Eur Spine J (2010) 19:122–128
DOI 10.1007/s00586-009-1171-x

ORIGINAL ARTICLE

Differentiation between deep and superficial fibers of the lumbar multifidus by magnetic resonance imaging

Nele Dickx · Barbara Cagnie · Erik Achten · Pieter Vandemaele · Thierry Parlevliet · Lieven Danneels

Received: 28 April 2009 / Revised: 13 August 2009 / Accepted: 13 September 2009 / Published online: 24 September 2009

Abstract The purpose of this study was to investigate the differentiation in muscle tissue characteristics and recruitment between the deep and superficial multifidus muscle by magnetic resonance imaging. The multifidus is a very complex muscle in which a superficial and deep component can be differentiated from an anatomical, biomechanical, histological and neuromotorial point of view. To date, the histological evidence is limited to low back pain patients undergoing surgery and cadavers. The multifidus muscles of 15 healthy subjects were investigated with muscle functional MRI. Images were taken under three different conditions: (1) rest, (2) activity without pain and (3) activity after experimentally induced low back muscle pain. The T2 relaxation time in rest and the shift in T2 relaxation time after activity were compared for the deep and superficial samples of the multifidus. At rest, the T2 relaxation time of the deep portion was significantly higher compared to the superficial portion. Following exercise, there was no significant difference in shift in T2 relaxation time between the deep and superficial portions, and in the pain or in the non-pain condition. In conclusion, this study demonstrates a higher T2 relaxation time in the deep portion, which supports the current assumption that the deep multifidus has a higher percentage of slow twitch fibers compared to the superficial multifidus. No differential recruitment has been found following trunk extension with and without pain induction. For further research, it would be interesting to investigate a clinical LBP population, using this non-invasive muscle functional MRI approach.

Keywords Multifidus muscle · Deep and superficial multifidus · Muscle functional magnetic resonance imaging · Muscle fiber type

This research was supported by the BOF-Ghent University.

N. Dickx (✉) · B. Cagnie · L. Danneels
Department of Rehabilitation Sciences and Physiotherapy, Ghent University, Campus Heymans (UZ) 3B3, De Pintelaan 185, 9000 Ghent, Belgium
e-mail: nele.dickx@ugent.be

E. Achten · P. Vandemaele
Department of Radiology, Faculty of Medicine, Ghent University, Ghent, Belgium

T. Parlevliet
Department of Physical Medicine and Orthopaedic Surgery, Faculty of Medicine, Ghent University, Ghent, Belgium

Introduction

It is widely accepted that dysfunction of the lumbar multifidus (MF) has an important impact on the etiology and recurrence of low back pain (LBP) [1–5]. Therefore, exercises to restore optimal MF function are commonly implicated in current rehabilitation strategies [5, 6]. More recently, attention has been focused on the deepest fibers of the MF muscle [7–9].

The MF is a very complex muscle in which a superficial and deep component can be differentiated from an anatomical [10], biomechanical [11], histological [12] and neuromotorial [13] point of view.

Typically for the MF is the anatomical organization in multiple fascicles. These fascicles insert cranially on the spinous process and lamina of each lumbar vertebral level. The greatest muscle mass consists of the most superficial fibers, which cross more than two spinal levels and insert caudally onto the mamillary process, lamina and posterior superior iliac spina and dorsal sacrum [10]. The deepest

fibers of the lumbar MF, which cross just two spinal levels and insert caudally onto the lamina, mamillary process [10] and zygophysial joint capsule [14] are often referred to as the deep MF [8].

The specific architecture of the deep and superficial fascicles of the MF has important biomechanical implications. The superficial fibers have a more optimal lever arm to produce sufficient torque to create extension of the lumbar spine. Therefore, it is assumed that the role of the superficial MF is to extend the lumbar spine in combination with the control of spine orientation due to enhanced spinal stiffness. In contrast to the superficial fibers, the deepest fibers are near the center of rotation of the lumbar vertebras, and therefore ideally placed to control intervertebral shear and torsion via intervertebral compression, with minimal associated torque. Therefore, it is believed that the primary role of these fibers is to provide segmental stabilization of the lumbar spine [10, 14–16].

