# Low back muscle fatigue during Sørensen endurance test in patients with chronic low back pain: relationship between electromyographic spectral compression and anthropometric characteristics

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## Abstract

*This study assessed low back muscle fatigue during Sørensen back endurance test in chronic low back pain (CLBP) patients and healthy controls, and investigated relationship between the erector spinae muscle fatigability and subject's anthropometric characteristics. Four groups (n = 10 per group) of middle-aged (47-52-year-old) subjects participated: 1) female CLBP patients, 2) healthy female subjects, 3) male CLBP patients and 4) healthy male subjects. Subjects performed Sørensen back endurance test until exhaustion, while electromyographic (EMG) power spectrum median frequency compression over time (MF slope) as indicator of the erector spinae muscle fatigability, and endurance time were recorded. The endurance time was shorter ($p < 0.05$) in male CLBP patients compared to the healthy male and female subjects. No significant gender differences in endurance time were found in CLBP patients and in healthy subjects. EMG power spectrum MF slope did not differ significantly in CLBP patients and in healthy subjects. However, MF slope was higher ($p < 0.05$) in healthy male than in female subjects. Body mass and BMI correlated moderately positively with MF slope ($r = 0.40$-$0.67$) in all measured groups. We conclude that male CLBP patients had lower back extensor muscle isometric endurance compared to the healthy subjects of both genders, whereas no gender differences in isometric endurance were found in CLBP patients and in healthy subjects. Healthy male subjects had greater lumbar erector spinae muscle fatigability compared to the healthy female subjects. Subjects with higher body mass and body mass index fatigued faster during Sørensen back endurance test.*

*Key-words: Electromyography – Fatigue – Low back pain – Erector spinae muscle.*

## Introduction

Low back pain is one of the most frequent health problems in industrial countries. Advanced age has been shown to increase the risk for nonspecific chronic low back pain (CLBP), the prevalence of which is highest in middle-age, whereas men and women have equal risk (13). It has been suggested that CLBP is associated with several structural and functional abnormalities in neuromuscular system such as atrophy of low back muscles or alteration of muscle fibers (20) and altered muscle coordination patterns (34). The alterations in the structure of low back muscles can lead to weakness and fatigability, to low back muscle impairments recognized as a potential cause of CLBP (20). In physically demanding occupations, low back muscle fatigue is easily developed during repetitive lifting, bending and twisting maneuvers, which have been shown to be occupational risk factors for CLBP (11).

Neuromuscular fatigue is generally defined as the failure to maintain the required or expected force (3). The assessment of low back muscle fatigue has

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been of interest for investigators over many years because of its tight association with low back pain. Numerous studies have identified an association between patients with low back pain and easily fatigued low back muscles, either based on subjective (endurance time) (2, 14, 19) or objective (electromyographic spectral analysis) (6, 8, 16, 17, 23, 27) assessment methods on muscle fatigue. Surface electromyography (EMG) is a noninvasive technique for assessing muscle function that has played a major role in basic understanding of the low back muscle fatigue in both normal subjects and in patients with low back pain during specific postures and movements. It has been suggested that muscle fatigue is present as soon as a muscle contraction starts (4) and can be measured by a shift of the EMG power spectrum to lower frequencies (spectral compression) caused by neural and metabolic factors in the muscle (18). The fatigue-induced EMG spectral compression has been related to the action potential conduction velocity propagation. This is most likely due to an accumulation of metabolites (e.g. $H^+$ and extracellular $K^+$) (4, 31) reducing intracellular pH (5) and, thus, decreasing sarcolemma excitability. Although the exact mechanisms underlying the EMG spectral compression are not fully understood, the resultant shift to lower frequencies during sustained contraction is recognized as an electrophysiological monitoring of fatigue process (16, 12, 21, 33).

