Eur Spine J (2002) 11:13–19
DOI 10.1007/s005860100314

ORIGINAL ARTICLE

L. A. Danneels
P. L. Coorevits
A. M. Cools
G. G. Vanderstraeten
D. C. Cambier
E. E. Witvrouw
H. J. De Cuyper

Differences in electromyographic activity in the multifidus muscle and the iliocostalis lumborum between healthy subjects and patients with sub-acute and chronic low back pain

Received: 2 February 2001
Revised: 12 May 2001
Accepted: 28 May 2001
Published online: 14 July 2001

L.A. Danneels (✉) · P.L. Coorevits
A.M. Cools · G.G. Vanderstraeten
D.C. Cambier · E.E. Witvrouw
University Hospital,
Department of Rehabilitation Sciences
and Physiotherapy,
De Pintelaan 185,
1B3, 9000 Ghent, Belgium
e-mail: lieven.danneels@rug.ac.be,
Tel.: +32-9-2402635, Fax: +32-9-2403811

H.J. De Cuyper
Gallifort Hospital,
Department of Motor Rehabilitation
and Physiotherapy, Antwerp

Abstract The present study was carried out to examine possible mechanisms of back muscle dysfunction by assessing a stabilising and a torque-producing back muscle, the multifidus (MF) and the iliocostalis lumborum pars thoracis (ICLT), respectively, in order to identify whether back pain patients showed altered recruitment patterns during different types of exercise. In a group of healthy subjects (*n*=77) and patients with sub-acute (*n*=24) and chronic (51) low back pain, the normalised electromyographic (EMG) activity of the MF and the ICLT (as a percentage of maximal voluntary contraction) were analysed during coordination, stabilisation and strength exercises. The results showed that, in comparison with the healthy subjects, the chronic low back pain patients displayed significantly lower (*P*=0.013) EMG activity of the MF during the coordination exercises, indicating that, over the long term, back pain patients have a reduced capacity to voluntarily recruit the MF in order to obtain a neutral lordosis. In contrast, during the stabilisation exercises, no significant differences between patients and controls were found for the normalised EMG activity of the two muscles. These findings indicated that, during low-load exercises, no insufficiencies in back muscle recruitment were evident in either sub-acute or chronic back pain patients. During the strength exercises, the normalised activity of both back muscles was significantly lower in chronic low back pain patients (*P*=0.017 and 0.003 for the MF and ICLT, respectively) than in healthy controls. Pain, pain avoidance and deconditioning may have contributed to these lower levels of EMG activity during intensive back muscle contraction. The possible dysfunction of the MF during coordination exercises and the altered activity of both muscles during strength exercises may be of importance in symptom generation, recurrence or maintenance of low back pain.

Keywords Low back pain · Back muscles · Electromyography · Coordination · Stabilisation · Strength

Introduction

The performance of voluntary trunk movements and the maintenance of trunk stability requires muscular activity. Each movement depends on specific coordination of the trunk muscles to produce a resultant force (torque) which has to be tuned with the variations in external and internal forces to give a smooth and appropriate movement [30].

Recent studies suggest that the back extensor muscles may not be considered as one muscle group and that different back muscles may have quite specific functions [2, 5, 27, 31, 33]. The multifidus (MF) muscle has been shown to make a major contribution to the control and segmental stabilisation of the lumbar spine [5, 9, 15, 27, 33], whereas the iliocostalis lumborum pars thoracis (ICLT) clearly has a torque-producing and general trunk-stabilising function [5, 19].

Epidemiological studies suggest that paraspinal muscle dysfunction may be important in the aetiology of low back pain [20, 22], and paraspinal muscle weakness has been documented in severe, chronic low back pain [1, 18, 20]. However, the muscular response to back pain may not be uniform among all muscles of the back [3, 4, 13, 29]. The fatigue rate of the MF muscle was shown to be greater in patients with chronic back pain compared to control subjects without back pain, while no such difference was evident for the ICLT [3]. In addition, a select atrophy of the MF has been shown in patients with chronic low back pain [4]. Thus monitoring the behaviour of individual back muscles may be necessary for an accurate assessment of back muscle function [21, 29, 31, 32].

The trunk muscle system has been researched extensively using various assessment techniques in order to accurately depict and define the nature of the muscle dysfunction. The use of surface electromyographic (EMG) techniques, in particular, has played a major role in understanding trunk muscle activity during specific postures and movements in both control subjects and patients with low back pain [7, 12, 17, 24]. Although the functional subdivision between the back muscles is thought to be important, differences in back muscle activity between "normal" subjects and patients with LBP are rarely analysed for each of the muscles separately.

