Electromyographic activity of trunk and hip muscles during stabilization exercises in four-point kneeling in healthy volunteers

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Abstract Stabilization exercises are intended to optimize function of the muscles that are believed to govern trunk stability. Debate exists whether certain muscles are more important than others in optimally performing these exercises. Thirty healthy volunteers were asked to perform three frequently prescribed stabilization exercises in four-point kneeling. The electromyographic activity of different trunk and hip muscles was evaluated. Average amplitudes obtained during the exercises were normalized to the amplitude in maximal voluntary contraction (% MVIC). During all three exercises, the highest relative muscle activity levels (> 20% MVIC) were consistently found in the ipsilateral lumbar multifidus and gluteus maximus. During both the single leg extension (exercise 1) and the leg and arm extension exercise (exercise 2) the contralateral internal oblique and ipsilateral external oblique reached high levels (> 20% MVIC). During exercise 2 there were also high relative activity levels of the ipsilateral lumbar part and the contralateral thoracic part of the iliocostalis lumborum and the contralateral lumbar multifidus. During the leg and arm extension exercise with contralateral hip flexion (exercise 3) there were high relative muscle activity

levels of all back muscles, except for the latissimus dorsi muscle. The lowest relative muscle activity levels (< 10% MVIC) were found in the rectus abdominis and the ipsilateral internal oblique during all exercises, and in the contralateral gluteus maximus during exercises 1 and 2. The results of this study show that in exercises in four-point kneeling performed by healthy subjects, hip and trunk muscles seem to work together in a harmonious way. This shows that when relative activity of muscles is measured, both “global and local” muscles function together in order to stabilize the spine.

Keywords Stabilization exercise · Trunk and hip muscles · Electromyography

Introduction

Joint stability is defined as the effective accommodation of the joints to each specific load demand through an adequately tailored joint compression (as a function of gravity and coordinated muscle and ligament forces) to produce effective joint reaction forces under changing conditions [43].

To meet this requirement for joint stability, specific training of the local muscles, like the lumbar multifidus (MF) and transversus abdominis (TA) muscles has been advocated [17, 35–38]. In particular, the difference in timing in so-called local and global muscles during specific exercises has been extensively investigated [18, 20, 21, 23]. In contrast, the current study focuses mainly on the evaluation of normal co-operative activity of several muscles by measuring the relative activity of these muscles.

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The division into a local and global muscle system refers to the functional classification to discriminate between the muscles responsible for inter-segmental stability (local) and spine motion (global), based on the anatomical division proposed in 1989 by Bergmark [7]. More current research based on relative muscle activity levels and stability analysis has shown that because this classification is not necessarily correct, some rethinking may be required [10, 26, 27, 32].

The division of trunk muscles into local and global ones mainly results from seeing the muscles in isolation and not taking into account their intricate functional relationship with collagenous structures like the fascia. An example could be the action of the gluteus maximus (GM) and latissimus dorsi (LD); within the framework of local and global, these muscles would typically be classified as global [7]. However, Vleeming et al. [44] have proposed that tension in the posterior layer of the thoracolumbar fascia (TLF) induced by the latter muscles may contribute to limitation of joint movement by simultaneously stiffening the muscles and fascia of the lumbar spine and sacroiliac joint while enabling transfer of loads between trunk and limbs. Besides the LD and GM the posterior layer of the TLF also has connections to the abdominal internal and external obliques, which was confirmed by Barker et al. [4].

Stabilization exercises are designed to improve function of the muscles that are believed to govern trunk stability and, when these muscles are functioning optimally, they will protect the spine from trauma [10]. Stabilization exercises are often used in clinical practice. The four-point kneeling position provides a relatively low-loaded, non-anti-gravity posture in which good balance can be easily achieved when a neutral spine position is maintained [14, 31].