Due to the anatomical and biomechanical differentiation of the superficial and deep MF, a difference in fiber type distribution can be hypothesized: it is assumed that the deep MF has a higher portion of type I fibers compared to the superficial MF [8]. Type I fibers are slow twitch fibers, which are fatigue resistant and ideally suited to provide low load tonic activity. Type II fibers are fast twitch fibers, which are less fatigue resistant, but able to produce a higher load activity [17]. To date, there is only scarce evidence that the deep portion of the MF has a higher percentage of type I fibers compared to the superficial MF [8, 12].

The standard method for determining fiber type is by muscle biopsy. Due to the invasiveness of reaching the deepest fibers of the MF, histological research is restricted to studies on LBP patients undergoing surgery or post-mortem studies. An alternative, noninvasive and in vivo method for determining muscle fiber type composition and distribution is by magnetic resonance imaging (MRI) [18]. MR signals are strongly related to the histochemical composition of the tissue. All tissues have specific ranges of T2 relaxation times (i.e., bone is different from muscle) and even within a muscle there may be differences in T2 times [18]. There is evidence that the T2 relaxation time is longer for slow twitch muscles compared to fast twitch muscles [19–21]. Therefore, it would be interesting to investigate if there is a difference in T2 relaxation times between the deep and the superficial MF.

Despite the anatomical, biomechanical and histological differentiation between the deep and superficial MF, few studies have compared neuromuscular control of the different components within the muscle [13]. Moseley et al. were the first to use selective intramuscular EMG electrodes to investigate deep and superficial MF activity. They provided evidence that the deep and superficial fibers were differentially active when the stability of the spine was challenged during movements of the arm [13] or a predictable perturbation of the trunk [22].

Recently, MacDonald et al. [23] demonstrated that the deep MF fibers were recruited before the superficial fibers during rapid arm movement in healthy subjects, whereas in LBP patients the muscle onset of the deep fibers was delayed. A specific approach to gain insight into the mechanisms of changed muscle activity during LBP is by induction of pain in healthy subjects. The advantage of using experimentally induced pain is that it provides a clear model to investigate the cause–effect relationship of nociceptor stimulation on motor control. Hodges et al. [24] investigated feedforward recruitment of the lumbar multifidus during experimentally induced LBP. Although expected, the authors found no consistent change in recruitment of the deep and superficial MF.

Evidence of differential MF activity in healthy subjects and in LBP patients is limited due to the difficulty in investigating the deep fibers, requiring invasive techniques, such as intramuscular EMG.

Muscle functional MRI (mfMRI) is an innovative, noninvasive method to investigate muscle recruitment. The method is based on changes in nuclear magnetic resonance transverse relaxation time (T2) of muscle water due to activity. Activated muscles show an acute increase in T2 relaxation time, which is reflected in the enhanced signal intensity of the recruited muscles [25, 26].

The mfMRI technique has been used before to investigate muscle recruitment in various muscles [27–29] and also specifically in lumbar back muscles [30, 31] during exercise.

One of the advantages of MRI is that not only a whole muscle, but also specific regions within a muscle can be investigated [25, 26, 30]. The recruitment patterns within the quadriceps muscle [32] and gastrocnemius muscle [33] have been evaluated before. To our knowledge the recruitment pattern within the MF muscle has never been investigated before with mfMRI.

Therefore, the aims of this study were to determine (1) whether a difference in T2 relaxation time can be detected between the deep and superficial MF, (2) whether mfMRI can demonstrate a difference in recruitment between the deep and superficial MF following exercise in healthy subjects and (3) whether mfMRI can demonstrate a difference in recruitment between the deep and superficial MF following exercise during experimentally induced LBP.

Methods

Subjects

Fifteen healthy male subjects volunteered for this study. Their mean age, height and weight were 23.33 (SD

0.82) years, 179.27 (SD 4.10) cm and 72.20 (SD 7.93) kg, respectively. Potential subjects were excluded from participation if they had any past or current back pain or if MRI was contraindicated. All procedures were approved by the Ghent University Ethics Committee and each volunteer signed a written informed consent.