The purpose of this study was to compare the level of back muscle activity in healthy controls and patients with sub-acute and chronic low back pain during coordination, stabilisation and strength exercises. To assess the performance of both a stabilising and torque-producing back muscle, the behaviour of the MF and the ICLT were monitored.

Methods

Subjects

After obtaining approval from the Ethical Committee of the Jan Palfijn Hospital (Campus Gallifort, Antwerp), healthy subjects and low back pain patients were enrolled in the study. All subjects gave their signed informed consent to participate.

Over a period of 2½ years, all patients referred to the Department of Physical Medicine and Rehabilitation at the Jan Palfijn Hospital (Campus Gallifort, Antwerp) for diagnostic evaluation and treatment were screened to assess back muscle function. All patients with a history of mechanical low back pain, with or without disc protrusion, were selected for the current study. Sub-acute pain was defined as pain lasting up to 12 months, and chronic pain was defined as pain lasting more than 12 months [4]. Exclusion criteria were very acute symptoms, previous lumbar surgery, the presence of a lumbar scoliosis exceeding 10, neuromuscular or joint disease, evidence of systemic decease, carcinoma or organ diseases. In addition, patients who had undergone sport or fitness training for the low back muscles in the past 3 months were excluded. To facilitate comparison with a normal active and working control group, the patient group only included those between 25 and 55 years of age. These inclusion criteria produced a select group of 24 sub-acute (12 women and 12 men) and 51 chronic patients (28 women and 23 men).

A control sample of 77 normal active volunteers (44 women and 33 men) with varied histories of occupational and leisure-time physical activity and with no history of disabling low back pain or known pathology (verified by a checklist) were randomly chosen from the staff of the Jan Palfijn Hospital (Campus Gallifort) and the University of Ghent. The three study groups were highly comparable with regard to height, weight and age (Table 1).

Exercises

The participants were asked to perform 15 exercises, subdivided into three categories: coordination, stabilisation and strength exercises [6]. The exercises are described in Table 2.

In the first category, the coordination exercises, the ability to coordinate the back muscles in order to obtain a physiological (appropriate neutral) lumbar lordosis was evaluated in four-point kneeling and in standing [26, 28]. Starting from a relaxed posture, the test subjects were asked to assume a physiological lordosis (four-point kneeling: about halfway between full extension and a flat position of the spine; standing: determined by horizontal alignment between the antero-superior iliac spine and the postero-superior iliac spine), sustain this posture and relax. Each phase (assuming the position – holding it – relaxing) took 2 s. The EMG activity of the MF and the ICLT was registered during the isometric activity in the middle phase.

In the second category, the stabilisation exercises were designed to evaluate back muscle activity with the patient maintaining a physiological lordosis while performing an exercise. In a first set of stabilisation exercises (stabilisation I; Table 2), back muscle activity in the neutral position of the lumbar spine was tested in a variety of body positions in conjunction with leg- and arm-loading activities. In a second set of stabilisation exercises (stabilisation II; Table 2), a physiological lordosis had to be assumed and maintained during slow, controlled movements of the trunk. Each stabilisation exercise was performed in a standardised and controlled manner, allowing 2 s for the concentric and 2 s for the eccentric movement of the arm, leg or trunk. The EMG activity of the par-

Table 1 Characteristics of the healthy subjects, sub-acute and chronic low back pain (LBP) group

Variable	Normals		Sub-acute		Chronic		P value
	Women	Men	Women	Men	Women	Men	
Subjects (*n*)	44	33	12	12	28	23	0.7
Age (years)	35.9±9.7	36.8±11.5	41.9±14.8	36.8±11.1	39.6±10.9	42.3±12.9	0.52
Height (cm)	167.1±6.1	178.8± 7.5	166.1± 7.7	177.2± 7.3	166.6± 6.4	178.1± 9.2	0.8
Weight (kg)	63.2±5.8	75.2±10.2	69.5± 8.3	76.8±13.8	66.4±12.8	77.4±11.1	0.59