A Sørensen back endurance test (2), i.e. holding the upper body in a horizontal and unsupported posture against the gravity, which is about 40-50% of maximal voluntary contraction force, is commonly used to measure the low back muscle fatigue during sustained submaximal isometric contraction (1, 16, 21, 27, 30). Kankaanpää et al. (16) investigated the influence of body mass index (BMI = ratio of body mass in kilograms to height in meters squared) on paraspinal muscle fatigability by using Sørensen back endurance test and found a strong influence of this factor. BMI showed a strong negative correlation with endurance time and a strong positive correlation with paraspinal muscle fatigability assessed by EMG power spectrum median frequency (MF) compression over time (MF slope). EMG power spectrum MF slope (fatigue) during the test was dependent on BMI in both sexes, but the effect of BMI was more pronounced in women than men. One of our earlier studies (27) demonstrated a strong negative correlation between BMI and endurance time during Sørensen test in patients with CLBP, whereas medium level positive correlation was found between BMI and MF slope of the lumbar erector spinae muscle during fatigue test. However, no gender differences were assessed in this study. There are some suggestions, that subject body mass and/or upper body mass may also influence the Sørensen test result (1, 21). Despite the wide-spread use of Sørensen back endurance test to monitor the low back muscle fatigue, the relationship between the EMG power spectrum compression during sustained isometric contractions and anthropometric characteristics in subjects with CLBP and healthy individuals and its gender differences are not well understood.

The aims of this study were 1) to compare low back muscle fatigability during Sørensen back isometric endurance test in patients with idiopathic CLBP and age- and gender-matched healthy control subjects, 2) to correlate objective patterns of the erector spinae muscle fatigability with subject's anthropometric parameters, and 3) to evaluate gender differences in low back muscle fatigue patterns. The erector spinae muscle fatigability during Sørensen back isometric endurance test was objectively assessed by EMG power spectrum MF slope. We hypothesized that subjects with higher body mass and BMI have a greater MF slope during Sørensen back isometric endurance test, i.e. will fatigue faster.

## Materials and methods

### *Subjects*

Four groups of middle-aged (47-52-year-old) subjects participated in this study: (1) female CLBP patients (n = 10), (2) healthy female control subjects (n = 10), (3) male CLBP patients (n = 10) and (4) healthy male control subjects (n = 10). The anthropometric parameters of the subjects are presented in Table 1. Patients were recruited through the Tartu University Hospital, where they had frequently sought medical attention for low back pain. In the initial clinical examination at the hospital, the cause of the low back pain was confirmed to be nonspecific, and patients with nerve root compression or disc prolapse, severe scoliosis, spondyloarthrosis, previous back surgery, and other serious and specific causes of low back pain were excluded. The CLBP diagnosis included the criteria that patients had low back pain for longer than 3 months (on the average for 6.8 ± 2.1 yrs) and that they did not have radicular symptoms. All patients completed questionnaires concerning their low back pain history. Current low back pain was subjectively assessed by 10 point visual analogue scale (VAS) and functional disability by Oswestry questionnaire (9). None of the control subjects had a history of pain in lower back or had experienced low back pain during the previous year. In addition, subjects were excluded if they had cardiovascular, respiratory, orthopedic, neurological, endocrine, or renal conditions that were contradictions to a sustained isometric exercise. Only pre-menopausal middle-aged women were recruited. All women were tested during the follicular phase of menstrual cycle. At the arrival in the laboratory subject's anthropometric measures (height, body mass) were collected and BMI ($kg \cdot m^{-2}$) was calculated. Subjects who had BMI of greater than 40 (morbidly obese) were also excluded. Written informed consent was obtained from all subjects. The study carried the approval of the University Ethics Committee for Human Studies.

*Sørensen back endurance test*

Back extensor muscle isometric endurance was evaluated using Sørensen test (2). The subject lay in a prone position on a treatment couch with the lower half of the body below the level of the anterior superior iliac spines strapped to the couch at three positions: at the ankles as close to the malleoli as possible, at the knee creases, and at the level of the greater trochanter of the femur. The seat belts were tightened as firmly as possible while considering the subject's level of comfort. The subject's hands were placed at the sides of the trunk, and the chest was supported at a 45° angle downward from the horizontal position. While the subjects performed Sørensen back endurance test, they were instructed at the beginning of the test to lift the upper trunk clear of the chair and maintain unsupported upper body in the horizontal plane as long as possible (until exhaustion). The horizontal position during the test was controlled by a small sack (hanging from the ceiling), which was placed between the scapulae. The test was terminated when the subject could no longer maintain upper body in the horizontal plane (defined as > 2 cm reduction in height for 2 s) despite strong verbal encouragement. The endurance time was recorded using a stopwatch and was taken as indicator of back extensor muscle isometric endurance.

