

1 **Muscle Functional MRI as an imaging tool to evaluate muscle activity**

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1 **Synopsis**

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3 Muscle functional MRI (mfMRI) is an innovative technique that offers a non-invasive method
4 to quantify changes in muscle physiology following the performance of exercise. The mfMRI-
5 technique is based on signal intensity changes due to increases in the relaxation time (T2) of
6 tissue water. In contemporary practice, mfMRI has proven to be an excellent tool for
7 assessing the extent of muscle activation following the performance of a task and for the
8 evaluation of neuromuscular adaptations as a result of therapeutic interventions. This article
9 focuses on the underlying mechanisms and methods of mfMRI, discusses the validity and
10 advantages of the method, and provides an overview of studies in which mfMRI is used to
11 evaluate the effect of exercise and exercise training on muscle activity in both experimental
12 and clinical studies.

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14 **Key words:** exercise, magnetic resonance imaging, muscle

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2 Dysfunction of the muscular system seems to play an important role in the occurrence,
3 persistence or recurrence of associated pain and disability in individuals with musculoskeletal
4 disorders. Changes in the physical structure (atrophy¹⁹, fat infiltration^{23, 25}, muscle fiber type
5 transformation⁵⁷) and behavior of muscles (timing and activation level^{7, 58}) are commonly
6 observed and measured. Pertinent to clinical practice, programs to retrain muscle function
7 have shown favorable responses in terms of improvements in pain, disability, and function.^{17,}
8^{36, 59} Physical therapists must be able to use knowledge of the structure and function of the
9 muscular system in order to accurately plan and evaluate the efficacy of therapeutic
10 measures. Therefore, contemporary methods to understand the anatomy and physiology of
11 the musculoskeletal system are needed.

12 The advent of modern imaging technology offers a variety of approaches for quantifying
13 muscle structure and function.⁵⁴ In particular, magnetic resonance imaging (MRI) is frequently
14 used to investigate anatomical information. In addition to its excellent spatial resolution, which
15 permits good quality imaging of muscle structure, MRI offers a non-invasive method to
16 quantify changes in muscle physiology following the performance of exercise. In particular,
17 signal intensity changes due to increases in the relaxation time (T2) of tissue water can be
18 measured to indicate exercise-induced activity of muscles.⁴⁰ This phenomenon was originally
19 described in 1965, when Bratton et al⁸ reported an increase in the T2 of isolated frog skeletal
20 muscle following stimulated isometric contractions. Subsequently, Fleckenstein et al³¹
21 reported the first similar phenomenon in living human subjects and as a consequence Fisher
22 et al²⁹ suggested that this prolongation in T2 relaxation time could be used as a quantitative
23 measurement for muscle activity. In contemporary practice this technique is referred to as
24 muscle functional MRI (mfMRI) and has proven to be an excellent tool for assessing the
25 extent of muscle activation following the performance of a task and for the evaluation of the
26 neuromuscular adaptations as a result of therapeutic interventions.

27 The purpose of this article is to review the underlying mechanisms and methods of mfMRI,
28 discuss the validity, reliability, advantages and limitations of the method, and provide an

1 overview of studies in which mfMRI is used to evaluate the effect of exercise and exercise
2 training on muscle activity in both experimental and clinical studies.

3

4 **Mechanisms and methods of mfMRI**

5 Basic principles of MRI.

6 An understanding of the basic mechanisms of mfMRI requires some discussion of nuclear
7 magnetic resonance physics. A nuclear magnetic resonance signal arises from magnetic
8 activity of hydrogen nuclei (protons) in tissue water and fat molecules.^{43, 48} When a tissue is
9 positioned in a strong magnetic field (B_0), the magnet bore of the scanner; most protons will
10 align with that field and are then considered to be in a low-energy state. The result is a net
11 magnetization vector along the longitudinal Z-axis. In this phase, the protons are in a state of
12 equilibrium while spinning (precessing) at the frequency of the static magnetic field; B_0 .