Experimental setup/protocol

A static–dynamic trunk extension exercise was used to activate the MF muscle. The static–dynamic exercise has been proven to activate the MF muscle to a higher extent compared to a dynamic exercise [34]. The exercise was performed on a variable angle chair, with the trunk supported at 45° of flexion. Hands were placed on the shoulders and legs were strapped to the chair. The subjects had to extend their upper body until horizontal. To standardize the horizontal position, a sensitive cue was provided by a rope (Fig. 1). Subjects were instructed to raise their trunk in 2 s, hold the horizontal position for 5 s and to lower the trunk in 2 s [34]. The exercise intensity was set at 40% of one repetition maximum [31, 34, 35]. To achieve this intensity, the upper body weight of the subjects had to be lowered by a pulley. To control the volume, each subject had to perform ten repetitions.

Pain induction

Immediately before the second exercise bout, pain was induced in the longissimus muscle using a standard protocol [24, 31]. As much as 1.5 ml of 5% hypertonic saline was injected into the right longissimus muscle, 4 cm lateral to the L4 spinous process, at a depth of 2.4 cm [24]. After the saline injection, subjects scored the pain on a visual analog scale (VAS) between 0 (no pain) and 10 (worst possible pain). To be included in the study, pain intensity had to reach at least 3/10 [24].

Fig. 1 Trunk extension exercise, horizontal position

mfMRI

Images were obtained using a 3 Tesla Siemens Trio Tim scanner (Siemens Erlangen). The subjects were placed in the magnetic bore in a comfortable and relaxed supine position. A flexible surface coil, fixed over the participant's abdomen, was combined with the phased-array spine coil as a receiver coil combination.

Three axial images of the lumbar region were obtained: (1) at rest, (2) immediately following exercise without pain and (3) immediately following exercise during induced pain. The resting MRI was taken after 30 min of supine lying [30]. After the first exercise bout, subjects rested supine for 60 min to allow the trunk muscles to recover from the exercise [28, 30].

A sagittal localizing sequence was performed every time the subject reentered the scanner to ensure a similar lumbar position in the magnet bore between repeated images.

A transaxial slice of 5 mm thickness was obtained from the L4 segmental level and was positioned parallel to the lower end plate of L4 (Fig. 2). A CPMG (Carr Purcell Meiboom Gill) sequence was applied, which was valuable for measuring T2 relaxation times. The sequence had the following parameters: repetition time of 2,500 ms, echo train of 16 equidistant echos ranging from 10.1 to 161.6 ms, 256 mm field of view, 128 × 128 matrix, voxel size 2 × 2 × 5 mm, and a total scan time of 5 min and 24 s. Imaging procedures were identical for the resting scan and the scans after exercise.

Data analysis

After scanning, images were analyzed using Image J (Java-based version of the public domain NIH Image Software; Research Services Branch, National Institutes of Health). A T2 value (in ms) was determined for each voxel on the image, using the MRI analysis calculator plug in.

Next, the regions of interest (ROI) were defined on the T2 image; within the MF muscle, a sample of the deep fibers and a sample of the superficial fibers were outlined, avoiding nonmuscular tissue such as fat, fascia and vessels. The sample of the deep MF was taken immediately adjacent to the lamina of the L4 vertebrae and the sample of the superficial MF was taken at the superficial and lateral border of the muscle [13, 24] (Fig. 2).

Sixteen echos were used in T2 calculation using a Simplex algorithm to fit the values from the specific slice in