Table 2 Coordination, stabilisation and strength exercises

Category	Exercise	Description
Coordination	1	Four-point kneeling: setting and holding a physiological lumbar lordosis
	2	Standing: setting and holding a physiological lumbar lordosis
Stabilisation I	3	Four-point kneeling: lifting right leg to horizontal position
	4	Four-point kneeling: lifting left leg to horizontal position
	5	Standing: lifting both arms to a horizontal position
	6	Standing: lifting both arms to a horizontal position holding a weight of 5 kg in each hand
	7	Sitting: lifting both arms to a horizontal position
Stabilisation II	8	Standing: bending forward with a straightened back, arms hanging vertically
	9	Standing: same as 8, but with 5 kg in each hand
	10	Standing: same as 8, but rotating to the right side, hands on shoulders
	11	Standing: same as 10, but rotating to the left side
	12	Sitting: same as 8, but rotating to the left side, hands on shoulders
	13	Sitting: same as 10, but rotating to the left side
Strength	14	Trunk extension in prone position
	15	Leg extension in prone position

avertebral muscles was recorded during a 2-s static period between the concentric and eccentric phase.

The strength exercises (category 3) consisted of trunk or leg-lifting from a prone position lying on a couch (the sternum or patellae, respectively, had to lose contact with the surface). Analogous with the stabilisation exercises, EMG activity was recorded for 2 s during the isometric performance.

A metronome was used to pace each exercise at a frequency of 60 beats/min. Each exercise was demonstrated by the experimenter and practised by the subject until properly paced. In order to minimise the effects of fatigue, the strength exercises were performed at the end of each session (exercises 14 and 15). Moreover, the time taken to explain each exercise provided adequate rest to prevent the onset of muscular fatigue.

At the end of the exercises, the EMG activity for both muscles was measured during maximal voluntary isometric contraction (MVIC) to provide a basis for normalisation [5]. For the MVIC, each subject lay in a prone position, with their forehead resting on their hands and their feet strapped to the examination table. The subjects were required to produce three maximal isometric extension efforts while resistance was provided to the scapular region by the examiner.

Equipment

After appropriate skin preparation, followed by cleaning with alcohol to reduce skin impedance (typically ≤10 kOhm), pairs of self-adhesive surface electrodes with an electrical contact surface area of approximately 1 cm^2 (Ag-AgCl; Bleu Sensor; Medicotest GmbH, Germany) were attached to the skin overlying the MF and ICLT, with a centre-to-centre spacing of 2.5 cm. An attempt to prevent cross-talk between the muscles of interest and other muscles was made using the following procedures. The electrodes were positioned well within the borders of the muscles and were aligned with the muscles' orientation. For the MF, the self-adhesive strips of the electrodes were placed bilaterally just lateral to the midline of the body, above and below a line connecting both posterior superior iliac spines [6, 16]. For the ICLT, the electrodes were placed above and below the level of the L1 spinous process midway between the midline and lateral aspect of the body [5, 6, 16, 31, 32]. A portable apparatus (ME 3000 Professional Muscle Tester, Mega Electronics, Finland), was used. All raw myoelectric signals were preamplified (overall gain, 412; common rate rejection ratio, 110 dB, filtered to produce a bandwidth of 8–500 Hz). All EMG signals were A/D converted (12-bit resolution) at 1000 Hz. In order to prevent artefacts, the cables were adequately controlled not to move during the recording.

Data acquisition

The EMG data were normalised with respect to time [6, 11] using a home-written computer program. The EMG data were reduced to a common number (500) of data samples. The zone of 0.5 s in which the maximal mean amplitude occurred was automatically selected for further analysis. Data analysis thus yielded a value for the parameter "averaged EMG" (AEMG) for each muscle during each exercise. Previous research has shown that this procedure is valid and highly reliable during these standardised coordination, stabilisation and strength exercises [6]. The AEMG from the 0.5 s of the maximal voluntary contraction (MVC) were used to normalise the EMG signals obtained under the various experimental conditions.

Data processing

In order to identify possible back muscle dysfunction, the normalised (to maximum) muscle activity of the MF and the ICLT during the different exercises was calculated and then averaged for each category of exercises.

Statistical analysis

Because the data were not normally distributed (Kolmogorov-Smirnov test significant), non-parametric statistical tests were applied. The normalised data for the MF and ICLT for each category of exercises are therefore presented as the median and interquartile range (Tables 3, 4). Differences in normalised EMG activity between the three groups were analysed using the Kruskall-Wallis test. Post hoc tests were performed using the Mann-Whitney U-test. In addition, boxplots were made to visualise the distribution of both variables, namely the normalised EMG activity of the MF and the ICLT (Fig. 1). For statistical analysis, the software SPSS 9.0. was used. Statistical significance was accepted at the 5% level. The power of the statistical analysis in this study was between 0.81 and 0.89.