13 The protons become excited by the application of a radio frequency (RF) pulse (B_1) of a
14 certain amplitude and time. Due to the RF pulse, the nuclei rotate so that the net
15 magnetization flips from the longitudinal Z-axis into the transverse XY-plane. In addition, the
16 pulse causes the nuclei to precess in phase in the XY-plane (phase-coherent oscillation).
17 When the nuclei dephase, a detectable magnetic signal is generated and recorded. As
18 protons prefer to be in a low energy state, they will emit their absorbed energy and return to
19 the equilibrium state by re-aligning with the longitudinal Z-axis (the magnetic field; B_0). This
20 process is called relaxation and can be divided in two independent parameters: T1 and T2
21 relaxation (FIGURE 1).

22 T1, or the longitudinal relaxation time, characterizes the rate at which the longitudinal
23 component of the magnetization vector recovers and is defined as the time (in milliseconds) it
24 takes for the longitudinal magnetization to reach 63% of its final value.⁵¹ This component of
25 the MR signal reflects structural aspects and is relatively insensitive to changes in the state of
26 the muscle.

27 T2, or transverse relaxation time, characterizes the rate at which the magnetization vector
28 decays in the transverse or XY plane. T2 is defined as the time (in milliseconds) it takes for

1 the transverse signal to reach 37% (1/e) of its initial value.⁵¹ In contrast to T1, T2 is sensitive
2 to changes in relaxation time of muscle water.

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4 Mechanism underlying mfMRI

5 The mfMRI-technique is based on an increase in T2 relaxation time of muscle water following
6 exercise. Specifically, exercise results in a slower decay of the muscle water signal, which
7 causes an enhancement in signal intensity of the activated muscles, and as a consequence,
8 activated muscles look brighter on T2 weighted images when compared to muscles imaged in
9 a resting state (FIGURE 2).⁴³

10 Different studies have been performed to elucidate the underlying physiological mechanism of
11 this shift in T2 relaxation time.^{18, 22, 32} The simplest explanation is that the influx of fluid during
12 activity is accompanied by an accumulation of osmolites (phosphate, lactate, sodium) in the
13 cytoplasm and their presence prolongs the relaxation time of muscle water.⁴³ The T2
14 relaxation time of total muscle water is composed of multiple components, such as 1) protein
15 bound intracellular water (34%), 2) free intracellular water (49%), and 3) extracellular water
16 (14%), each experiencing a change in their respective T2 relaxation time.⁵³ The summed
17 effect of changes in these components results in the net activity-induced increase in T2.
18 Although all of the components act synergistically to increase overall T2, it should be clear
19 that activity-dependent increases in T2 are believed to primarily result from intracellular
20 events.⁴⁸

21

22 Measurement protocols

23 The general mfMRI measurement protocol is that images are acquired at rest (pre-exercise
24 image) and immediately following (post-exercise image) a specific exercise. Regions of
25 interest (ROI) may then be developed for each muscle of interest. Care should be taken to
26 avoid the inclusion of non-muscular tissue (e.g. fat, fascia or blood vessels) in all ROIs. For
27 each ROI, the T2 value may then be calculated and the change in T2 value recorded from the
28 pre- and post-exercise image is referred to as the T2 shift. From these calculations of T2

1 shifts, inferences regarding the activity level of specific muscles can be made and compared
2 for different exercise protocols.

3 The half-life of exercise-induced changes in muscle T2 has been shown to be approximately
4 7 minutes²⁹, which requires the subjects to be accurately placed in the scanner immediately
5 following the performance of the exercise. The time between the end of the exercise and the
6 start of the scan will depend upon what body part is imaged and the imaging coils that are
7 used. Future applications might enable patient to perform exercise in the scanner, thereby
8 enabling scanning as soon as exercise is finished. Although there is a fast decay of T2, full
9 recovery of muscle T2 is much slower, as T2 generally remains elevated for approximately 30
10 minutes following exercise.^{29, 61} If the effect of different exercises on muscle activity is to be
11 evaluated, it is recommended to permit at least 45 minutes of rest between exercise sets, as
12 this would allow full-recovery of any established T2 shifts.¹⁵

13 Different sequences can be used of which multi-spin echo sequences are mostly applied.
14 During a spin-echo pulse sequence, the RF field is applied in two pulses: a 90° RF pulse with
15 a 180° RF pulse to rephrase spins to form an echo.⁵¹ The time between the peak of the 90°
16 RF pulse and the peak of the echo is called the echo time (TE). The time it takes to go
17 through the pulse sequence once is called the repetition time (TR). Multi-echo spin-echo
18 pulse sequences use multiple 180° RF pulses to generate multiple echoes in which each
19 echo can be used to create a separate image. Turbo or fast spin echo sequences use the
20 same sequence but instead of each echo forming a different image data set, all the echoes
21 are used to create a single image data set at a faster rate, saving imaging time.

