due to the loss of type I fibres in this population [25]. Studies have shown that instantaneous spectra derived from wavelet decomposition of EMG signals are associated with activity from different muscle fibre types using a range of approaches including electrical nerve stimulation [28] and voluntary contractions [49]. In addition, previous findings using conventional Fourier transformation demonstrated a correlation between the change in median frequency in ES during fatiguing exercise and the relative area of the muscle occupied by type I fibres in healthy subjects [18]. Anatomical evidence from biopsy studies is equivocal, with some studies demonstrating differences in muscle fibre-type proportions in paraspinal muscles between patients with LBP and healthy subjects [50 51], whilst others show no differences [52 53]. Nevertheless, studies using twitch interpolation to assess central neural drive to muscles suggest that decreases in time-to-peak amplitude of superimposed twitches at increasing levels of voluntary contraction reflect the recruitment of different types of motor units [32 54-56]. Further, given patients with chronic LBP have been shown to exhibit longer time-to-peak amplitudes of twitches during MVICs, this supports the view that these patients have alterations in muscle fibre-type composition [8]. In the current study, the spectra obtained from the patients with LBP had a shift in the peak power towards the lower frequencies; this might reflect alterations in motor control or in muscle fibre-type proportions. Further, the correlation between the EMG spectral characteristics and back pain-related disability scores suggests that altered motor control or fibre-type proportions of paraspinal muscles has an impact on functional activities, which is reflected in higher disability scores. This highlights the importance of rehabilitation to restore muscle function in patients with LBP, which may reduce the levels of disability reported in these patients.

The approach used in the current study may provide a valuable tool for clinical assessment. Surface EMG recordings are easy to use in clinics and the task is feasible for people with chronic LBP as all of our patients were able to perform the 3 maximal isometric back extensions. While factors such as fear avoidance or pain inhibition likely affect muscle activity, our subjects were asked to report pain levels during the MVICs and also to give an indication (on a modified Borg scale) of the degree of effort used to perform the MVICs. Patients reported no increase in pain, and levels of effort comparable to the controls. Wavelet transform is a robust approach for the surface EMG signal and could reveal extra features which may be useful to monitor subtle changes in muscle function during rehabilitation. A further study to test whether the wavelet approach is able to detect the therapeutic effect on muscle function is therefore warranted.

In conclusion, the patients with LBP recruited in the current study had lower maximal force of the back extensors and smaller ES muscle activity during the MVICs. The wavelet transform further revealed alterations in EMG profile and its association with the self-related back pain disability, indicating that spectral characteristics of EMG reflect muscle function.

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**Competing interests:** None declared.

**Author's contributions:** SYC and PHS conceived and designed the study. SYC and PHS conducted the experiment. SYC, EK and PHS analysed the data and interpreted the data. PG provided guidance on the data analysis. All authors drafted the manuscript and read, edited and approved the final version of the manuscript. All authors had full access to all of the data in the study and can take responsibility for the integrity of the data and the accuracy of the data analysis.

**Data sharing statement:** No additional data are available.

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**Figure Captions**

**Figure 1.** Experimental setup (top left) and peak torque and EMG activity recorded from left and right erector spinae at T12 (L ES and R ES) from a representative subject during one maximal voluntary isometric contraction (MVIC, top right). A representative 3 dimensional matrix of power, scale (frequency) and time calculated from a continuous wavelet transform analysis of the EMG data centred around the peak torque (bottom right). The bottom left figure represents the sum of the power collapsed across the time-window. The area under the curve has been split according to the ratio 1.8 (see data analysis) and the corresponding scale was used to split the curve derived from each patient dataset.

**Figure 2.** Group mean (±SEM) data showing (A) peak power and (B) its corresponding frequency from erector spinae muscles at vertebral levels T12 (ES T12) and L4 (ES L4) in the controls and in patients with LBP. *p<0.05, between-group comparison.

**Figure 3.** Correlation between the ratio of energy at low to high (low:high) frequencies and Roland-Morris Disability Questionnaire (RMDQ) in subjects with LBP.

Table 1. Demographic data.

| Characteristics | Controls (n = 10) | LBP (n = 15) | P value |
|---|---|---|---|
| Age (years) | 44.6 ± 7.9 | 43.5 ± 6.3 | 0.72 |
| Gender | 5Male; 5Female | 6Male; 9Female | 0.70 |
| Body stature (m) | 1.70 ± 0.09 | 1.70 ± 0.07 | 0.95 |
| Body mass (kg) | 72.37 ± 10.32 | 87.67 ± 24.39 | 0.04 |
| Edinburgh Handedness Inventory | 64.44 ± 54.34 | 79.00 ± 33.21 | 0.51 |
| Roland-Morris Disability Questionnaire (0-24) | 0.0 ± 0.0 | 10.27 ± 6.45 | < 0.001 |
| VAS (0-10) | 0.0 ± 0.0 | 5.20±2.84 | < 0.001 |

Data are presented as mean ± standard deviation. LBP: low back pain; VAS: visual analogue pain scale. For the Edinburgh Handedness Inventory, -100 indicates left handed whereas 100 indicates right handed; for the VAS, 0 means no pain at all and 10 means maximum pain imaginable; for the Roland-Morris Disability Questionnaire, the scores range from 0, no disability to 24, maximum disability.