Table 3 Median and interquartile range of the relative EMG activity (as a percentage of the maximal voluntary contraction, MVC) of the iliocostal muscle for the three groups and the four categories of exercises

Group	Exercise category							
	Coordination		Stabilisation I		Stabilisation II		Strength	
	Median	Interquartile range	Median	Interquartile range	Median	Interquartile range	Median	Interquartile range
Normals	19.9	12.8–17.9	27.5	19.3–34.2	28.7	22–37.3	74.2	59.3–89.7
Sub-acute	19.4	14.2–26.1	26.3	22.6–33.5	28.2	22.2–34.8	69.7	54.9–78.8
Chronic	15.6	10.1–23.2	26.2	18.7–36.5	26.8	21–33.9	61.3	51.9–79.9
1–2–3[a]	0.102		0.96		0.78		0.012	
1–2[b]							0.207	
2–3[c]							0.29	
1–3[d]							0.003	

[a] *P* value between the three groups
[b] *P* value between the normal subjects and the sub-acute patients
[c] *P* value between the between the sub-acute and the chronic patients
[d] *P* value between the between the normal subjects and the chronic patients

Table 4 Median and interquartile range of the relative EMG activity (as a percentage of the maximal voluntary contraction, MVC) of the multifidus muscle for the three groups and the four categories of exercises

Group	Exercise category							
	Coordination		Stabilisation I		Stabilisation II		Strength	
	Median	Interquartile range	Median	Interquartile range	Median	Interquartile range	Median	Interquartile range
Normals	30.4	17.9–42.9	31.4	25.6–41.9	29.8	22.1–38.9	79.8	64.9–98.9
Sub-acute	27.7	22.4–34.6	34.8	28.3–42.5	31.1	23.5–40.1	70	55.3–90.4
Chronic	21.6	15.5–29.8	32.9	27.4–41.7	32.1	25.4–40.5	71.3	55.5–82.2
1–2–3[a]	0.031		0.64		0.57		0.046	
1–2[b]	0.39						0.18	
2–3[c]	0.097						0.63	
1–3[d]	0.013						0.017	

Results

Maximal voluntary contractions

The intra-class reliability coefficient, *R*, between the three repeated trials was high (MF left, R=0.98; MF right, R=0.97; ICLT left, 0.94; ICLT right, 0.94). Since the variance of the maximum EMG activity of the different muscles within the subjects was acceptable (MF left, 18.6%; MF right, 18.9%; ICLT left, 25.6%; ICLT right, 26.8%), further calculations were performed with the mean of the repeated trials.

Coordination exercises

For the MF muscle, there was a significant difference between the three groups for the normalised AEMG during the coordination exercises. Post hoc tests showed that the differences were only significant between the healthy subjects and the chronic low back pain patients. No significant differences were found for the ICLT muscle (Table 3, Fig. 1).

Stabilisation exercises

For both categories of stabilisation exercises, the comparison of normalised AEMG between all groups did not reveal any significant differences for either the MF muscle or the ICLT muscle (Tables 3, 4, Fig. 1).

Strength

For both muscles, highly significant differences were found in AEMG between the three groups. Post hoc tests revealed that the differences were only significant be-