The single leg extension task in four-point kneeling provides both low joint loading and limited muscular activity, suggesting that this position could be an appropriate choice for persons starting a rehabilitation program for lumbopelvic pain [8]. In four-point kneeling an isolated contraction of the inferior fibres of the internal oblique muscle (IO) can be achieved more often and more consistently compared with a prone position [6, 38]. Haynes [15] suggests that the four-point kneeling exercise involves the whole body and in this way it could prepare the muscular loop and slings for upright bipedal functional tasks.

Although these kinds of stabilization exercises are often used in clinical practice, a clear description of the relative muscle activity during these exercises has only been described in small unisex populations [27, 31], or with a restricted focus on certain muscles [1, 40].

Therefore this study investigated the relative activation level of certain trunk and hip muscles during these exercises in four-point kneeling. In this way a normative database, which is necessary to interpret the results of patients performing these exercises, can be created.

Materials and methods

Study participants

Thirty healthy volunteers (15 men and 15 women) participated in this study; their mean age was 19.6 (range 19–23) years, mean height was 176.6 (range 157–194) cm, and mean weight was 66.9 (range 42–84) kg. All subjects signed an informed consent. The subjects had no previous experience with stabilization exercises. Subjects were excluded if they reported any past or current low back pain (LBP), current neurologic deficits, and/or pain or disability of the upper or lower limbs. The Ethics Committee of the Ghent University Hospital approved the protocol.

Equipment

The skin was prepared by shaving excess hair and rubbing the skin with alcohol to reduce impedance (typically ≤ 10 k Ω). Disposable Ag/AgCl surface electrodes (Blue Sensor, Medicotest GmbH, Germany) were attached parallel to the muscle fibre orientation, bilaterally over the following abdominal muscles: internal oblique (IO) [13, 24, 41], external oblique (EO) [8, 9, 13, 24, 41, 42] and rectus abdominis (RA) [2, 3, 8, 9, 13, 40]. Marshall et al. [30] showed that on the site medial and inferior to the anterior superior iliac spine, the fibres of the TA and IO are blended, so a distinction between the muscle signals cannot be made in this location. The selected back muscles were: lumbar multifidus (MF) [11, 29], the lumbar part of the iliocostalis lumborum (ICLL) (lateral to the vertical line through the posterior superior iliac spine, above the iliac crest) [29] and the thoracic part of the iliocostalis lumborum (ICLT) [11, 13, 29]. Regarding the arm and leg movements, the activity of the latissimus dorsi (LD) [13] and gluteus maximus (GM) [13] were measured.

The maximum interelectrode spacing between the recording electrodes was 2.5 cm as recommended by Ng et al. [33], and each electrode had an approximately 1.0 cm² pick-up area. The raw surface electromyographic signals were analogue/digital (A/D) converted (12-bit resolution) at 1,000 Hz (MyoSystem 1400 Noraxon).

Three-dimensional data of the movements were collected by using an ultrasonic movement analysis system (Zebris CMS 50, Isny, Germany) with local markers. Spatial marker positions were derived by angulation and used to standardize the angular positions of the lumbar spine (L1, L3, L5) in the sagittal plane.

Data acquisition

Maximum voluntary isometric contractions (MVIC) of the muscles were measured in three trials before the experimental tasks. These exercises were performed to provide a basis for EMG signal amplitude normalization [1–3, 6, 13, 24, 40, 42]. Danneels et al. reported a description of the different isometric exercises [13].

After the registration of the MVICs, the subjects performed three experimental exercises often used in clinical practice to train stability of the lower back. These exercises were performed in the four-point kneeling position with movements of the extremities of both sides (Figs. 1, 2, 3). The exercises were executed in a random sequence. To standardize the position of the subject and the equipment, markers were placed on the floor. At the beginning of each exercise a neutral spine position was assumed by the examiner and the subject was encouraged to hold this position during the course of the total exercise. The neutral spine position was set about halfway between full extension and a flat position of the spine [11]. The dynamic phases, lifting and lowering of the extremities and movement of the trunk, lasted 2 s. During the static phase, the leg was held for 5 s in an extended position. The pace of 60 beats/min was set by a metronome. Three trials for every exercise were performed. A pause of at least 15 s was allowed between the trials. The starting positions of the lumbar spine were determined in the sagittal plane. The complementary angle between the line connecting the markers on the spinous process of L1 and L3 and the line connecting the markers on the spinous process of L3 and L5 was calculated.