Table 2. Root-mean-square EMG (mV) during maximal isometric back extension.

| | ES T12 | | | ES L4 | | |
|---|---|---|---|---|---|---|
| | Left | Right | Average | Left | Right | Average |
| Control | 0.21±0.08 | 0.20±0.07 | 0.21±0.07 | 0.22±0.10 | 0.22±0.10 | 0.22±0.09 |
| LBP | 0.13±0.07 | 0.12±0.08 | 0.12±0.07* | 0.12±0.12 | 0.14±0.07 | 0.13±0.12* |

Data are presented as mean ± standard deviation. LBP: low back pain. *p<0.05 between the LBP group and the control group.

Figure 1

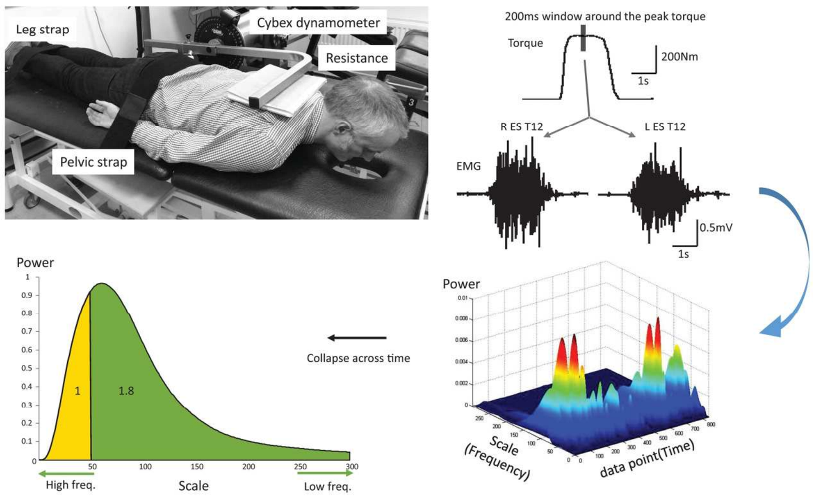


Figure 1. Experimental setup (top left) and peak torque and EMG activity recorded from left and right erector spinae at T12 (L ES and R ES) from a representative subject during one maximal voluntary isometric contraction (MVIC, top right). A representative 3 dimensional matrix of power, scale (frequency) and time calculated from a continuous wavelet transform analysis of the EMG data centred around the peak torque (bottom right). The bottom left figure represents the sum of the power collapsed across the time-window. The area under the curve has been split according to the ratio 1.8 (see data analysis) and the corresponding scale was used to split the curve derived from each patient dataset.

190x107mm (300 x 300 DPI)

Figure 2

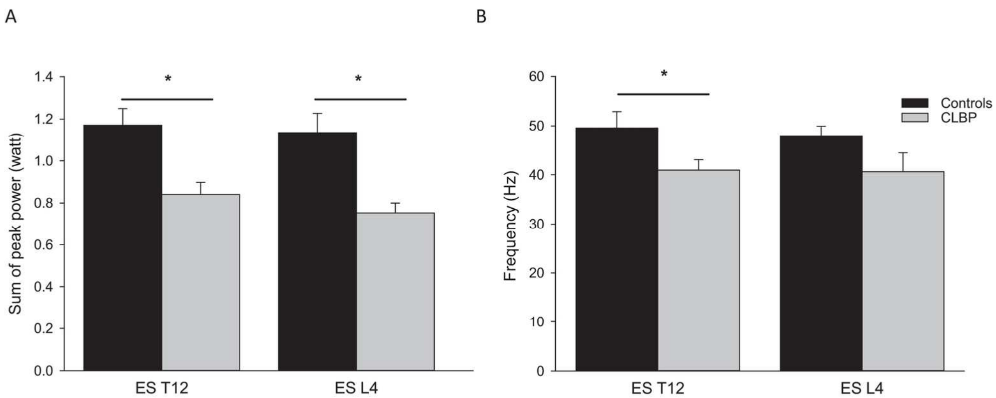


Figure 2. Group mean (±SEM) data showing (A) peak power and (B) its corresponding frequency from erector spinae muscles at vertebral levels T12 (ES T12) and L4 (ES L4) in the controls and in patients with LBP. *p<0.05, between-group comparison.

147x81mm (300 x 300 DPI)