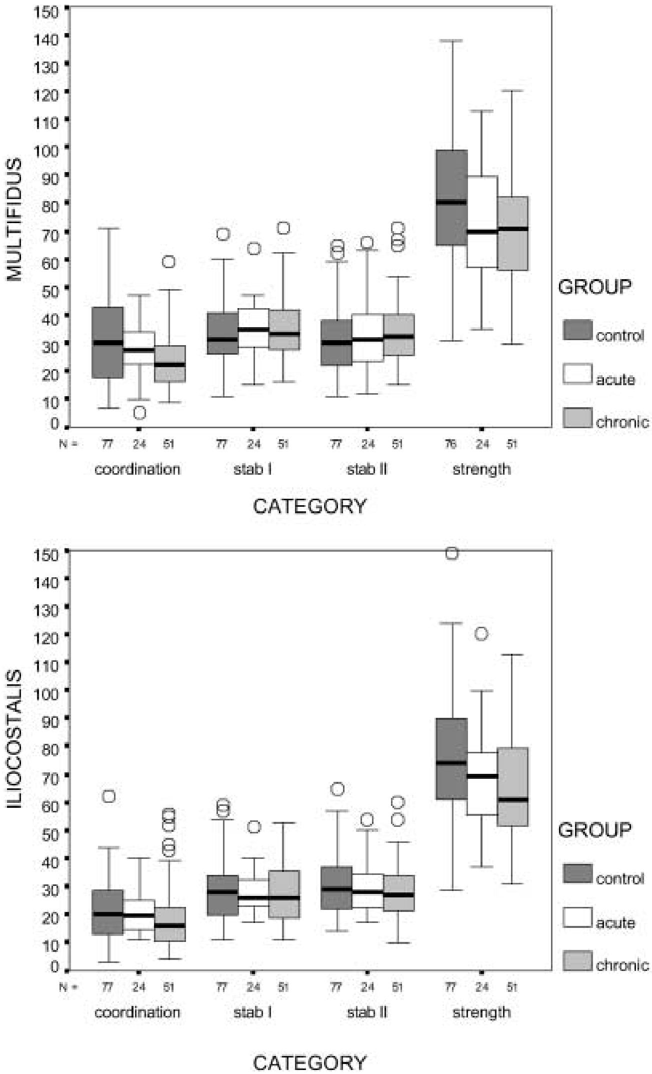

Fig. 1 Box-and-whisker plots of the relative EMG activity (percentage of the maximal voluntary contraction, showing the lowest, 25, 50, 75 and highest relative frequencies). *O*, outlier

tween the chronic low back pain patients and the healthy controls (Table 3, 4, Fig. 1).

Discussion

As a first step in developing rehabilitation strategies to enhance recovery from back injuries, it is necessary to carefully characterise changes in muscle function due to back pain. In the present context, muscle dysfunction is defined as an unusual pattern of muscle recruitment during a prescribed set of movements.

The first category of exercises in the present study allowed evaluation of coordination in activating the back muscles to obtain a physiological lordosis. The results showed that in chronic low back pain patients the activity of the MF was significantly lower than in healthy controls, whereas no significant difference was found for the ICLT.

The notion of a diminished ability to recruit the MF, found in the chronic low back pain population, supports the results of a previous study in which the cross-sectional area of the MF was found to be statistically smaller in chronic low back pain patients compared with healthy controls [4]. It was discussed that an aetiological relationship between atrophy of the MF and the occurrence of low back pain could not be ruled out as a possible explanation. Alternatively, the muscular changes may be a consequence of pain and possible long-loop inhibition of the MF, whereby a combination of reflex inhibition and substitution patterns of the trunk muscles might result in selective atrophy of the MF. The fact that, in this study, the differences in normalised MF activity were greater in the patient group with a longer duration of pain suggests that the implementation of substitution patterns may have played an important role. With low back disorders, even in the early stages, different recruitment patterns result in other muscles becoming active in an attempt to substitute the stabilising muscles, particularly the MF [25]. If this mechanism becomes chronic, the consequence is selective atrophy of the MF. Since this muscle is considered important for lumbar segmental stability, the development of MF atrophy may be one of the reasons for the high recurrence rate of low back pain.

For the ICLT, no significant differences between the patients and controls were found for the category of coordination exercises. Differences in the influence of low back pain on the behaviour of the ICLT and the MF muscles have also been demonstrated with regard to their fatigability. Biedermann et al. [3] examined the MF and the ICLT muscles and showed that only the MF demonstrated greater fatigue rates in the low back pain patients than in the normal control subjects. Roy et al. [29] also compared subjects with a history of chronic low back pain with asymptomatic control subjects and again showed that the MF muscles of the patients demonstrated higher fatigue rates than those of the controls.

For the stabilisation exercises, no statistically significant differences were found in the comparison of AEMG between the three groups. When arm, leg or trunk movements were performed, both the stabilising and the torque-producing back muscles apparently displayed a comparable amount of normalised EMG activity. Considering the findings in the coordination exercises, the results in the MF were somewhat surprising. A possible explanation might be that the MF is automatically recruited during the low-load stabilisation exercises, whereas it was perfectly possible to stand or to keep a four point kneeling posture during the coordination exercises without extra back muscle activity. During the coordination exercises, the specific ability to voluntary recruit back muscle was tested, whereas during the stabilisation exercises the automatic recruitment of the back muscles may have been necessary to maintain stability and balance.