22

23 Key Points:

- 24 • T2 relaxation time characterizes the rate at which the magnetization vector decays in
25 the transverse plane and is sensitive to changes in the state of the muscle.
- 26 • mfMRI is based on an activity-induced increase in the T2 relaxation time of muscle
27 water which is directly responsible for the increased intensity of the MR signal on the
28 T2 weighted imaging following exercise

- While the exact underlying mechanism behind T2-shifts is not yet fully understood, it is generally accepted that the T2 shift is associated with biochemical processes related to muscle activity
- T2 shifts can be recorded from the pre- and post-exercise images allowing quantification of the the activity level of specific muscles and such methodologies provides for comparison between different exercise protocols and their effects on muscular tissue.

Validity and reliability of mfMRI measurements

In an effort to validate mfMRI as an evaluation tool for muscle activity, the relationship between T2 shift and various other parameters of exercise has been investigated.^{1, 29, 33, 35, 38,}

⁶¹ Studies have shown that T2 shifts are quantitatively dependent on the intensity of skeletal muscle activation when exercises are performed over a wide range of intensities,^{1, 29, 35, 38} supporting a linear relationship between T2 times and exercise intensity. Fisher et al²⁹ demonstrated that increases in T2 values of the human tibialis anterior were linearly related to the forces generated during exercise ($r=0.87$), whereas Jenner et al³⁵ demonstrated a similar correlation when exercise intensity was altered by increasing the rate of contractions at a constant target force ($r=0.64$; $p<0.01$). Similar results were found by Dickx et al²¹ who investigated multifidus and erector spinae muscle activity during a trunk extension exercise at 5 increasing loads (from 40% to 80% of 1 repetition maximum) with both MRI and EMG. They demonstrated a linear association for the lumbar paraspinals ($R^2 = 0.92$; $p\leq 0.001$) and revealed that for both muscles an increase of 10% exercise intensity corresponds with an increase of the T2 value of 1.18 (95% CI: 0.89-1.47) ms. Studies by Fleckenstein et al³³, Mayer et al⁴² and Cheng et al¹⁴, however, do not support a linear relationship between T2 times and all levels of intensity of muscular activity, but rather support a sigmoid-shape relationship. Differences between studies can be attributed to differences in statistical approach (linear regression analysis compared to mixed model analysis) and methodology. For example, Mayer et al⁴² performed the exercises at 3 different intensities on the same day,

1 with 60 minutes of rest in between, whereas Dickx et al²¹ tested subjects on 5 consecutive
2 days, to allow the trunk musculature to recover. Residual fatigue in the lumbar muscles may
3 have confounded muscle recruitment. However, it is still unknown whether the association
4 also applies for lower and higher exercise intensities. It can be expected that changes in T2
5 reaches a ceiling, as the value depends on physiologic processes related to muscle output.
6 Therefore, it is considered that T2 shifts are useful for inferences regarding moderate levels
7 of muscle activity, but less valid for the lower and higher levels of activity.
8 Several studies have compared T2 contrast shifts and electromyography (EMG) signal
9 amplitude of muscles in both the lower extremities and lumbar spine.^{1, 21, 38, 52} Results vary
10 among studies and muscles, and although MRI and surface EMG measurements are not in
11 complete agreement, they demonstrate a consistent relationship.^{1, 21, 38, 52} Lack of complete
12 agreement between EMG and T2 shift recordings may be indicative of the different
13 physiological basis of both measures. EMG signal amplitude reflects the electrical activation
14 of muscle tissue, where T2 shifts record metabolic activity within the muscle tissue itself.
15 With regards to measurement reliability, measurements of T2 shifts have shown high inter-
16 tester reliability with intra-class correlation coefficients and standard error of measurements
17 ranging from 0.87 to 0.94 and 1.64 to 2.75 ms respectively (depending on the muscles
18 evaluated).^{10, 12, 24} This high reproducibility of results is an important advantage of the MRI
19 method over surface and fine-wire EMG methods.⁵⁶

20

21 Key Points:

- 22 • T2 shifts are useful for inferences regarding moderate levels of muscle activity, but
23 less valid for the lower and higher levels of activity.
- 24 • No absolute agreement has been observed between EMG and mfMRI measures of
25 muscle activity which is indicative of their different measurement properties.
- 26 • mfMRI is a highly reliable measurement tool of resting and exercised skeletal muscle,
27 with a small amount of measurement error.