Figure 3

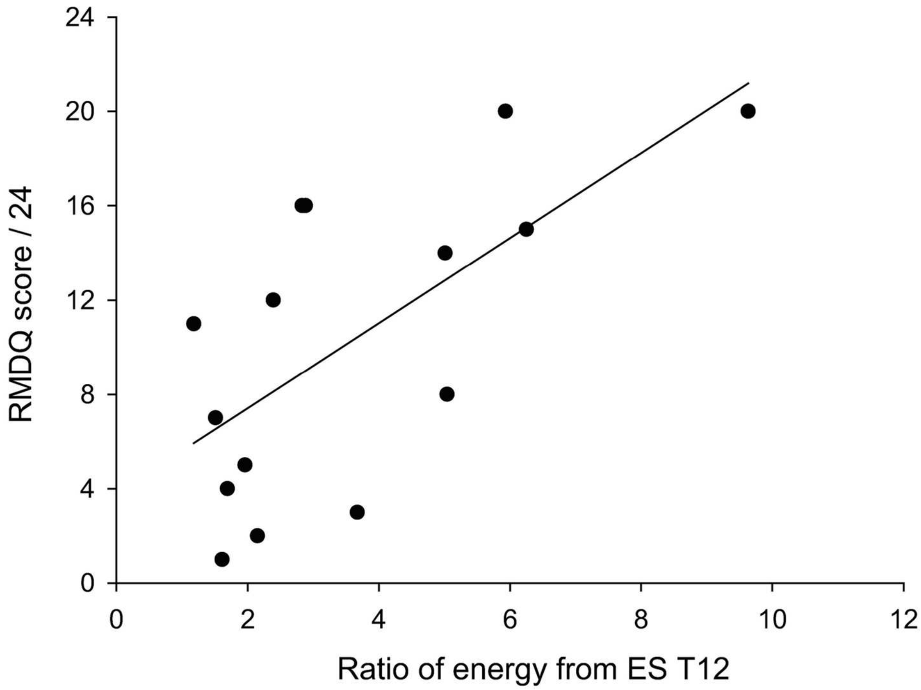


Figure 3. Correlation between the ratio of energy at low to high (low:high) frequencies and Roland-Morris Disability Questionnaire (RMDQ) in subjects with LBP.

135x115mm (300 x 300 DPI)

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# Association between spectral characteristics of paraspinal muscles and functional disability in low back pain patients: a cohort study.

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**Association between spectral characteristics of paraspinal muscles and functional disability in low back pain patients: a cohort study.**

Shin-Yi Chiou, PhD[1], Ermis Koutsos, PhD[2], Pantelis Georgiou, PhD[2], Paul H Strutton, PhD[1,*].

[1] The Nick Davey Laboratory, Human Performance Group, Division of Surgery, Department of Surgery and Cancer, Faculty of Medicine, Imperial College London, Charing Cross Hospital, London W6 8RF, UK.

[2]Department of Electrical and Electronic Engineering, Centre for Bio-inspired Technology, Imperial College London, London SW7 2AZ, UK.

* Corresponding author Address: The Nick Davey Laboratory, Human Performance Group, Division of Surgery, Department of Surgery and Cancer, Faculty of Medicine, Imperial College London, W6 8RF. Tel: +44 (0)20 331 38837; fax: +44 (0)20 331 38835. Email: p.strutton@imperial.ac.uk

**Abstract**

**Objectives.** Characteristics of muscle activity, represented by surface electromyography (EMG), have revealed differences between patients with low back pain and healthy adults; how they relate to functional and clinical parameters remains unclear. The purpose of the current study was to examine the correlation between frequency characteristics of EMG (analysed using continuous wavelet transform (CWT) analysis) and patients' self-rated score of disability.

**Design and setting.** This is a case control study with fifteen patients with mechanical low back pain (LBP) without radicular symptoms. Patients were recruited from the orthopaedic clinic at Charing Cross Hospital. Ten healthy adults were recruited from the staff working in the hospital and associated university. Patients completed the Roland-Morris Disability Questionnaire (RMDQ) and bilateral EMG activity was obtained from erector spinae at vertebral levels L4 and T12. Subjects performed 3 brief maximal isometric voluntary contractions (MVCs) of the back extensors and the torque was measured using a dynamometer. CWT was applied to the EMG signals of each muscle in a 200ms window centred around the peak torque obtained during the MVCs. The ratio (low/high frequencies) of the energy, the peak power, and the frequency of the peak power were calculated for each recording site, averaged and correlated with the individual's RMDQ score.

**Results.** Patients had lower peak power (T12 and L4) and lower frequency of the peak power (at T12) than the healthy adults. Additionally, RMDQ positively correlated to the average ratio of energy at T12 (rho=0.63; p=0.012), i.e. greater self-rated disability corresponded to a dominant distribution of energy in the lower frequencies.

**Conclusion.** The current findings reveal alterations in EMG profile and its association with self-related back pain disability, suggesting that spectral characteristics of EMG reflect muscle function.


**Keywords:** trunk muscles; isometric; electromyography; wavelet transform; back pain.

**Strengths and limitations of this study**

- This study uses a computational approach to decompose the signals of surface electromyography obtained from paraspinal muscles in patients with low back pain with a view to revealing information that may not be detected from a conventional amplitude analysis.
- The methodology of combining maximal voluntary isometric contraction of paraspinal muscles and wavelet transform analysis offers the opportunity for a simple and quick assessment of function of the back muscles.
- A difference in body mass between patients and controls indicates that careful interpretation of the findings are required.