*Surface EMG recordings*

While the Sørensen back isometric endurance test was performed, surface EMG was recorded bilaterally from the centre of the lumbar erector spinae muscle. After the skin was shaved, abraded, and then cleaned with alcohol, pairs of bipolar surface EMG electrodes (Ag-AgCl, 8-mm diameter, 20-mm interelectrode distance) were attached bilaterally over the lumbar erector spinae muscle at the level of L3 (approximately 3 cm laterally to the center of the spinous process). As a reference electrode a large carbon rubber plate (Nemectron, Germany, 7 × 12.5 cm) was placed on the iliac crest. The EMG signals were amplified and displayed with Medicor MG-440 preamplifiers with the frequency band ranging 1 Hz - 1 kHz. The output signals from EMG preamplifiers were digitized on-line (sampling frequency 1 kHz) by analogue-to-digital converter installed in personal computer. The digitized signals were stored on a hard disk for further analysis. EMG power spectrum MF was calculated by using Fast Fourier Transform Algorithms (18), where a 1024 data point window (1 s) slides over the whole recorded signal area with a 512 point shift (50% overlap). During Sørensen back isometric endurance test the MF was determined and averaged over each period of 5 s, whereas the following characteristics were calculated: initial MF as the mean of the first 5 s, end MF as the mean of the last 5 s and MF slope as the percent change from initial value ($\% \cdot min^{-1}$). MF slope was taken as indicator of the erector spinae muscle fatigability.

*Statistical analysis*

Standard statistical methods were used for the calculation of means and standard errors of the means (±SE). One-way analysis of variance (ANOVA) followed by Tukey *post hoc* comparisons was used to evaluate differences between the groups and between body sides. Pearson's correlation coefficient was used to estimate linear relationships between subject's anthropometric characteristics, endurance time and EMG power spectrum parameters. Statistical significance was accepted at $p < 0.05$.

## Results

### *Endurance time*

Male CLBP patients had shorter ($p < 0.05$) endurance time in Sørensen test compared to the healthy female and male subjects (Fig. 1). No significant differences in endurance time were observed between the healthy male and female subjects, and female CLBP patients.

### *Changes in surface EMG spectral median frequency*

Initial MF of the erector spinae muscle during Sørensen back isometric endurance test in healthy male subjects was higher ($p < 0.01$) compared to the healthy female subjects (Fig. 2A). No significant differences ($p < 0.05$) in initial MF were observed between the female and male CLBP patients and healthy female subjects. Healthy male subjects had higher ($p < 0.05$ - $0.01$) MF slope than healthy female subjects (Fig. 2B). No significant differences in MF slope were found between the female and male CLBP patients, and between patients and healthy subjects.

### *Correlation analysis*

Tables 2 and 3 provide the correlation coefficients between anthropometric parameters and low back muscle fatigue characteristics in female subjects and in male subjects, respectively. In female and male CLBP patients and healthy female subjects the endurance time correlated moderately to strongly negatively ($r = -0.46$ to $-0.75$) with MF slope. In male CLBP patients and in healthy female subjects body mass and BMI correlated moderately negatively with endurance time ($r = -0.44$ to $-0.69$). Female CLBP patients had strong positive correlation and healthy control subjects had moderate positive correlation between endurance time and initial MF for right side during Sørensen test ($r = 0.72$ and $0.49$, respectively). Body mass and BMI correlated moderately positively with MF slope ($r = 0.40$-$0.67$) in all measured subject groups. In healthy female subjects MF slope correlated moderately positively with initial MF ($r = 0.45$-$0.61$).