28

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2 **Advantages and limitations of mfMRI**

3 MfMRI is a valuable complementary evaluation technique to EMG in measuring muscle
4 behavior. While both techniques have unique measurement qualities, there are some
5 advantages of mfMRI, making it a valuable evaluation method particularly with regard to the
6 non-invasive access to deeper muscle structures and elimination of a common limitation with
7 EMG measures; cross-talk.

8

9 Non-invasive access to deep muscles

10 MfMRI has some advantages over methods such as EMG in that it permits non-invasive
11 measurements at multiple locations within multiple muscles from a single MRI scan. This is
12 particularly advantageous for deeper muscle structures within the musculoskeletal system
13 that, due to their depth and intimate proximity to structures such as visceral organs, may not
14 be directly amenable to other methods of assessment such as surface or intramuscular EMG.
15 Accordingly, mfMRI has gained popularity in studies evaluating muscle function including
16 deep paraspinal muscles^{9, 10, 15, 20, 24, 42} that were previously difficult to achieve and not without
17 some risk with invasive EMG.^{26, 27, 34, 46, 60}

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19 Elimination of measurement issues such as cross-talk

20 While EMG measures have the advantage of evaluating the activity levels of muscles in real
21 time, there are signal issues associated with surface EMG techniques. There is difficulty in
22 obtaining an EMG signal representing isolated activity of the target muscle with surface EMG
23 on the basis of the inaccessibility of deeper muscles with surface electrodes⁵⁵ and the
24 generation of EMG signal by neighboring muscles resulting in signal cross-talk.⁴⁸ While it may
25 be argued that the use of intramuscular EMG techniques eliminates cross-talk, a single
26 intramuscular electrode will record signals from a population of motor units limited to its
27 insertion site and therefore may not be representative of activity levels of the entire muscle. In
28 contrast mfMRI permits measures to be taken with no issues of signal cross-talk. Additionally,

1 mfMRI avoids other signal issues associated with EMG attributed to impedance from
2 subcutaneous tissue and electrode type and placement.

3

4 Limitations of mfMRI measures

5 Besides the absolute contraindications for MRI, including pacemakers, brain aneurysm clips,
6 metallic foreign bodies and claustrophobia, there are several limitations inherent to mfMRI.

7 At present, investigation using mfMRI is limited to evaluate spatial aspects (amount of
8 activation) of muscle behavior that is in contrast to EMG techniques which have the
9 advantage of evaluating both temporal (timing of activation) and spatial elements of muscle
10 behavior in real time. Additionally mfMRI is a post-exercise evaluation of muscle activity and
11 as yet the latency effects on the T2 shift measurement due to the delay between completion
12 of the exercise and the commencement of the MRI scan is still not fully understood.

13 Secondly, mfMRI appears to be limited to evaluating exercise of at least moderate exertion
14 such as resistance exercises, whereas evaluation of exercises at lower and higher intensities
15 are expected to be less valid. Although several studies have demonstrated a relationship
16 among exercise intensity, EMG signal amplitude, and T2 times, the lowest activity threshold to
17 induce a significant shift in signal is still not known.^{1, 33, 35} It would appear that EMG has a
18 lower muscle activity detection threshold than MR imaging.⁵⁴ A sensitivity study revealed that
19 changes in T2 times for the elbow-flexor muscles can be detected with as few as 2 repetitions
20 (1 repetition being 1 second concentric and 1 second eccentric contraction) when performed
21 at a high intensity (80% maximum voluntary contraction (MVC)).^{15, 54, 61} Lower intensity
22 exercises (25% MVC) may require up to 5 contractions before changes in T2 times can be
23 appreciated.⁶¹ In conclusion, while both mfMRI and EMG can be used independently to
24 assess muscle activity relevant to research and clinical practice, their utility may depend on
25 the nature of the muscular activity of interest. It is possible that combining both techniques will
26 provide additional information when evaluating overall muscle function.