## Introduction

Low back pain (LBP) is a common health condition with 60-80% of people in the UK reporting it at some point in their lives[1 2] . The costs of back pain alone account for 20% of the total UK's health expenditure [3] and LBP is also an important cause of work absence. It has wide ranging impact upon both biological and psychosocial aspects such as physical impairments, mental health and loss of employment [2 4]. Evidence has shown that subjects with chronic low back pain (LBP) have changes in trunk muscle control by the central nervous system [5 6], including reduced corticospinal excitability [7] and neural drive [8] in addition to anatomical changes such as in trunk muscle size and muscle fibre type which may account for observed altered activity patterns during functional tasks [9 10] and reductions in muscle strength and endurance [11 12]. Electromyographic (EMG) activity, including its temporal and spectral characteristics, has been commonly used to investigate muscle function. Changes in EMG signal amplitude are used as an indirect measure of overall muscle activity and of muscle contraction force [13 14]; however, the precise nature of the relationship between EMG amplitude and force output has not been established [15 16]. The frequency distribution of the EMG signals has been reported to be associated with the underlying muscle fibre type characteristics [17 18]. For example, fatigability of back muscles has shown to be related to the muscle fibre type area distribution in healthy subjects [18]. These observations indicate complex alterations in temporal (e.g. EMG signal amplitude) and spectral (e.g. median frequency) characteristics of muscle activity. Therefore, a simultaneous assessment of changes across these domains may provide more information on neuromuscular alterations of back muscles in patients with LBP.

Wavelet transform is a time-frequency method of signal analysis, which has been proposed to be more suitable for analysis of surface EMG since these are non-stationary[19] spikey[20] signals than short-time Fourier transform (STFT). Wavelet transform projects a signal into space comprised of functions limited in duration. This technique consists of mapping the signal in frequency and time from a series of base functions, which produces a family of ordered decompositions located in

different frequency bands. From a single basic wavelet, a so-called mother wavelet, stretching and shifting (dilating and translating) the wavelet allows for discovery of the frequency content and location in time of the signal [21].

Studies have shown associations between wavelet transform and muscle function. In healthy adults, changes in EMG spectral power and frequency have been observed in limb and trunk muscles during fatiguing exercise [22 23]. Previous work has demonstrated that energy distribution between low and high frequency bands from leg muscles was different in individuals with diabetic neuropathy and in postoperative total knee arthroplasty patients compared to controls [24-26]. This may be due to changes in motor unit recruitment or muscle fibre type distribution in patients [27 28]. In patients with LBP, the total power in the trunk muscles was lower and could be used to discriminate patients from controls [29]. However, whether there are changes in energy distribution between low and high frequency bands from trunk muscles and whether these changes correlate with any clinical or functional scores (i.e. pain, disability) remains unclear.

The purpose of the current study was to investigate whether time and frequency domain EMG characteristics, obtained using continuous wavelet transform (CWT), of erector spinae muscles (ES) in people with LBP are associated with levels of back pain disability and pain. We hypothesised that the EMG characteristics would be different between people with LBP and controls and that the energy distribution between low and high frequency bands would be associated with the level of disability and/or pain.

**Materials and Methods**

*Participants.*

With ethical approval (07/Q0410/5 - NHS NRES Committee London – Harrow) and written informed consent, 15 patients with mechanical, non-specific low back pain (LBP group) were recruited from the orthopaedic clinic at Charing Cross Hospital and 10 healthy controls were recruited from the staff working in the hospital and associated university. Only subjects with mechanical LBP without

radicular symptoms were included; those with back pain related to rheumatologic disease, spondylolisthesis or spinal trauma or with constant severe pain were excluded. All of the subjects were asked to complete the Edinburgh Handedness Inventory, a 10-item questionnaire with a score between -100 (left handed) and 100 (right handed) [30] and a visual analogue pain scale (VAS; 0 - no pain to 10 - maximum pain); patients additionally completed a 24-item Roland-Morris Disability Questionnaire (RMDQ), a disease specific functional measure [31]; the scores range from 0, no disability to 24, maximum disability.

*Recordings.*

***Torque.*** Back extensor isometric torque was measured using a Cybex Norm Isokinetic Testing System (CSMInc., Stoughton, MA, USA) with an extendable input lever arm. The output from the Cybex was sampled at 500Hz by a data acquisition system [Power 1401 plus and Spike2 v5; Cambridge Electronic Design (CED), Cambridge, UK] connected to a personal laptop for subsequent offline analysis. ***Electromyography (EMG).*** Bilateral EMG recordings were obtained from the erector spinae (ES) muscles at vertebral levels T12 and L4. Pairs of Ag/AgCl electrodes (self-adhesive, 2cm diameter, CareFusion, UK) were positioned 3cm either side of the spinous processes, parallel to the fibre orientation of ES muscles, with an inter-electrode distance of 2cm. A ground electrode was placed over the left anterior superior iliac spine. The EMG signals were filtered (10Hz–1kHz), and amplified (1000×; Iso-DAM, World Precision Instruments, UK) before being sampled at 4kHz by the data acquisition system; both torque and EMG data were collected simultaneously.

*Experimental procedure.*

The experimental setup has been used previously [8 32]. Briefly, subjects were positioned prone on the dynamometer bench, with their ankles and hips strapped securely, to help isolate back muscle movements as well as limit the contributions of hip extensors; the arms were by the sides and the iliac crests were aligned with the pivot of the dynamometer lever arm. The lever arm was positioned over the lower edge of the scapulae (see Fig. 1); this was confirmed by a physiotherapist (SYC) who

identified the inferior angle of the scapula for each subject by palpation. Subjects had a gentle warm-up consisting of several push-ups into extension without using their arms. Following this, three brief (~3s) maximal voluntary isometric contractions (MVICs) of the trunk extensors were performed with at least 10 seconds interval between each contraction; consistent verbal encouragement was given throughout. After each contraction, subjects were asked to indicate how much effort they used on a modified Borg scale (from 0, no effort to 10, maximal effort)[33].