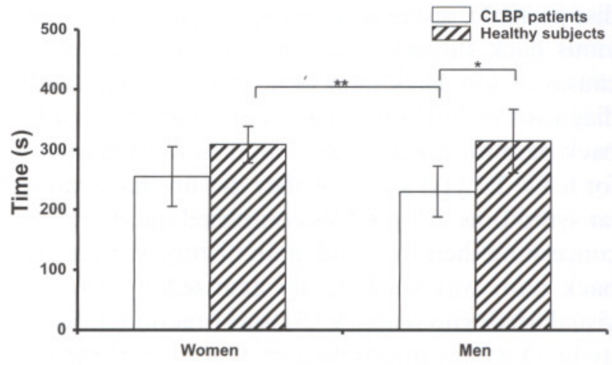


Fig. 1. – Endurance time in chronic low back pain (CLBP) patients and healthy subjects (mean ± SE). * $p < 0.05$; ** $p < 0.01$.

## Discussion

The results of the present study suggested that male CLBP patients had a reduced back extensor muscle isometric endurance compared to the healthy control subjects of both gender when performed Sørensen back endurance test until exhaustion. Male CLBP patients had shorter endurance time, i.e. fatigued faster than healthy control subjects despite the subjects having been strongly verbally encouraged to continue throughout the sustained isometric contraction. Several previous studies demonstrated a reduced back extensor muscle isometric endurance in CLBP patients compared to the healthy control subjects (2, 14, 25). Many studies comparing men to women during Sørensen back isometric endurance test reported shorter endurance time in men (2, 21, 24, 26). However, the relative weight of the trunk is generally lower for women resulting in a longer endurance time in this test (15, 16). No gender differences in endurance time when performing Sørensen test were observed in CLBP patients and in healthy control subjects in the present study.

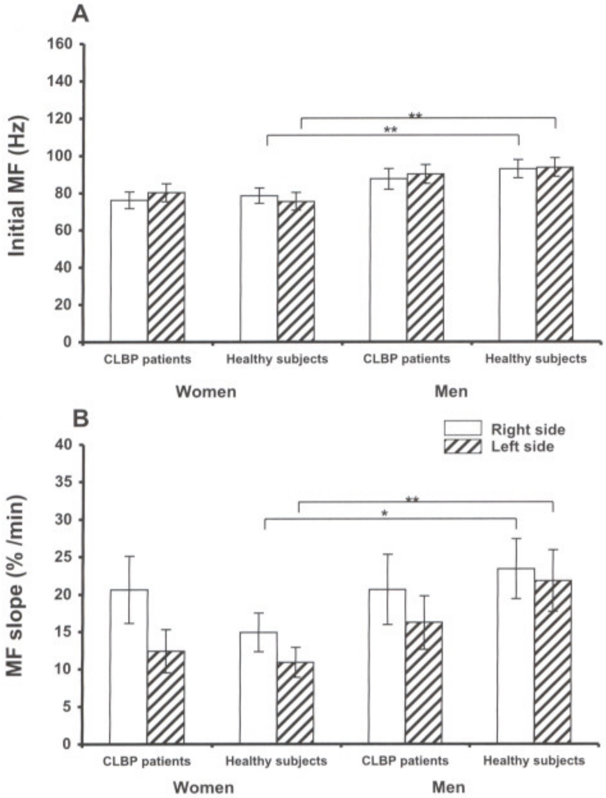


Fig. 2. – Initial median frequency (MF) of EMG power spectrum (A) and MF slope (B) of the erector spinae muscle during Sørensen back endurance test in chronic low back pain (CLBP) patients and healthy subjects (mean ± SE). * $p < 0.05$; ** $p < 0.01$.

Table 1. – *Anthropometric characteristics of the subjects (mean ± SE)*

| Variable | Women | | Men | |
|---|---|---|---|---|
| | CLBP patients (n = 10) | Healthy subjects (n = 10) | CLBP patients (n = 10) | Healthy subjects (n = 10) |
| Age (years) | 50.3 ± 3.4 | 49.6 ± 1.3 | 50.7 ± 11.9 | 49.3 ± 6.5 |
| Height (cm) | 164.7 ± 2.2 | 163.2 ± 1.1 | 177.8 ± 2.5 | 177.5 ± 1.7 |
| Body mass (kg) | 71.9 ± 3.9 | 67.2 ± 3.9 | 81.2 ± 3.7 | 80.5 ± 3.4 |
| BMI ($kg \cdot m^{-2}$) | 26.9 ± 1.4 | 24.6 ± 1.4 | 25.6 ± 1.2 | 25.6 ± 1.3 |

CLBP – chronic low back pain; BMI – body mass index.