27 Lastly, while mfMRI is an emerging and exciting tool for evaluation of muscle activity, it is not
28 without some inherent costs. Although mfMRI can be performed with the MR technology that

1 is currently present in most hospitals for routine patient evaluation, it is primarily only
2 available to research laboratories. Thus, the cost-effectiveness of utilizing such a potentially
3 expensive modality for assessment and plan of care is currently unknown. Limiting practice
4 variability at reduced costs is a major focus in delivering medical and rehabilitative services,
5 worldwide. Thus, a cost-effectiveness study would be required before final recommendation
6 that mfMRI become standard physical therapy and rehabilitation practice.

7

8 Key Points:

- 9 • MfMRI has the advantage, especially for the spinal muscles, to non-invasively
10 evaluate muscle activity, adjacent muscles and even overlying muscles, without cross-
11 talk.
- 12 • MfMRI is of questionable value in measuring muscles function during activities that
13 are of a low intensity nature.
- 14 • While both mfMRI and EMG provide information regarding muscle function, they are
15 complementary measures.
- 16 • The cost-effectiveness of using mfMRI for patient assessment and plan of care is
17 currently unknown.

18

19 **mfMRI and exercise**

20 Early studies utilizing mfMRI measures investigated activity levels of specific muscles during
21 exercise at specific intensity levels relative to maximal exertion, while others compared
22 muscle activity over increasing intensity levels to maximal exertion.^{2, 30, 31, 33, 35, 61} More recent
23 studies have utilized mfMRI measures to specifically compare muscle activity during various
24 clinically based exercises in healthy individuals and individuals with painful musculoskeletal
25 disorders.^{10, 12, 15, 24, 38, 40, 42, 44, 56} Therefore, T2 shift measures provide a powerful technique to
26 assess 1) muscle function during specific exercise/rehabilitation protocols, 2) changes in
27 activity patterns in patients with musculoskeletal disorders, and 3) the efficacy of interventions
28 delivered over time.

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Muscle function during specific exercise/rehabilitation protocols

Most studies utilizing mfMRI have investigated muscle activity patterns during commonly prescribed clinically based exercises. The superior spatial resolution of MRI provides a unique opportunity to study multiple muscles and demonstrate whether the target muscle has been activated, how effectively it has been activated, or whether substitution has occurred. Studies have evaluated muscle activity during exercise of the lower (knee extension, ankle extension and flexion, running, and cycling),^{29, 35, 38, 39, 47, 50} and upper extremities as well as the spine.^{10, 15, 24, 42, 43, 53, 56, 61} Other studies have evaluated the impact on muscle activity of altering the parameters (type of contraction, velocity, intensity) of the exercise being performed.^{20, 41, 42} For example the rectus femoris muscle has been shown to be more activated than the other portions of the quadriceps muscle during isokinetic knee extension exercise but not during isotonic knee extension exercise.^{5, 49} Kulig et al⁴¹ investigated the effect of contraction velocity on activity within the primary elbow flexors during 2 isotonic exercise protocols that differed in the velocity of their eccentric phase. Their findings demonstrated a variable response to the different velocity conditions that had not previously been detected with similar studies using EMG, indicating that mfMRI may be a more sensitive measure to explore this phenomenon. The findings suggest that signal intensity changes are associated with task-dependent differences and likely influenced by metabolic demand and/or neural activation.³

MfMRI also offers the clinician insight into the effectiveness of whether an exercise targets a specific muscle or muscle group. Takeda et al⁵⁶ demonstrated significantly greater increases in T2 relaxation time for the supraspinatus muscle in response to empty can and full can exercises (shoulder abduction performed in the scapular plane with thumb down and up, respectively) in comparison to a horizontal abduction exercise in healthy individuals. These findings suggest that these exercises (empty can/full can) may provide a better approach to specifically evaluate or train the performance (eg. strength, endurance) of the supraspinatus muscle.³⁷ Cagnie et al¹⁰ used mfMRI to evaluate cervical flexor muscles activity during