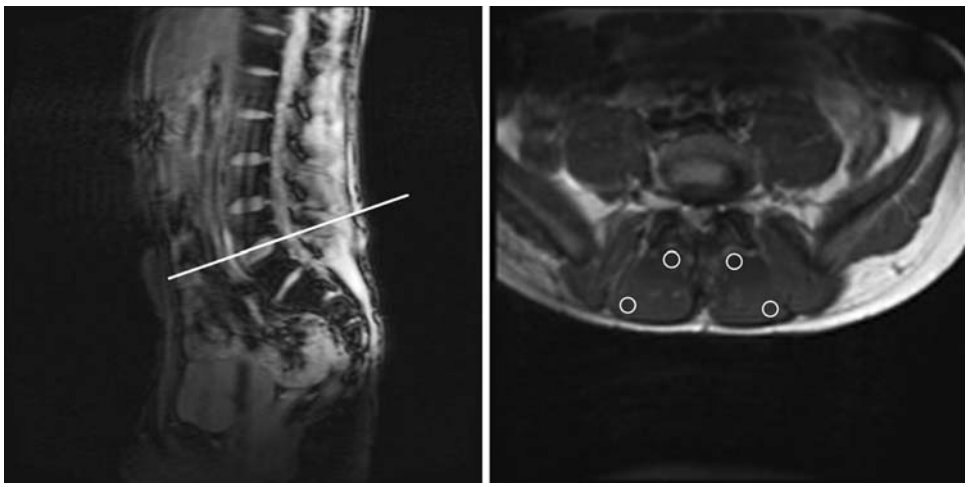

Fig. 2 *Left* positioning of the transversal slice at the L4 vertebral body. *Right* transversal slice at the L4 level. Samples of the deep and superficial MF at the left and right side of the body

a T2 image volume to the exponential $S_n = S_0\exp(-\mathrm{Te}n/\mathrm{T2})$, $(n = 1{:}16)$, where TE is echo time, S_0 is signal intensity at 0 ms, and S_n is signal intensity at Ten.

The mean T2 relaxation time (ms) was derived for each ROI and used for further analysis.

The intraclass correlation coefficient for intra-rater agreement of the T2 values for the DM and the SM taken in nine different subjects was 0.923 and 0.826, respectively, indicating a good to excellent reliability.

Statistical analysis

Analysis was performed using SPSS statistical software (version 16).

Descriptive statistics (mean and standard deviation) were calculated for the T2 relaxation time (ms) and the shift in T2 relaxation time (ms) due to activity. The T2 shift is defined as the difference between the T2 relaxation time after exercise and the T2 relaxation time at rest.

The differences between the deep and superficial MF for the T2 relaxation time and the shift in T2 relaxation time were analyzed by means of a paired-sample t test. The left and right side were analyzed separately because the pain was only induced in the right longissimus muscle.

Results

T2 relaxation time

At rest, the T2 value was significantly higher for the deep, compared to the superficial, fibers of the multifidus. This significant difference was also present for the values obtained following exercise, with and without pain. The mean T2 values, standard deviations and p values are described in Table 1.

Table 1 Mean T2 relaxation time (in ms) and standard deviation (SD) for the deep multifidus (MF) and the superficial multifidus during the rest condition, at the left and right side of the body

Deep MF		Superficial MF		Paired t test
Mean	SD	Mean	SD	p value
Left				
51.07	3.54	41.73	2.31	<0.001
Right				
53.53	3.50	42.00	2.83	<0.001

Results of the paired t test are given as a p value (significance level $p < 0.05$)

Shift in T2 relaxation time following exercise

Both in the non-pain and the pain condition, the shift in T2 relaxation time following the extension exercise was not significantly different between the deep and superficial samples. The mean shift in T2 relaxation time, standard deviations and p values are represented in Table 2.

Pain scores

After pain induction, the mean score for pain intensity on a VAS is 5.6/10 (±1.1). In the middle of the exercise bout, the pain intensity was scored as 5.9/10 (±1.4) and at the end of the exercise bout, immediately before scanning pain intensity was 5.3/10 (±1.6).

Discussion

In this study, histological and functional differences between the deep and superficial fibers of the MF were investigated using T2 relaxation times. The results of this MRI analysis show a significant difference between deep and superficial muscle tissue, whereas, no difference in

Table 2 Mean shift in T2 value (in ms) and standard deviation (SD) for the deep multifidus (MF) and the superficial multifidus at the left and right side of the body, for the non-pain and pain conditions

Side	Deep MF		Superficial MF		Paired *t* test
	Mean	SD	Mean	SD	*p* value
Non-pain condition					
Left	0.23	1.71	1.23	1.46	0.203
Right	1.00	1.84	0.50	1.31	0.347
Pain condition					
Left	0.80	1.87	1.33	1.23	0.307
Right	1.10	2.14	0.77	1.37	0.612

Results of the paired *t* test are given as a *p* value (significance level $p < 0.05$)

recruitment during a trunk extension exercise with and without experimental LBP.