The most commonly used EMG variable for assessing low back muscle fatigue is MF or half-power point of the EMG (10). The initial value of MF was associated to the distribution of the muscle fiber type recruited (22), while MF slope, i.e. the rate of change over time, was associated to the fatigability properties of the active motor units (7). In the present study, healthy male subjects had a higher initial EMG power spectrum MF of the erector spinae muscle compared to the healthy female subjects when performing Sørensen back endurance test. This is an indicator of the greater pre-fatigue loading of the erector spinae muscle during sustained isometric contraction in healthy men than in women. Concerning gender, the differences between healthy men and women in low back muscle function have been found, indicating greater low back muscle fatigability for men (25, 29). In the present study, a steeper MF slope of the erector spinae muscle during the Sørensen back endurance test in healthy male control subjects was observed compared to the healthy female control subjects, indicating greater fatigability in men. A steeper MF slope obtained from the lumbar erector spinae muscle in healthy men compared to the women during an unsupported trunk holding test has been reported previously (33), which is in good agreement with the present results. The observed gender differences in fatigability of the low back muscles have been attributed to greater type I (slow twitch)/type II (fast twitch) muscle fiber area ratios in women (32), suggesting a difference in the functional capacity of the lumbar back muscles between females and males. In several previous studies, low back muscle fatigue has been assessed by using EMG power spectrum indices (8, 21, 24). It has been suggested that EMG power spectrum MF slope during fatigue reflects the changes in the action potential propagation of individual muscle fibers that are a result of the underlying accumulation of metabolic by-products (lactate and extracellular $K^+$) during the fatiguing contraction (5, 35).

Differences in EMG power spectrum compression parameters during fatiguing contraction in CLBP patients compared with those in healthy control subjects have usually shown a steeper slope (27, 28). However, no significant differences in MF slope between female and male CLBP patients were found in the present study and this finding is somewhat surprising for us. These differences between our findings and previous studies may be caused by the differences in the experimental settings and the number of the subjects who participated in this study.

It has been indicated that MF slope obtained from the low back muscles during a sustained submaximal contraction is approximately linear and strongly negatively correlated with endurance time,

Table 2. – *Correlations between anthropometric parameters and low back muscle fatigue characteristics during Sørensen back endurance test in female CLBP patients and healthy subjects*

| Parameters | Height | BM | BMI | $t_{endur}$ | Initial MF (right) | Initial MF (left) | MF slope (right) | MF slope (left) |
|---|---|---|---|---|---|---|---|---|
| CLBP patients (n = 10) | | | | | | | | |
| Height | X | 0.23 | –0.28 | –0.20 | –0.38 | –0.38 | –0.01 | 0.16 |
| BM | | X | 0.85* | –0.21 | –0.01 | 0.30 | 0.64* | 0.52 |
| BMI | | | X | –0.12 | 0.15 | 0.50 | 0.57 | 0.44 |
| $t_{endur}$ | | | | X | 0.72* | 0.29 | –0.63* | –0.75* |
| Initial MF (right) | | | | | X | 0.70* | –0.38 | –0.15 |
| Initial MF (left) | | | | | | X | 0.22 | 0.22 |
| MF slope (right) | | | | | | | X | 0.45 |
| MF slope (left) | | | | | | | | X |
| Healthy subjects (n = 10) | | | | | | | | |
| Height | X | 0.01 | 0.07 | 0.08 | –0.37 | 0.28 | –0.15 | –0.01 |
| BM | | X | 0.88* | –0.44 | 0.27 | 0.46 | 0.40 | 0.52 |
| BMI | | | X | –0.65* | 0.42 | 0.68* | 0.47 | 0.64* |
| $t_{endur}$ | | | | X | –0.33 | –0.35 | –0.16 | –0.59 |
| Initial MF (right) | | | | | X | 0.47 | 0.60 | 0.58 |
| Initial MF (left) | | | | | | X | 0.45 | 0.61 |
| MF slope (right) | | | | | | | X | 0.51 |
| MF slope (left) | | | | | | | | X |

CLBP - chronic low back pain; BM - body mass; BMI - body mass index; $t_{endur}$ – endurance time; MF - median frequency; MF slope - median frequency decrease over time. * $p < 0.05$.