Fig. 1 Exercise 1: single-leg lift, performed by extending the leg out to the horizontal and returning it to the basic four-point kneeling position

Fig. 2 Exercise 2: the leg extension of exercise 1 coupled with the simultaneous raising of the contralateral arm to the horizontal and then returning to the basic four-point kneeling position

Fig. 3 Exercise 3: same as exercise 2, but coupled with 30° increased hip flexion

Data analysis

For the EMG amplitude analysis, manually selected, artefact-free, raw EMG sections were used. The stored data were full-wave rectified and smoothed. For each of the muscles the root mean square (RMS) was calculated for the three repetitions of the different exercises. The mean MVICs were used to provide a basis for EMG signal amplitude normalization. The static phases of the exercises were analysed, using an interval of 4,700 ms after the defined starting point of the holding position. The mean (of the three repetitions) normalized EMG values were calculated. Noraxon MyoResearch software 2.10 was used. The ipsilateral and contralateral muscle activity values during the asymmetric bridging exercises were averaged. Ipsilateral involved the same side as the extended leg and contralateral represented the other side. Three general activity levels were created: high, moderate, and low relative muscle activity.

Statistical analysis

Statistical analyses were performed using SPSS 11.0 software package (SPSS Inc., Chicago, IL) for Windows. The level for statistical significance was set at $\alpha = 0.05$. A two-way analysis of variance (ANOVA) was used to analyse the effects of the factors muscle and exercise. There was a significant interaction be-

tween the two factors ($P < 0.001$). Consequently, least significant difference LSD post-hoc tests were performed on the differences between the muscles in the separate exercises. Given the huge amount of data, only the most relevant differences in relation to the research question are presented in the results section.

Results

Figures 4 and 5 present the relative EMG levels (% MVIC) of the different muscles, and a classification is made into high, moderate and low muscle activity.

The muscles that show *high* relative activity ($> 20\%$ MVIC) during all exercises are the ipsilateral MF and GM; the difference in activity between these two muscles is not significant ($P \leq 0.44$). During exercises 1 and 2 the abdominal obliques, contralateral IO and ipsilateral EO, show a similar high relative muscle activity ($P \leq 0.86$). During exercise 3, both the ICLL and ICLT (on both sides) have high activity levels. In contrast, during exercise 2, only the relative muscle activity of the ipsilateral ICLL and contralateral ICLT is high. During exercises 2 and 3, the relative muscle activity of the contralateral MF is high.

The muscles that demonstrate a *moderate* relative muscle activity ($10\text{--}20\%$ MVIC) during all exercises are the contralateral EO and the bilateral LD; there is no significant difference between the activity of the contralateral EO and the LD ($P \leq 0.94$), or between the two LD muscles ($P \leq 0.74$). The abdominal obli-

ques, contralateral IO and ipsilateral EO (no significant difference: $P = 0.41$), and the contralateral GM show a moderate relative muscle activity only during exercise 3. The relative muscle activity of the GM is not significantly different from the activity of the abdominal obliques during this exercise ($P \leq 0.22$). The contralateral ICLL and the ipsilateral ICLT show similar ($P \leq 0.76$) moderate activity levels during exercises 1 and 2. In addition, the ipsilateral ICLL and the contralateral ICLT and MF show moderate activity levels only in exercise 1; in this exercise the difference between the ICLL and ICLT muscle activity is not significant ($P = 0.93$), but the relative muscle activity of the contralateral MF is significantly lower than that of the ipsilateral ICLL ($P = 0.01$) and the contralateral ICLT ($P = 0.01$).