During the strength exercises, the back muscles of the chronic low back pain patients displayed significantly smaller EMG amplitudes in comparison with the healthy subjects. The fact that these differences were only significant between the healthy subjects and the chronic patients suggests that inactivity or the phenomenon of deconditioning may have played a major role. However, further analysis of the data distribution by means of boxplots showed that this phenomenon might not have influenced both muscles to the same extent. For the ICLT, the normalised EMG activity during the sub-maximal strength exercises showed a decrease with increasing pain duration. This probably suggests that the changes in EMG amplitudes were not only the result of neural activation patterns that are directly involved in pain sensation [23] and not only related to the diminished capacity of the affected muscle to generate force [8], but that inactivity or deconditioning was also involved. It is unclear whether the back muscle inactivity may have been aetiologically important in this respect or whether in the (sub-)acute phase pain, pain avoidance or structural damage may have caused slightly reduced muscle activity, reinforced by deconditoning in the chronic phase.

For the MF, the group differences in the normalised EMG amplitudes during the strength exercises differed somewhat from those described above for the ICLT. Only small differences existed between the sub-acute and chronic patient populations, suggesting that acute-phase pain, pain avoidance or structural damage may have been more involved than deconditioning. A possible explanation for these findings may concern the functional subdivision between the back muscles. To train the stabilisers in their holding and controlling role, the magnitude of resistance must be approximately 30% of maximum [14], whereas it is common knowledge that much higher levels of activity are required to maintain optimal condition of torque-producing muscles [10]. Consequently, relative inactivity would have a greater influence on the torque-producing muscles.

Conclusion

Examination and treatment of the muscles of the trunk has long been advocated as an important part of the physical therapy of (chronic) low back pain patients. However, until recently, the basis for this approach has been based largely on empirical knowledge and clinical observations rather than on research-derived knowledge of the function and dysfunction of the neuromuscular system.

The results of this study suggest that, over the long term, back pain patients have a poorer ability to voluntarily recruit the MF in order to obtain a physiological lordosis. On the other hand, both the MF and the ICLT muscles displayed normal levels of EMG activity during stabilisation exercises, indicating normal recruitment of the back muscles during low-load exercises. During strength exercises, the reduced EMG activity of both MF and ICLT muscles in low back pain patients may have resulted from pain, pain avoidance and/or deconditioning.

The possible dysfunction of the MF during coordination exercises and the altered activity of both muscles during strength exercises may be important in the symptom generation, recurrence or maintenance of low back pain.

Acknowledgement The authors wish to express their thanks to Dr. Anne Mannion for her advice and proof-reading of the manuscript. They also would like to thank Manu Halsberghe for his assistance in collecting the data.

References

1. Addison R, Schultz A (1980) Trunk strengths in patients seeking hospitalisation for chronic low back pain. Spine 5:539–544
2. Bergmark A (1989) Stability of the lumbar spine. A study in mechanical engineering. Acta Orth Scand 60 [Suppl] 230:20–24
3. Biedermann H, Shanks G, Forrest W, Inglis J (1991) Power spectrum analyses of electromyographic activity. Discriminators in the differential assessment of patients with chronic low back pain. Spine 16:1179–1184
4. Danneels L, Vanderstraeten G, Cambier D, Witvrouw E, De Cuyper H (2000) SSE Clinical Science Award 2000: CT imaging of trunk muscles in chronic low back pain patients and healthy control subjects. Eur Spine J 9:266–272
5. Danneels L, De Cuyper H, Vanderstraeten G, Cambier D, Witvrouw E, Stevens V (2001) A functional subdivision of hip, abdominal, and back muscles during asymmetric lifting. Spine 26:E114–121
6. Danneels L, Cagnie B, Cools A, Vanderstraeten G, Cambier D, Witvrouw E, De Cuyper H (2001) The intra- and interrater reliability of the EMG activity of the multifidus and the iliocostalis lumborum during natural lifting movements. Manual Ther (in press)
7. De Luca C (1993) The use of surface EMG signal for performance evaluation of back muscles. Muscle Nerve 16:210–216
8. Edgerton V, Wolf S, Levendowski D, Roy R (1996) Theoretical basis for patterning EMG amplitudes to assess muscle dysfunction. Med Sci Sports Exerc 28:744–751
9. Goel V, Kong W, Han J, Weinstein J, Gilbertson L (1993) A combined finite element and optimization investigation of lumbar spine mechanics with and without muscles. Spine 18:1531–1541
10. Goldspink G (1992) Cellular and molecular aspects of adaptation in skeletal muscle. In: Komi PV (ed) Strength and power in sport. Blackwell, Oxford, pp 211–229
11. Grabiner M, Koh T, El Ghazawi A (1992) Decoupling of bilateral paraspinal excitation in subjects with low back pain. Spine 17:1219–1223
12. Greenough C, Oliver C, Jones A (1998) Assessment of spinal musculature using surface electromyographic spectral color mapping. Spine 23: 1768–1774