The first aim of this study was to determine whether MRI can detect a difference in T2 relaxation time between the deep and superficial components of the MF. Earlier MRI experiments demonstrated that type I muscle fibers have a longer T2 relaxation time compared to type II fibers [19–21]. Based on the anatomical and biomechanical differentiation between both components and the scarce histological evidence [12], it is assumed that the deep muscle fibers have a higher percentage of type I fibers compared to the superficial MF. Our results are in line with this hypothesis and demonstrate a significantly longer T2 relaxation time for the deep, compared to the superficial, MF. To our knowledge, this is the first study to provide evidence for this hypothesis based on healthy subjects, as earlier research was limited to biopsies of muscle tissue in cadavers or LBP patients undergoing surgery [8, 12, 36].

The second aim of the study was to determine whether mfMRI can demonstrate a difference in recruitment between the deep and superficial MF following exercise in healthy subjects. Previous mfMRI studies revealed that the MF muscle is significantly activated following trunk extension exercise [30, 31]. The results of the current experiment show no difference in activation between the deep and superficial fibers, which indicates an equal amount of activation of deep and superficial fibers during the trunk extension.

In contrast to our study, Moseley et al. [22] found differential activation of the deep and superficial fibers in tasks that challenge stability of the spine. During voluntary arm movements, the onset of the superficial MF was dependent on the direction of the movement, whereas the onset in the deep MF was independent of the direction of movement. This differentiation in timing has also been found in expected trunk loading, but not in unexpected perturbation of the trunk.

Comparison between the experiments of Moseley et al. and the current experiment should be done with caution, as different aspects of neuromotor control and different tasks were studied.

First, Mosely et al. investigated the timing of muscles, while in the current experiment the amount of activation was studied. A differentiation in timing between the deep and superficial MF does not require a differentiation in the amount of activity. Therefore, the results of both studies are not necessarily contradictory.

Second, there are clear differences between the arm movement task of Moseley et al. and the trunk extension in the present experiment. When the MF is recruited to stabilize the spine, for example during arm movement or trunk loading, there is need for a low load tonic contraction of the MF [13, 22]. A low load tonic contraction selectively activates type I (slow twitch) muscle fibers, as these have the lowest threshold for activation [37]. On the contrary, the static–dynamic trunk extension exercise in our experiment has been proven to highly activate the MF muscle [31, 34]. According to the size principle of motor unit recruitment, when the load on the muscle increases, more motor units will be recruited with an increasing contribution of type II (fast twitch) fibers [37].

It can be hypothesized that there is only differential activation of the deep and superficial MF, when the low threshold motor units are recruited solely during low load contraction. As there is a higher portion of type I muscle fibers in the deep MF, this muscle part will be more activated compared to the superficial MF. When there is need to recruit more motor units, during higher load contractions, the superficial MF will be recruited with the help of the deep MF. This hypothesis is supported by the current evidence that the deep MF is recruited to provide segmental stabilization of the spine, while the superficial MF is recruited to provide trunk extension, combined with control of spine orientation [10, 14–16].

The third aim of the study was to investigate whether mfMRI can demonstrate a difference in recruitment between the deep and superficial MF during induced LBP. An earlier mfMRI experiment of our researcher group proved that activity of the MF was significantly diminished in the pain condition [31]. In literature it is mentioned that the type I muscle fibers are potentially more susceptible to the adverse affects of pain [38]. Therefore, it could be hypothesized that the deep MF is more affected by pain, compared to the superficial MF. However, this hypothesis is not supported by our results as there is no difference in the shift of the T2 relaxation time following exercise in the pain condition.

Our results are in line with the results of another pain induction experiment. Hodges et al. [24] investigated muscle recruitment during arm movements after pain

induction and, although expected, they did not find a consistent difference between the deep and superficial MF.

These results from experimental studies are in contrast with a recent clinical study [23]. MacDonald et al. investigated the timing of the deep and superficial MF recruitment during an arm movement task in LBP patients and demonstrated delayed recruitment, specifically for the deep MF.

As there is a difference in results between the experimental and clinical LBP studies, it should be interesting to investigate a clinical LBP population using mfMRI.

The current study has some limitations. Using MRI as a noninvasive, in vivo technique to determine fiber type in skeletal muscles seems promising. However, to date, research is limited and the technique has to be further explored. Also, mfMRI for assessment of muscle activation patterns is an upcoming technique with new perspectives; however, further research is needed. The method has been intensively used before to investigate muscle activity of entire muscles [27, 29–31, 39, 40]; however, the investigation of differences between samples within the same muscle is limited [32, 33].