A *low* relative muscle activity ($< 10\%$ MVIC) is created by the ipsilateral IO, the contralateral GM (except for exercise 3), and the bilateral RA. The bilateral RA shows a significantly lower relative muscle activity compared with all other muscles during all exercises. In exercises 1 and 2 the ipsilateral RA is also significantly lower than the contralateral RA. In exercise 1, the contralateral GM muscle activity is significantly lower than the ipsilateral muscle activity of the IO, but not in exercise 2.

The measurements of the lumbar curve in the sagittal plane at the beginning of the exercises were $13.06^\circ \pm 5.00^\circ$ (range $4.17^\circ\text{--}21.87^\circ$) in exercise 1, $12.65^\circ \pm 4.77^\circ$ (range $3.08^\circ\text{--}21.19^\circ$) in exercise 2, and $11.72^\circ \pm 3.95^\circ$ (range $3.47^\circ\text{--}19.58^\circ$) in exercise 3.

Fig. 4 Abdominal and hip muscles: relative EMG activity and *I* SD *I* ipsilateral, *C* contralateral, *IO* internal oblique; *RA* rectus abdominis; *EO* external oblique; *GM* gluteus maximus

Fig. 5 Back muscles: relative EMG activity and $1\ SD\ I$ ipsilateral, C contralateral, MF lumbar multifidus, $ICLL$ iliocostalis lumborum pars lumborum, $ICLT$ iliocostlis lumborum pars thoracis, LD latissimus dorsi

Discussion

The present study investigated the relative activation levels of major trunk and hip muscles during exercises in four-point kneeling. A classification into three general activity levels was created, and a possible relationship with the anatomical classification of local and global muscles was studied.

The ipsilateral GM and MF show a high relative muscle activity ($> 20\%$ MVIC) during all exercises in four-point kneeling. Although this is in accordance with earlier studies [1, 8, 40], the latter results are only available for certain muscles, and only for exercises 1 and 2. In addition, our results seem to indicate that the chosen sequence of the presented exercises challenging the balance and whole body stability correlates with increased and more varied muscle activity.

The results also show a high activity of the contralateral IO and the ipsilateral EO during exercises 1 and 2. As previous studies showed lower activity levels of these muscles during exercises 1 and 2 [8, 40], these results raise doubts about the statement that this type of exercise mainly activates the paraspinal muscles and not the abdominal muscles [8]. It was suggested that the contralateral IO muscles were activated to maintain a neutral pelvis and spine posture, in effect balancing the internal moments and lateral shear forces [8], but this seems to occur in association with ipsilateral EO activity. In this way, the results of the current study indicate that the abdominal obliques to create a stable unit accomplish an ideal co-operation.

Also dorsally, there seems to be a co-operation between the ipsilateral and contralateral back muscles. Recruitment patterns of the ipsilateral ICLL together with the contralateral ICLT are recognized. This is consistent with the findings of Callaghan et al. [8], although that group reported lower activity levels concerning the contralateral MF.

The contralateral EO and the bilateral LD show moderate activity levels (10–20% MVIC) during all exercises. In contrast to earlier findings [8], the results of the present study show that extension of the upper extremity does not seem to influence the LD muscle activity. In general, in contrast to its classification as a “global” muscle, symmetrical activity is confirmed during all exercises. A possible reason for such equalized action of the LD could be the tensioning of the TLF in a cranial direction, needed to control the trunk irrespective of the movement or position of the upper limb.

In exercise 3 there are moderate relative activity levels in both the contralateral IO and the ipsilateral EO, and the difference between them is not significant. It seems as if the contralateral IO and the ipsilateral EO can play a role in supporting the stable position to control the neutral spine position. This can not be confirmed by earlier research, as some researchers did not discriminate between ipsilateral and contralateral muscle activity [1, 40] and others did not generalize to those terms because of varied results for the contralateral IO [31]. The hip flexion that is added in exercise 3 in comparison to exercise 2 seems to create a lower abdominal muscle activity ($P \leq 0.005$, except for the ipsilateral IO).