Table 3. – *Correlations between anthropometric parameters and low back muscle fatigue characteristics during Sørensen back endurance test in male CLBP patients and healthy subjects*

| Parameters | Height | BM | BMI | $t_{endur}$ | Initial MF (right) | Initial MF (left) | MF slope (right) | MF slope (left) |
|---|---|---|---|---|---|---|---|---|
| CLBP patients (n = 10) | | | | | | | | |
| Height | X | 0.28 | –0.39 | 0.19 | –0.40 | –0.68 | 0.23 | 0.22 |
| BM | | X | 0.77 | –0.58 | 0.07 | 0.16 | 0.67* | 0.64* |
| BMI | | | X | –0.69* | 0.32 | 0.61 | 0.65* | 0.57 |
| $t_{endur}$ | | | | X | –0.26 | –0.57 | –0.46 | –0.66* |
| Initial MF (right) | | | | | X | 0.78* | 0.02 | 0.10 |
| Initial MF (left) | | | | | | X | 0.14 | 0.39 |
| MF slope (right) | | | | | | | X | 0.30 |
| MF slope (left) | | | | | | | | X |
| Healthy subjects (n = 10) | | | | | | | | |
| Height | X | 0.51 | 0.43 | 0.07 | 0.39 | 0.35 | 0.29 | 0.22 |
| BM | | X | 0.90* | 0.22 | 0.65* | 0.91* | 0.61 | 0.46 |
| BMI | | | X | 0.02 | 0.41 | 0.71* | 0.56 | 0.59 |
| $t_{endur}$ | | | | X | 0.49 | 0.42 | –0.31 | –0.36 |
| Initial MF (right) | | | | | X | 0.83* | 0.11 | 0.01 |
| Initial MF (left) | | | | | | X | 0.01 | 0.06 |
| MF slope (right) | | | | | | | X | 0.97* |
| MF slope (left) | | | | | | | | X |

CLBP - chronic low back pain; BM - body mass; BMI - body mass index; $t_{endur}$ – endurance time; MF - median frequency; MF slope - median frequency decrease over time. * $p < 0.05$.

suggesting it being a sensitive, objective, and motivation-independent indicator providing information regarding the degree of muscle fatigue (12, 21, 26). In the present study, MF slope of the erector spinae muscle during Sørensen back endurance correlated moderately to strongly with endurance time in female and male CLBP patients and healthy female control subjects.

One purpose of this study was to correlate objective patterns of the low back muscle fatigue with subject's anthropometric parameters. A moderate to strong negative correlation between body mass and BMI, and endurance time evaluated during Sørensen test was observed in male CLBP patients and in healthy female control subjects. Body mass and BMI correlated moderately negatively with MF slope in all measured groups of subjects. Thus, the correlation analysis indicated that subjects with higher body mass and BMI appeared to fatigue faster during Sørensen back endurance test than that of subjects with lower body mass and BMI. However, the relationship between anthropometric characteristics and low back muscle fatigability in different loading conditions and its association with gender and CLBP need further clarification.

The present study has limitations, because only a small number of CLBP patients and healthy control subjects of the both gender were measured. However, despite limitations this study indicated that low back muscle fatigability is associated with subject's body mass and BMI.

In conclusion, the present study demonstrated that middle-aged male CLBP patients had lower back extensor muscle isometric endurance when performing Sørensen test compared to the healthy male and female subjects. However, no gender differences were found in isometric endurance in CLBP patients and in healthy subjects. The erector spinae muscle fatigability parameter (MF slope) during Sørensen back endurance test did not detect differences between CLBP patients and healthy subjects, but unexpectedly, healthy male subjects demonstrated higher erector spinae muscle fatigability than demonstrated healthy female subjects. This greater erector spinae muscle fatigability in healthy male subjects was associated with greater pre-fatigue MF compared to healthy female subjects. Correlation analysis revealed that erector spinae muscle fatigability in CLBP patients and healthy subjects was associated with anthropometric characteristics: subjects with higher body mass and BMI fatigued faster. But the subject population was small and further investigation is warranted.