In conclusion, this study demonstrates differences in T2 relaxation time between the deep and superficial MF and supports the current assumption that the deep MF has a higher percentage of slow twitch fibers compared to the superficial MF. The use of MRI to investigate fiber type distribution seems very promising and has to be further explored, as there is need for a noninvasive and in vivo technique to determine fiber type.

No differential recruitment has been found following trunk extension with and without pain induction. For further research, it should be interesting to investigate a clinical LBP population, using this noninvasive mfMRI approach.

Acknowledgment This research was supported by the BOF-Ghent University.

References

1. Danneels LA, Vanderstraeten GG, Cambier DC, Witvrouw EE, De Cuyper HJ (2000) CT imaging of trunk muscles in chronic low back pain patients and healthy control subjects. Eur Spine J 9:266–272
2. Hides JA, Richardson CA, Jull GA (1996) Multifidus muscle recovery is not automatic after resolution of acute, first-episode low back pain. Spine 21:2763–2769
3. Hides JA, Stokes MJ, Saide M, Jull GA, Cooper DH (1994) Evidence of lumbar multifidus muscle wasting ipsilateral to symptoms in patients with acute/subacute low back pain. Spine 19:165–172
4. Hodges P, Holm AK, Hansson T, Holm S (2006) Rapid atrophy of the lumbar multifidus follows experimental disc or nerve root injury. Spine 31:2926–2933
5. Hodges PW, Moseley GL (2003) Pain and motor control of the lumbopelvic region: effect and possible mechanisms. J Electromyogr Kinesiol 13:361–370
6. Hides JA, Jull GA, Richardson CA (2001) Long-term effects of specific stabilizing exercises for first-episode low back pain. Spine 26:E243–E248
7. Whittaker J (2007) Ultrasound imaging for rehabilitation of the lumbopelvic region. A clinical approach. Churchill Livingstone, Edinburghl, pp 66–77
8. Macdonald DA, Lorimer Moseley G, Hodges PW (2006) The lumbar multifidus: does the evidence support clinical beliefs? Man Ther 11:254–263
9. Richardson CA, Hodges PW, Hides JA (2004) Therapeutic exercise for lumbopelvic stabilization. A motor control approach for the treatment and prevention of low back pain. Churchill Livingstone, Edinburgh
10. Macintosh JE, Bogduk N, Munro RR (1986) The morphology of the human lumbar multifidus. Clin Biomech 1:196–204
11. Bogduk N, Macintosh JE, Pearcy MJ (1992) A universal model of the lumbar back muscles in the upright position. Spine 17:897–913
12. Sirca A, Kostevc V (1985) The fibre-type composition of thoracic and lumbar paravertebral muscles in man. J Anat 141:131–137
13. Moseley GL, Hodges PW, Gandevia SC (2002) Deep and superficial fibers of the lumbar multifidus muscle are differentially active during voluntary arm movements. Spine 27:E29–36
14. Jemmett RS, Macdonald DA, Agur AM (2004) Anatomical relationships between selected segmental muscles of the lumbar spine in the context of multi-planar segmental motion: a preliminary investigation. Man Ther 9:203–210
15. Danneels LA (2007) Clinical anatomy of the lumbar multifidus. In: Vleeming A, Mooney V, Stoeckart R (eds) Movement, stability and lumbopelvic pain integration of research and therapy. Elsevier, Churchill Livingstone, pp 85–94
16. Kay A (2000) An extensive literature review of the lumbar multifidus: anatomy. J Man Manip Ther 8:102–114
17. Henneman E, Olson CB (1965) Relations between structure and function in the design of skeletal muscles. J Neurophysiol 28:581–598
18. Segal RL (2007) Use of imaging to assess normal and adaptive muscle function. Phys Ther 87:704–718. doi:ptj.20060169[pii] 10.2522/ptj.20060169
19. Adzamli IK, Jolesz FA, Bleier AR, Mulkern RV, Sandor T (1989) The effect of gadolinium DTPA on tissue water compartments in slow- and fast-twitch rabbit muscles. Magn Reson Med 11:172–181
20. English AE, Joy ML, Henkelman RM (1991) Pulsed NMR relaxometry of striated muscle fibers. Magn Reson Med 21:264–281
21. Polak JF, Jolesz FA, Adams DF (1988) NMR of skeletal muscle. Differences in relaxation parameters related to extracellular/intracellular fluid spaces. Invest Radiol 23:107–112
22. Moseley GL, Hodges PW, Gandevia SC (2003) External perturbation of the trunk in standing humans differentially activates components of the medial back muscles. J Physiol 547:581–587. doi:10.1113/jphysiol.2002.0249502002.024950[pii]
23. Macdonald D, Moseley GL, Hodges PW (2009) Why do some patients keep hurting their back? Evidence of ongoing back muscle dysfunction during remission from recurrent back pain. Pain. doi: S0304-3959(08)00721-5[pii]10.1016/j.pain.2008.12.002
24. Hodges PW, Moseley GL, Gabrielsson A, Gandevia SC (2003) Experimental muscle pain changes feedforward postural responses of the trunk muscles. Exp Brain Res 151:262–271
25. Patten C, Meyer RA, Fleckenstein JL (2003) T2 mapping of muscle. Semin Musculoskelet Radiol 7:297–305