*Data analysis.*

The peak torque achieved during the 3 MVICs was identified and the EMG signals obtained during the MIVC from each back muscle in a 200ms window centred on the peak torque were calculated as root-mean-square amplitude (rmsEMG). They were then resolved into their respective intensities in time-frequency space using a continuous wavelet transform (CWT), processed in MATLAB R2014a (MathWorks, Natick, Massachusetts). Specifically, the Daubechies family of wavelet (in particular the db4 wavelet) was selected for CWT decomposition due to the similarity between the wavelet and the waveforms of motor unit action potentials [34 35]. Performing a CWT on a time waveform results in a matrix of normalized coefficients calculated over scale and time. Scales were tested from 5 to 300 (corresponding to 595.29Hz-9.92Hz) with regards to the common signal bandwidth of surface EMG [36 37]; the sum of the energy of the wavelet coefficient for the 200ms window was obtained for each scale (Fig 1). The scales were then converted into their corresponding frequencies for further analyses. Parameters including peak power and its corresponding frequency were obtained. Furthermore, since the ratio of muscle fibre type I to type II in the ES has been reported to be approximately 1.8 [38], the scale splitting the energy matrix into the ratio 1.8 of lower to higher energy (low:high frequencies) for each muscle was identified from the controls. The scale was then used to split the energy matrix obtained from the LBP group into two parts representing lower to higher energy. The ratio of these two parts from the energy matrix was then calculated for each muscle for individuals in the LBP group.

*Statistical analysis.*

Data were analysed using Statistical Program for the Social Sciences (SPSS) version 22 (IBM Corp, Armonk, NY). Demographic data and modified Borg scale scores were compared between the control group and the LBP group using independent-t tests and Chi-Square tests for scale data and for nominal data (gender), respectively. Normal distribution was tested by the Shapiro-Wilk test for spectral parameters and rmsEMG; since the variables of frequency at the peak power and the ratio were not normally distributed ($p<0.05$) and our sample sizes of two groups were not equal, non-parametric tests were applied. Wilcoxon Signed Rank tests and Mann-Whitney *U* tests were used to examine within-group and between-group differences, respectively. Within-group comparisons were made between left and right sides for rmsEMG at T12 and L4; between-group comparisons were made between rmsEMG, peak power and its corresponding frequency and the ratio of energy. Given that this ratio was based on the presumed ratio of muscle fibre type I to type II in the ES [38], Spearman correlation coefficients were performed between the scores of questionnaires (RMDQ and VAS) and the ratio of energy in the LBP group. Statistical significance was set at $p<0.05$ and Bonferroni correction was applied to allow for multiple comparisons.

**Results**

*Group characteristics.*

Demographic data of the groups are shown in Table 1. The median (interquartile range) duration of back pain episode was 20 (22) months in patients with LBP. Of 15 patients with LBP, 6 had pain on the right side and 9 had bilateral pain. The MVIC torque (normalized to body mass) of patients was smaller than that of controls (mean±SD: LBP: 2.88±1.03 Nm/kg; C: 4.11±1.42Nm/kg; Z=-2.16; *p*=0.03). Further, the VAS reported by patients was 5.2±2.84; as anticipated, controls reported no pain (i.e. 0.0). All subjects completed all aspects of the protocol; no data were excluded from analyses. During the MVICs, the modified Borg scale scores reported by the subjects were not different between the groups (LBP: 8.80±1.04; C: 9.42±0.60; *p*=0.07).

*Root-mean-square (RMS) EMG.*

There was no side difference in rms EMG in the LBP group (T12: Z=-1.36; *p*=0.18; L4: Z=-1.07; *p*=0.29) or in the controls (T12: Z=-0.30; *p*=0.77; L4: Z=-0.15; *p*=0.88; Table 2). The mean rmsEMG, averaged from left and right ES, at T12 and L4 vertebral levels was significantly lower in the LBP group than in the controls (T12: Z=-2.69; *p*=0.007; L4: Z=-2.33; *p*=0.02; Table 2).

*Spectral parameters.*

The peak power (Fig 2A) and its corresponding frequency (Fig 2B) of the transformed EMG were different between the two groups. For the ES T12, the peak power and its corresponding frequency were lower in the LBP group (peak power: 0.84±0.22; frequency: 40.94±8.21Hz) than in the controls (peak power: 1.17±0.25; frequency: 49.56±10.56Hz; peak power: Z=-2.88; *p*=0.004; frequency: Z=-2.16; *p*=0.030; Fig 2). For the ES L4, the peak power was lower in the LBP group (peak power: 0.75±0.18) than in the controls (peak power: 1.13±0.29; Z=-2.99; *p*=0.003; Fig 2A), whereas its corresponding frequency (LBP group: 40.64±14.81Hz; control group: 47.97±6.16Hz) was not different between two groups (Z=-1.66; *p*=0.096; Fig 2B).