The ICLL and ICLT seem to act together and also reach similar moderate activity levels [8]. By the stretch the hip flexion in exercise 3 causes on the contralateral GM, this muscle exhibits a significant higher muscle activity in exercise 3 in comparison to exercise 2 ($P < 0.001$). It seems that to counteract the more challenging body position by adding the hip flexion, there is a compensation of the ipsilateral GM and ICLT and the contralateral MF.

The low-level symmetric activity of the RA throughout all exercises is confirmed by previous studies [8, 40] and by studies of related exercises [6]. According to Callaghan et al. [8] it indicates that this muscle was not functionally active and did not contribute to stability. However, as the muscle is bilaterally active at a constant level during all exercises, stability analysis (including external loads) is needed to assume that the limited activity is irrelevant. In the current study the contralateral GM also seems to show relative low activity levels during exercises 1 and 2. During all exercises (even on the side opposite to the leg extension) the GM muscle is still active, preventing flexion of the hips and thus preventing destabilization of the spine. The ipsilateral IO also creates a small relative muscle activity.

Although a distinction is made between high, moderate and low relative muscle activity, the electromyographic activity never exceeds 32% of MVIC. It is mentioned that useful stabilization exercises for the clinic with the aim to hold and control the lumbar spine in a neutral position, work the trunk muscles at approximately 30% of their maximum [25].

The results of this study show that in uncomplicated exercises in four-point kneeling performed by healthy subjects, the investigated muscles seem to work together in a harmonious way. These results tend to confirm the recent findings describing that, based on relative muscle activity, no single muscle appears to be superior in enhancing spine stability, but as loads are applied to the spine there is an integration of the different muscles in order to balance the stability and moment demands [26, 27]. However, the results of this four-point kneeling position cannot be extrapolated to the erect posture, which is the usual posture for the population being investigated.

It seems relevant that in the present study muscles are active in stabilization exercises that are also strongly related to the main thoracolumbar fascia (TLF), such as the IO, EO, GM and LD. Muscles like the ICLL, ICLT and MF have a hydraulic amplifier effect on the different layers of the TLF. The posterior layer of the TLF is ideally positioned to regulate tension via its extensive muscular attachments to both

“local” and “global” muscles [5]. When loading the TLF for instance by the IO or EO, deformation and structural integrity of the fascia should be protected by muscles like the LD and GM. The overall effect of these muscles acting together could have a positive cascading effect on the stiffening of both the lumbar spine and sacroiliac joint [44].

Based on the results of differences in cross-sectional area [12, 16] and timing [19, 22], there may be some inhibition of certain muscles and dominance of other muscles [38] to maintain a stable body position in LBP patients. The RA activity during flexion-extension movements [39] and the EO activity during both flexion-extension [39] and left rotation movements [34], as well as the muscle activity of the left thoracic erector spinae during lateral flexion movements [28] were higher in LBP patients than in healthy controls. However, during coordination and left rotation exercises the MF showed lower activity levels in LBP patients than in healthy controls [11, 34]. So-called local muscles might demonstrate lower and so-called global muscles higher activity levels in LBP patients compared to healthy subjects. The present study, describing both local and global muscle activity, provides a normative database, which allows comparison with specific pain populations in future research. Apart from the muscle activity levels, further integrated research on muscle strength, muscle timing and movement patterns in specific LBP populations is necessary to effectively distinguish between normal and abnormal spinal function.

Conclusion

Based on the harmonious way in which all trunk and hip muscles work together in controlling the neutral spine position during these exercises in four-point kneeling, no single muscle seems to be superior in enhancing spine stability, at least seen from the perspective of muscle activity and not timing. Our study results indicate that both “global and local” muscles function together to stabilize the spine, and this study provides a normative database with which to compare specific pain populations in future research.