13. Hides J, Richardson C, Jull G (1996) Multifidus recovery is not automatic following resolution of acute first episode of low back pain. Spine 21: 2763–2769
14. Jull G, Richardson C (1994) Rehabilitation of active stabilisation of the lumbar spine. In: Twomey L, Taylor J (eds) Physical therapy of the low back, 2nd edn. Churchill Livingstone, New York, pp 251–273
15. Kaigle A, Holm S, Hansson T (1995) Experimental instability in the lumbar spine. Spine 20:421–430
16. Macintosh J, Bogduk N (1987) The morphology of the lumbar erector spinae. Volvo award in basic science. Spine 7:658–668
17. Mannion A, Connolly B, Wood K, Dolan P (1997) The use of surface EMG power spectral analysis in the evaluation of back muscle function. J Rehab Res Devel 34:427–439
18. Mayer T, Smith S, Keeley J, Mooney V (1985) Quantification of lumbar function. 2. Sagittal plane trunk strength in chronic low-back pain patients. Spine 10:765–772
19. McGill S (1991) Electromyographic activity of the abdominal and low back musculature during the generation of isometric and dynamic axial trunk torque: implications for lumbar mechanics. J Orthop Research 9:91–103
20. McNeil T, Warwick D, Anderson G, Schultz A (1980) Trunk strengths in attempted flexion, extension and lateral bending in healthy subjects and patients with low-back disorders. Spine 6:529–538
21. Ng J-F, Richardson C (1996) Reliability of EMG power spectral analysis of back muscle endurance in healthy subjects. Arch Phys Med Rehab 77:259–264
22. Nicholaison T, Jorgenson K (1985) Trunk strength, back muscle endurance and low back trouble. Scand J Rehab Med 17:121–7
23. Nouwen A, Van Akkerveeken P, Versloot J (1987) Patterns of muscular activity during movement in patients with chronic low back pain. Spine 12:777–782
24. Oddsson L, Giphart J, Buijs R, Roy S, Taylor H, De Luca C (1997) Development of new protocols and analysis procedures for the assessment of LBP by surface EMG techniques. J Rehab Res Devel 34:415–426
25. O'Sullivan P, Twomey L, Allison G (1997) Dysfunction of the neuro-muscular system in the presence of low back pain – implications for physical therapy management. J Man Manipulative Ther 5:20–26
26. O'Sullivan P, Twomey L, Allison G (1997) Dynamic stabilization of the lumbar spine. Crit Rev Phys Rehab Med 9:315–330
27. Panjabi M (1992) The stabilizing system of the spine. I. Function, dysfunction, adaptation, and enhancement. J Spinal Disord 5:383–389
28. Richardson C, Jull G, Hodges P, Hides J (1999) Therapeutic exercise for spinal segmental stabilization in low back pain Scientific basis and clinical approach. Churchill Livingstone, New York, p 14
29. Roy S, De Luca C, Casavant D (1989) Lumbar muscle fatigue and chronic lower back pain. Spine 14:992–1001
30. Thorstensson A, Oddsson L, Carlson H (1985) Motor control of voluntary trunk movements in standing. Acta Physiol Scand 125:309–321
31. Vink P 1986 Functional subdivision between parts of the intrinsic lumbar back muscles (in Dutch). Ned Tijdschr Fysiother 96:260–262
32. Vink P, van der Velde E, Verbout A (1988) A functional subdivision of the lumbar extensor musculature. Recruitment patterns and force- R.A.-EMG relationships under isometric conditions. Electromyogr Clin Neurophysiol 28: 517–525
33. Wilke H, Wolf S, Claes L, Arand M, Wiesend A (1995) Stability increase of the lumbar spine with different muscle groups. A biomechanical in vitro study. Spine 20:192–198