In the controls, the mean (±SD) scales splitting the energy matrix into the ratio to ~1.8 of low to high energy for T12 (the mean ratio was 1.72±0.05) and L4 (1.74±0.04) were 36.8±10.52 and 34.25±9.60, respectively; the corresponding frequencies were 87Hz for T12 and 96Hz for L4. The splitting scales used in the LBP group were therefore 37 for T12 and 34 for L4; the mean ratios (low/high) at these two scales were 3.56±2.36 for T12 (Z=-2.11; *p*=0.035, compared to the control group) and 4.32±3.19 for L4 (Z=-1.94; p=0.052) scales in the LBP group. Spearman correlation analysis showed a correlation between the ratios from ES T12 and the RMDQ scores (rho=0.63; *p*=0.012; Fig 3); however, the ratios from ES L4 did not significantly correlate with the RMDQ scores (rho=0.47; *p*=0.075). The ratios did not correlate with the VAS scores (ES T12: rho=0.09; *p*=0.76. ES L4: rho=0.01; *p*=0.96*p*>0.05).

**Discussion**

The current study used continuous wavelet transform to decompose the surface EMG signals recorded from the ES during maximal isometric back extensions performed by patients with LBP and controls. In patients with LBP, there was a lower peak power in ES T12 and L4 and the overall energy distribution in ES T12 was shifted toward lower frequencies than in the controls. Moreover, the ratios of energy between low and high frequencies, calculated from ES T12, correlated with patients' self-rated back pain disability which may highlight the potential clinical application of wavelet analysis in monitoring the progression of, or response to treatment, for back pain.

Frequency analysis has been widely applied to analyse EMG signals recorded from paraspinal muscles in patients with chronic LBP and short-time Fourier transform (STFT) has been used in the majority of studies. Mean and median frequencies were lower in patients with chronic LBP than in controls [29 39]; however, controversial results are still reported [40 41]. Although there is evidence that analysis of back muscle EMG activity using STFT and wavelet transform provides similar information [23 42 43], some studies suggest that wavelet transform could detect changes in muscle fatigue earlier and be more sensitive than the STFT [44-46]. A recent study used discrete wavelet transform on surface EMG of trunk muscles during the contraction in subjects with chronic LBP and in controls. Patients with chronic LBP had lower spectral power in the trunk muscles compared to the healthy subjects [29]; however, their study did not include any subjective measurements (e.g. pain scores, disability scores) or compare energy distribution between low and high frequency bands, which may reflect alterations in motor unit recruitment or muscle fibre type distributions. Our results show patients with LBP presented different EMG characteristics from healthy subjects, including lower peak power (both ES T12 and L4) and its corresponding frequency (ES T12), and higher ratio of energy between low and high frequencies (ES T12), in line with previous findings that patients with chronic LBP have an overall shift of energy distribution toward lower frequencies in the back muscles[47]. We further demonstrate a correlation between the energy distribution calculated from the EST12 and the

RMDQ, indicating an association between muscle function and self-rated disability. However, the reduced volume muscle at the lumbar level [38] might explain the differences in the findings between ES T12 and L4 levels. Together with previous work showing that EMG variables recorded from ES may identify people at increased risk of developing low back pain in two years [48], we suggest that the EMG characteristics could be useful in clinics to monitor progression of back pain as well as the effectiveness of therapeutic interventions.

Changes in spectral energy from leg and thigh muscles have been found in individuals with diabetic neuropathy and are suggested to be related to alterations in muscle recruitment strategies due to the loss of type I fibres in this population [25]. Studies have shown that instantaneous spectra derived from wavelet decomposition of EMG signals are associated with activity from different muscle fibre types using a range of approaches including electrical nerve stimulation [28] and voluntary contractions [49]. In addition, previous findings using conventional Fourier transformation demonstrated a correlation between the change in median frequency in ES during fatiguing exercise and the relative area of the muscle occupied by type I fibres in healthy subjects [18]. Anatomical evidence from biopsy studies is equivocal, with some studies demonstrating differences in muscle fibre-type proportions in paraspinal muscles between patients with LBP and healthy subjects [50 51], whilst others show no differences [52 53]. Nevertheless, studies using twitch interpolation to assess central neural drive to muscles suggest that decreases in time-to-peak amplitude of superimposed twitches at increasing levels of voluntary contraction reflect the recruitment of different types of motor units [32 54-56]. Further, given patients with chronic LBP have been shown to exhibit longer time-to-peak amplitudes of twitches during MVICs, this supports the view that these patients have alterations in muscle fibre-type composition. In the current study, the spectra obtained from the patients with LBP had a shift in the peak power towards the lower frequencies; this might reflect alterations in motor control or in muscle fibre-type proportions. Further, the correlation between the EMG spectral characteristics and back pain-related disability scores suggests that altered motor control or fibre-type proportions of paraspinal muscles may be reflected in self-rated disability scores. This highlights the importance of rehabilitation to restore motor control and muscle function in patients with LBP, which may reduce the levels of disability reported in these patients.