**Acknowledgements**

This study was partly supported by Estonian Science Foundation, Grant No. 5504.

## References

1. Alaranta, H., Hurri, H., Heliövaara, M., Soukka, A. and Harju, R.: Non-dynamometric trunk performance tests: reliability and normative data. *Scand. J. Rehabil. Med.*, 26: 211-215, 1994.
2. Biering-Sørensen, B.: Physical measurement as risk indicators for low back trouble over one year period. *Spine*, 9: 106-119, 1984.
3. Bigland-Ritchie, B., Jones, D.A., Hosking, G.P. and Edwards, R.H.T.: Central and peripheral fatigue in sustained maximum voluntary contractions of human quadriceps muscle. *Clin. Sci. Mol. Med.*, 54: 609-614, 1978.
4. Bigland-Ritchie, B., Donovan, E.F. and Roussos, C.S.: Conduction velocity and EMG power spectrum changes in fatigue of sustained efforts. *J. Appl. Physiol.*, 51: 1300-1305, 1981.
5. Brody, L.R., Pollock, M.T., Roy, S.H., De Luca, C.J. and Celli, B.: pH-induced effects on medial frequency and conduction velocity of the myoelectric signal. *J. Appl. Physiol.*, 71: 1878-1885, 1991.
6. Da Silva, R.A., Arsenault, A.B., Gravel, D., Lariviere, S. and De Oliveira, E.: Back muscle strength and fatigue in healthy and chronic low back pain subjects: A comparative study of three assessment protocols. *Arch. Phys. Med. Rehabil.*, 86: 722-729, 2005.
7. De Luca, C.J.: Use of the surface EMG signal for performance evaluation of back muscles. *Muscle Nerve*, 16: 210-216, 1993.
8. Elfing, B., Dedering, A. and Nemeth, G.: Lumbar muscle fatigue and recovery on patients with long-term low-back trouble – electromyography and health-related factors. *Clin. Biomech.*, 18: 619-630, 2003.
9. Fairbank, J.C.T., Couper, J., Davies, J. and O'Brien, J.: The Oswestry low back pain disability questionnaire. *Physiotherapy*, 66: 271-273, 1980.
10. Farina, D. and Merletti, R.: Comparison of algorithms for estimation of EMG variables during voluntary isometric contraction. *J. Electromyogr. Kinesiol.*, 10: 337-355, 2000.
11. Frymoyer, J.W., Pope, M.H., Clements, J.H., Wilde, D.G., Mac Pherson, B. and Ashikaga, T.: Risk factors in low-back pain. Epidemiological survey. *J. Bone Joint Surg. Am.*, 65: 213-218, 1983.