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References

1. Arokoski JP, Kankaanpää M, Valta T et al (1999) Back and hip extensor function during therapeutic exercises. *Arch Phys Med Rehabil* 80:842–850

2. Arokoski JP, Valta T, Airaksinen O et al (2001) Back and abdominal muscle function during stabilization exercises. *Arch Phys Med Rehabil* 82:1089–1098
3. Arokoski JP, Valta T, Kankaanpää M et al (2004) Activation of lumbar paraspinal and abdominal muscles during therapeutic exercises in chronic low back pain patients. *Arch Phys Med Rehabil* 85:823–832
4. Barker PJ (2005) Applied anatomy and biomechanics of the lumbar fasciae: implications for lumbopelvic control. PhD thesis, University of Melbourne, Australia
5. Barker PJ, Briggs CA (1999) Attachments of the posterior layer of lumbar fascia. *Spine* 24(17):1757–1764
6. Beith ID, Synnott E, Newman A (2001) Abdominal muscle activity during the abdominal hallowing manoeuvre in the four point kneeling and prone positions. *Man Ther* 6(2):82–87
7. Bergmark A (1989) Stability of the lumbar spine. A study in mechanical engineering. *Acta Orthop Scand* 230(Suppl):20–24
8. Callaghan JP, Gunning JL, McGill SM (1998) The relationship between lumbar spine load and muscle activity during extensor exercises. *Phys Ther* 78(1):8–18
9. Cholewicki J, Panjabi MM, Khachatrian A (1997) Stabilizing function of trunk flexor-extensor muscles around a neutral spine posture. *Spine* 22(19):2207–2212
10. Cholewicki J, Van Vliet JJ (2002) Relative contribution of trunk muscles to the stability of the lumbar spine during isometric exertions. *Clin Biomech* 17:99–105
11. Danneels LA, Coorevits PL, Cools AM et al (2002) Differences in electromyographic activity in multifidus muscle and the iliocostalis lumborum between healthy subjects and patients with subacute and chronic low back pain. *Eur Spine J* 11:13–19
12. Danneels LA, Vanderstraeten GG, Cambier DC et al (2000) CT imaging of trunk muscles in chronic low back pain patients and healthy control subjects. *Eur Spine J* 9(4):266–272
13. Danneels LA, Vanderstraeten GG, Cambier DC et al (2001) A functional subdivision of hip, abdominal, and back muscles during asymmetric lifting. *Spine* 26(6):E114–E121
14. Gill KP, Callaghan MJ (1998) The measurement of lumbar proprioception in individuals with and without low back pain. *Spine* 23(3):371–77
15. Haynes W (2004) Core stability and the unstable platform device. *J Bodyw Mov Ther* 8:88–103
16. Hides JA, Stokes MJ, Saide M et al (1994) Evidence of lumbar multifidus muscle wasting ipsilateral to symptoms in patients with acute/subacute low back pain. *Spine* 19(2):165–172
17. Hodges PW, Moseley GL (2003) Pain and motor control of the lumbopelvic region: effect and possible mechanisms. *J Electromyogr Kinesiol* 13:361–370
18. Hodges PW, Richardson CA, Jull G (1996a) Evaluation of the relationship between laboratory and clinical tests of TA function. *Physiother Res Int* 1(1):30–40
19. Hodges PW, Richardson CA (1996b) Inefficient muscular stabilization of the lumbar spine associated with low back pain: a motor control evaluation of transversus abdominis. *Spine* 21:2640–2650
20. Hodges PW, Richardson CA (1997a) Contraction of the abdominal muscles associated with movement of the lower limb. *Phys Ther* 77:132–144
21. Hodges PW, Richardson CA (1997b) Feedforward contraction of transversus abdominis is not influenced by the direction of arm movement. *Exp Brain Res* 114:362–370
22. Hodges PW, Richardson CA (1998) Delayed postural contraction of transversus abdominis in low back pain associated with movement of the lower limbs. *J Spinal Disord* 11:46–56