The approach used in the current study may provide a valuable tool for clinical assessment. Surface EMG recordings are easy to use in clinics and the task is feasible for people with chronic LBP as all of our patients were able to perform the 3 maximal isometric back extensions. While factors such as fear avoidance or pain inhibition likely affect the values of maximal muscle activity, our subjects were given adequate warm-up time as well as asked to repeat the contractions 3 times, with the highest value taken. They were also asked to report pain levels during the MVICs and to give an indication (on a modified Borg scale) of the degree of effort used to perform the MVICs. Patients reported no increase in pain, and levels of effort comparable to the controls. Wavelet transform is a robust approach for the surface EMG signal and could reveal extra features which may be useful to monitor subtle changes in muscle function during rehabilitation. A further study to test whether the wavelet approach is able to detect the therapeutic effect on muscle function is therefore warranted.

In conclusion, the patients with LBP recruited in the current study had lower maximal force of the back extensors and smaller ES muscle activity during the MVICs. The wavelet transform further revealed alterations in EMG profile and its association with the self-related back pain disability, indicating that spectral characteristics of EMG reflect muscle function.

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**Competing interests:** None declared.

**Author's contributions:** SYC and PHS conceived and designed the study. SYC and PHS conducted the experiment. SYC, EK and PHS analysed the data and interpreted the data. PG provided guidance on the data analysis. All authors drafted the manuscript and read, edited and approved the final version of the manuscript. All authors had full access to all of the data in the study and can take responsibility for the integrity of the data and the accuracy of the data analysis.

**Data sharing statement:** No additional data are available.

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**Figure Captions**

**Figure 1.** Experimental setup (top left) and peak torque and EMG activity recorded from left and right erector spinae at T12 (L ES and R ES) from a representative subject during one maximal voluntary isometric contraction (MVIC, top right). A representative 3 dimensional matrix of power, scale (frequency) and time calculated from a continuous wavelet transform analysis of the EMG data centred around the peak torque (bottom right). The bottom left figure represents the sum of the power collapsed across the time-window. The area under the curve has been split according to the ratio 1.8 (see data analysis) and the corresponding scale was used to split the curve derived from each patient dataset.

**Figure 2.** Group mean (±SEM) data showing (A) peak power and (B) its corresponding frequency from erector spinae muscles at vertebral levels T12 (ES T12) and L4 (ES L4) in the controls and in patients with LBP. *p<0.05, between-group comparison.

**Figure 3.** Correlation between the ratio of energy at low to high (low:high) frequencies and Roland-Morris Disability Questionnaire (RMDQ) in subjects with LBP.

Table 1. Demographic data.

| Characteristics | Controls (n = 10) | LBP (n = 15) | P value |
|---|---|---|---|
| Age (years) | 44.6 ± 7.9 | 43.5 ± 6.3 | 0.72 |
| Gender | 5Male; 5Female | 6Male; 9Female | 0.70 |
| Body stature (m) | 1.70 ± 0.09 | 1.70 ± 0.07 | 0.95 |
| Body mass (kg) | 72.37 ± 10.32 | 87.67 ± 24.39 | 0.04 |
| Edinburgh Handedness Inventory | 64.44 ± 54.34 | 79.00 ± 33.21 | 0.51 |
| Roland-Morris Disability Questionnaire (0-24) | 0.0 ± 0.0 | 10.27 ± 6.45 | < 0.001 |
| VAS (0-10) | 0.0 ± 0.0 | 5.20±2.84 | < 0.001 |

Data are presented as mean ± standard deviation. LBP: low back pain; VAS: visual analogue pain scale. For the Edinburgh Handedness Inventory, -100 indicates left handed whereas 100 indicates right handed; for the VAS, 0 means no pain at all and 10 means maximum pain imaginable; for the Roland-Morris Disability Questionnaire, the scores range from 0, no disability to 24, maximum disability.

Table 2. Root-mean-square EMG (mV) during maximal isometric back extension.

| | ES T12 | | | ES L4 | | |
|---|---|---|---|---|---|---|
| | Left | Right | Average | Left | Right | Average |
| Control | 0.21±0.08 | 0.20±0.07 | 0.21±0.07 | 0.22±0.10 | 0.22±0.10 | 0.22±0.09 |
| LBP | 0.13±0.07 | 0.12±0.08 | 0.12±0.07* | 0.12±0.12 | 0.14±0.07 | 0.13±0.12* |

Data are presented as mean ± standard deviation. LBP: low back pain. *p<0.05 between the LBP group and the control group.