12. HAGG, G.M.: Interpretation of EMG spectral alterations and alteration indexes at sustained contraction. *J. Appl. Physiol.*, 73: 1211-1217, 1992.
13. HELIOVAARA, M.: Risk factors for low back pain and sciatica. *Ann. Med.*, 21: 257-264, 1989.
14. HULTMAN, G., NORDIN, M., SARASTE, H. and OHLSEN, H.: Body composition, endurance, strength, cross-sectional area, and density of m. erector spinae in men with and without low back pain. J. *Spinal Disord.*, 6: 114-123, 1993.
15. JØRGENSEN, K. and NICOLAISEN, T.: Two methods for determining trunk extensor endurance. A comparative study. *Eur. J. Appl. Physiol.*, 55: 639-644, 1986.
16. KANKAANPÄÄ, M., LAAKSONEN, D., TAIMELA, S., KOKKO, S.-M., AIRAKSINEN, O. and HÄNNINEN, O.: Age, sex, and body mass index as determinants of back and hip extensor fatigue in the isometric Sørensen back endurance test. *Arch. Phys. Med. Rehabil.*, 79: 1069-1075, 1998.
17. KLEIN, A.B., SNYDER-MACLER, L., ROY, S.H. and DE LUCA, C.J.: Comparison of spinal mobility and isometric trunk extensor forces with electromyographic spectral analysis in identifying low back pain. *Phys. Ther.*, 71: 445-454, 1991.
18. LINDSTRÖM, L., MAGNUSSON, R. and PETERSEN, I.: Muscular fatigue and action potential conduction velocity changes studied with frequency analysis of EMG signal. *Electromyography*, 10: 341-356, 1970.
19. LUOTO, S., HELIÖVAARA, M., HURRI, H. and ALARANTA, H.: Static back endurance and risk of low-back pain. *Clin. Biomech.*, 10: 323-324, 1995.
20. MANNION, A.F.: Fiber type characteristics and function of the human paraspinal muscles: normal values and changes in association with low back pain. *J. Electromyogr. Kinesiol.*, 9: 363-377, 1999.
21. MANNION, A.F. and DOLAN, P.: Electromyographic median frequency changes during isometric contraction of the back extensors to fatigue. *Spine*, 19: 1223-1229, 1994.
22. MANNION, A.F. and DOLAN, P.: The effects of muscle length and force output on the EMG power spectrum of the erector spinae. *J. Electromyogr. Kinesiol.*, 6: 159-168, 1996.
23. MANNION, A.F., CONNOLLY, B., WOOD, K. and DOLAN, P.: The use of surface EMG power spectral analysis in the evaluation of back muscle function. *J. Rehabil. Res. Dev.*, 34: 427-439, 1997.
24. MAYER, T.G., SMITH, S.S., KEELEY, J. and MOONEY, V.: Quantification of lumbar function. Part 2: sagittal plane strength in low back pain patients. *Spine*, 10: 765-772, 1985.
25. NICOLAISEN, T. and JØRGENSEN, K.: Trunk strength, back muscle endurance and low-back trouble. *Scand. J. Rehab. Med.*, 17: 121-127, 1985.
26. ODDSON, L.I.E. and DE LUCA, C.J.: Activation imbalances in lumbar spine muscles in the presence of chronic low back pain. *J. Appl. Physiol.* 94: 1410-1420, 2003.
27. PÄÄSUKE, M., JOHANSON, E., PROOSA, M., ERELINE, J. and GAPEYEVA, H.: Back extensor muscle fatigability in chronic low back pain patients and controls: relationship between electromyogram power spectrum and body mass index. *J. Back Musculoskel. Rehabil.* 16: 17-24, 2002.
28. ROY, S.H., DE LUCA, S.J. and CASAVANT, D.A.: Lumbar muscle fatigue and chronic lower back pain. *Spine*, 14: 992-1001, 1998.
29. SMIDT, G.L. and BLANPIED, P.R.: Analysis of strength tests and resistive exercises commonly used for low-back disorders. *Spine*, 12: 1025-1034, 1987.
30. SUNG, P.S., ZURCHER, U. and KAUFMAN, M.: Nonlinear analysis of electromyography time series as a dignostic tool for low back pain. *Med. Sci. Monit.*, 11: S 1-5, 2005.
31. TESCH, P.A., KOMI, P.V., JACOBS, I., KARLSSON, J. and VIITASALO, J.T.: Influence of lactate accumulation of EMG frequency spectrum during repeated concentric contractions. *Acta Physiol. Scand.*, 119: 61-67, 1983.
32. THORSTENSSON, A. and CARLSON, H.: Fiber types in human lumbar back muscles. *Acta Physiol. Scand.*, 131: 195-202, 1987.
33. UMEZU, Y., KAWAZU, T., TAIJIMA, F. and OGATA, H.: Spectral electromyographic fatigue analysis of back muscles in healthy adult compared with men. *Arch. Phys. Med. Rehabil.*, 79: 536-538, 1998.
34. VAN DIEEN, J.H., SELEN, L.P. and CHOLEWICKI, J.: Trunk muscle activation in low-back pain patients: an analysis of the literature. *J. Electromyogr. Kinesiol.*, 13: 333-351, 2003.
35. VESTGAARD-POULSEN, P., THOMSEN, T., SINKJAER, T. and HENRIKSEN, O.: Simultaneous 31P-NMR spectroscopy and EMG in exercising and recovering human skeletal muscle: a correlation study. *J. Appl. Physiol.*, 79: 1469-1478, 1995.

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