26. Meyer RA, Prior BM (2000) Functional magnetic resonance imaging of muscle. Exerc Sport Sci Rev 28:89–92
27. Kinugasa R, Akima H (2005) Neuromuscular activation of triceps surae using muscle functional MRI and EMG. Med Sci Sports Exerc 37:593–598. doi:00005768-200504000-00010[pii]
28. Conley MS, Meyer RA, Bloomberg JJ, Feeback DL, Dudley GA (1995) Noninvasive analysis of human neck muscle function. Spine 20:2505–2512
29. Cagnie B, Dickx N, Peeters I, Tuytens J, Achten E, Cambier D, Danneels L (2008) The use of functional MRI to evaluate cervical flexor activity during different cervical flexion exercises. J Appl Physiol 104:230–235. doi:00918.2007[pii]10.1152/japplphysiol.00918.2007
30. Mayer JM, Graves JE, Clark BC, Formikell M, Ploutz-Snyder LL (2005) The use of magnetic resonance imaging to evaluate lumbar muscle activity during trunk extension exercise at varying intensities. Spine 30:2556–2563
31. Dickx N, Cagnie B, Achten E, Vandemaele P, Parlevliet T, Danneels L (2008) Changes in lumbar muscle activity because of induced muscle pain evaluated by muscle functional magnetic resonance imaging. Spine 33:E983–E989. doi:10.1097/BRS.0b013e31818917d000007632-200812150-00021[pii]
32. Adams GR, Harris RT, Woodard D, Dudley GA (1993) Mapping of electrical muscle stimulation using MRI. J Appl Physiol 74:532–537
33. Kinugasa R, Kawakami Y, Fukunaga T (2006) Quantitative assessment of skeletal muscle activation using muscle functional MRI. Magn Reson Imaging 24:639–644
34. Danneels LA, Vanderstraeten GG, Cambier DC, Witvrouw EE, Bourgois J, Dankaerts W, De Cuyper HJ (2001) Effects of three different training modalities on the cross-sectional area of the lumbar multifidus muscle in patients with chronic low back pain. Br J Sports Med 35:186–191
35. Pollock ML, Leggett SH, Graves JE, Jones A, Fulton M, Cirulli J (1989) Effect of resistance training on lumbar extension strength. Am J Sports Med 17:624–629
36. Rantanen J, Hurme M, Falck B, Alaranta H, Nykvist F, Lehto M, Einola S, Kalimo H (1993) The lumbar multifidus muscle five years after surgery for a lumbar intervertebral disc herniation. Spine (Phila Pa 1976) 18:568–574
37. Henneman E, Somjen G, Carpenter DO (1965) Functional significance of cell size in spinal motoneurons. J Neurophysiol 28:560–580
38. Appell HJ (1990) Muscular atrophy following immobilisation. A review. Sports Med 10:42–58
39. Price TB, Kamen G, Damon BM, Knight CA, Applegate B, Gore JC, Eward K, Signorile JF (2003) Comparison of MRI with EMG to study muscle activity associated with dynamic plantar flexion. Magn Reson Imaging 21:853–861. doi:S0730725X03001838[pii]
40. Adams GR, Duvoisin MR, Dudley GA (1992) Magnetic resonance imaging and electromyography as indexes of muscle function. J Appl Physiol 73:1578–1583