23. Hodges PW, Richardson CA (1999) Transversus abdominis and the superficial abdominal muscles are controlled independently in a postural task. *Neurosci Lett* 265(2):91–94
24. Hubley-Koezy CL, Vezina MJ (2002) Muscle activation during exercises to improve trunk stability in men with low back pain. *Arch Phys Med Rehabil* 83:1100–1108
25. Jull GA, Richardson GA (1994) Rehabilitation of active stabilization of the lumbar spine. In: Twomey LT, Taylor JR (eds) *Physical therapy of the low back*. 2nd edn. Churchill Livingstone, New York pp 251–273
26. Kavcic N, Grenier S, McGill SM (2004) Determining the stabilizing role of individual torso muscles during rehabilitation exercises. *Spine* 29(11):1254–1265
27. Kavcic N, Grenier S, McGill SM (2004) Quantifying tissue loads and spine stability while performing commonly prescribed low back stabilization exercises. *Spine* 29(20):2319–2229
28. Larivière C, Gagnon D, Loisel P (2000) The comparison of trunk muscles EMG activation between subjects with and without chronic low back pain during flexion-extension and lateral bending tasks. *J Electromyogr Kinesiol* 10:79–91
29. Macintosh JE, Bogduk N (1987) Volvo award in basic science. The morphology of the lumbar erector spinae. *Spine* 12(7):658–668
30. Marshall PW, Murphy BA (2003) The validity and reliability of surface EMG to assess the neuromuscular response of the abdominal muscles to rapid limb movement. *J Electromyogr Kinesiol* 13:477–489
31. McGill SM (1998) Low back exercises: evidence for improving exercise regimens. *Phys Ther* 78(7):754–765
32. McGill SM, Grenier S, Kavcic N et al (2003) Coordination of muscle activity to assure stability of the lumbar spine. *J Electromyogr Kinesiol* 13:353–359
33. Ng JK, Kippers V, Richardson CA (1998) Muscle fibre orientation of abdominal muscles and suggested surface EMG electrode positions. *Electromyogr Clin Neurophysiol* 38(1):51–58
34. Ng JK, Richardson CA, Parnianpour M et al (2002) EMG activity of trunk muscles and torque output during isometric axial rotation exertion: a comparison between back pain patients and matched controls. *J Orthop Res* 20(1):112–121
35. O'Sullivan PB (2000) Lumbar segmental 'instability': clinical presentation and specific stabilizing exercise management. *Man Ther* 5(1):2–12
36. O'Sullivan PB, Twomey L, Alison GT (1997) Dynamic stabilization of the lumbar spine. *Crit Rev Phys Rehabil Med* 9(3&4):315–330
37. Richardson CA, Jull GA (1995) Muscle control–pain control. What exercises would you prescribe? *Man Ther* 1:2–10
38. Richardson C, Jull G, Hides J et al (1999) *Therapeutic exercise for spinal stabilisation*. Scientific basis and practical techniques, Harcourt, London
39. Silfies SP, Squillante D, Maurer P et al (2005) Trunk muscle recruitment patterns in specific chronic low back pain populations. *Clin Biomech* 20:465–473
40. Souza GM, Baker LL, Powers CM (2001) Electromyographic activity of selected trunk muscles during dynamic spine stabilization exercises. *Arch Phys Med Rehabil* 82:1551–1157

41. Vera-Garcia FJ, Grenier SG, McGill SM (2000) Abdominal muscle response during curl-ups on both stable and labile surfaces. *Phys Ther* 80(6):564–569
42. Vezina MJ, Hubley-Kozey CL (2000) Muscle activation in therapeutic exercises to improve trunk stability. *Arch Phys Med Rehabil* 81:1370–1379
43. Vleeming A, Albert HB, van der Helm FCT et al (2004) Proceedings of the fifth interdisciplinary world congress on low back and pelvic pain, Melbourne, p.14
44. Vleeming A, Pool-Goudzwaard AL, Stoeckart R et al (1995) The posterior layer of the thoracolumbar fascia. Its function in load transfer from spine to legs. *Spine* 20(7):753–758