Figure 1

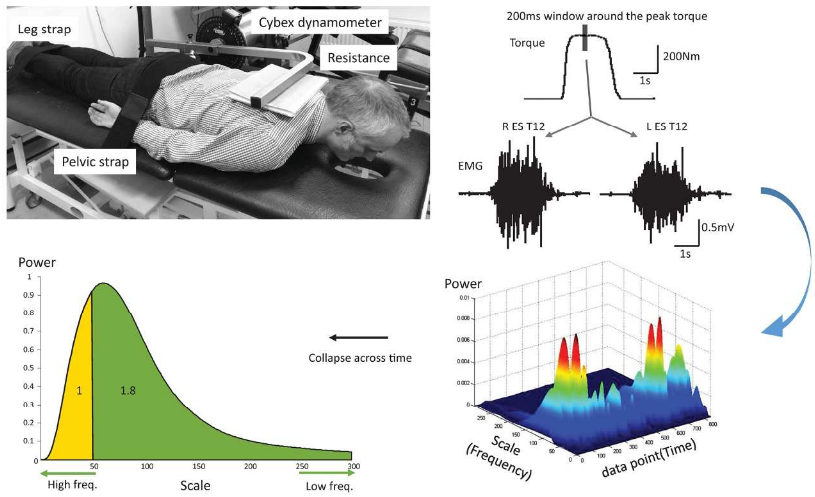


Figure 1. Experimental setup (top left) and peak torque and EMG activity recorded from left and right erector spinae at T12 (L ES and R ES) from a representative subject during one maximal voluntary isometric contraction (MVIC, top right). A representative 3 dimensional matrix of power, scale (frequency) and time calculated from a continuous wavelet transform analysis of the EMG data centred around the peak torque (bottom right). The bottom left figure represents the sum of the power collapsed across the time-window. The area under the curve has been split according to the ratio 1.8 (see data analysis) and the corresponding scale was used to split the curve derived from each patient dataset.

190x107mm (300 x 300 DPI)

Figure 2

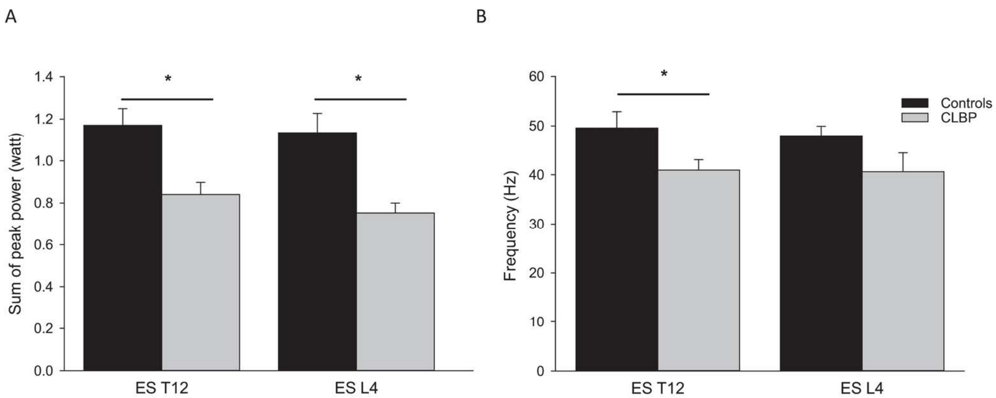


Figure 2. Group mean (±SEM) data showing (A) peak power and (B) its corresponding frequency from erector spinae muscles at vertebral levels T12 (ES T12) and L4 (ES L4) in the controls and in patients with LBP. *p<0.05, between-group comparison.

147x81mm (300 x 300 DPI)

Figure 3

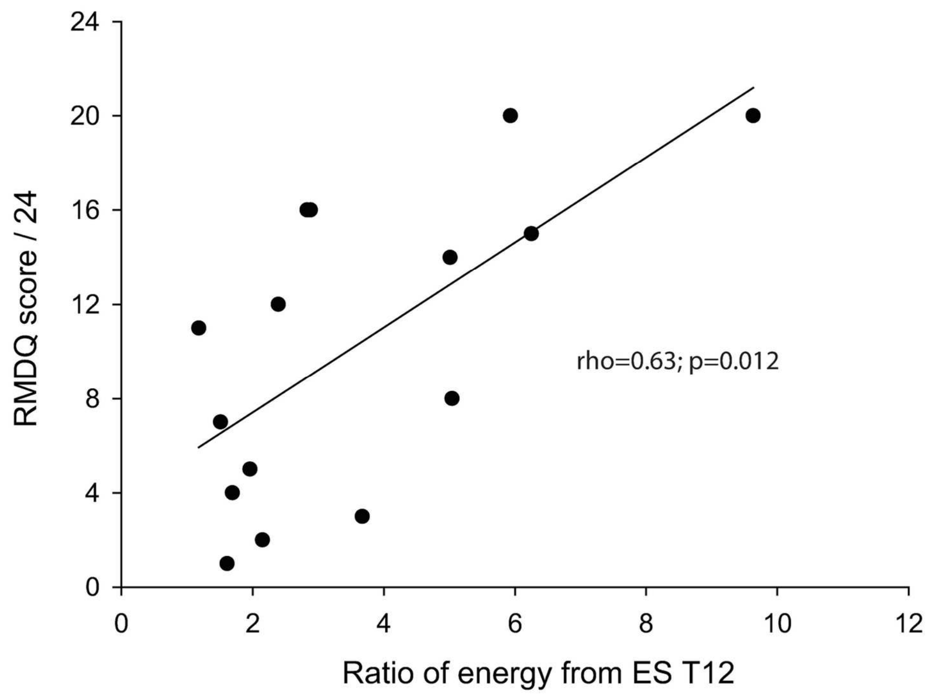


Figure 3. Correlation between the ratio of energy at low to high (low:high) frequencies and Roland-Morris Disability Questionnaire (RMDQ) in subjects with LBP.

135x115mm (300 x 300 DPI)