1 different cervical flexion exercises. It was determined that the deep longus capitis muscle was
2 more active than the more superficial cervical flexor muscles during a craniocervical flexion
3 exercise. This confirmed the appropriateness of craniocervical flexion as an exercise for
4 patients with neck pain who are known to exhibit reduced activity of their deep cervical flexor
5 muscles in the presence of heightened superficial flexor muscle activity.²⁸ These findings of
6 cervical flexor function of Cagnie and colleagues were also consistent with those of a
7 previous study utilizing EMG measures.⁴⁵ A comparable study has recently been undertaken
8 by Elliott et al²⁵ utilising mfMRI to evaluate the impact of craniocervical orientation on cervical
9 extensor muscle activity during extensor exercises in healthy individuals. While both the deep
10 and superficial extensor muscles were active in both exercises evaluated, significantly greater
11 T2 shifts were observed for the more superficial semispinalis capitis muscles when the
12 exercise was performed with the craniocervical region in an extended orientation. The findings
13 of this study are of benefit to clinicians when prescribing exercise to train the cervical
14 extensors.

15

16 Changes in activation patterns in patients with musculoskeletal disorders

17 There are only a few clinical studies which investigated changes in muscle activation pattern
18 in patients with musculoskeletal disorders using mfMRI. Cagnie et al¹² investigated the
19 cervical flexor muscles activity in patients with whiplash-associated disorders (WAD).
20 Although not significant, there was a strong trend for lesser activity of the deep muscles in the
21 group with WAD compared to the control group, which is in agreement with the results of a
22 previously published EMG study.²⁸ O'Leary et al⁴⁴ performed a similar study for the cervical
23 extensor muscles and found some alteration in the differential activation of the cervical
24 extensors in patients with mechanical neck pain. Based on this study, they concluded that
25 further investigation of this muscle group in neck pain disorders is warranted.

26 One potential challenge with mfMRI is that across individuals there is considerable variability
27 in the activity-dependent T2 response. Accordingly, the use of T2 mapping to compare
28 activation strategies and recruitment intensity among individuals remains controversial. The

1 correlation between T2 and exercise intensity is stronger within a single individual than across
2 individuals. Thus, analytical techniques that compare relative changes in signal intensity
3 within individuals across time or exercise, or comparing the injured to the uninjured side
4 appear most appropriate.⁴

5 Another approach to circumvent limitations of T2-shift measures, is to use an experimental
6 pain paradigm. This offers the possibility to evaluate the influence of acute muscle pain on
7 muscle activity within the same individual. Dickx et al²⁰ demonstrated that experimental pain,
8 induced into the right longissimus muscle, resulted in a significant decrease in muscle activity
9 of the lumbar multifidus, lumbar erector spinae, and psoas muscles. Cagnie et al^{11, 13} recently
10 undertook two experimental pain studies for the evaluation of both cervical flexor and
11 extensor muscles with mfMRI. In both studies, the results suggest that local excitation of
12 nociceptive afferents causes an immediate reorganisation of the cervical muscle activity
13 similar to that identified in clinical populations, which support recommendations for evaluation
14 of cervical muscle function early in the management of painful cervical spine injuries.

15

16 The efficacy of interventions delivered over time

17 MfMRI has also been used to evaluate neuromuscular adaptations as a result of resistance
18 training. However, there is a paucity of available information in the literature to definitely
19 ascribe and generalize its use to this aspect of clinical assessment.^{6, 16, 49} Ploutz et al⁴⁹ and
20 Conley et al¹⁶ demonstrated that derecruitment of previously active muscles occurred when
21 performing exercise with the same absolute loads after resistance training but that there was
22 no change in the oxidative metabolic demand of muscle fibers, suggesting that fewer motor
23 units were being activated when performing the exercise. Akima et al⁶ concluded that
24 resistance training prevents deconditioning of neuromuscular systems and or metabolic
25 capacity and that this type of exercise could be useful for the prevention of muscle
26 deconditioning.

27

28 Key points

1 • T2 shift measures provide a powerful technique to assess muscle function during
2 specific exercise/rehabilitation protocols

3 • Clinical studies which investigate changes in activity pattern in patients are emerging
4

5 **Future research**

6 Studies with mfMRI are still sparse and there is a need for further research investigating the
7 underlying mechanisms of mfMRI and the technical optimization of this technique. For
8 example, efforts will need to be made to improve image quality, to reduce artifacts, and to
9 expand the volume of muscles that can be investigated simultaneously. The potential of
10 mfMRI to map spatial variation in activity within a muscle has been indicated in literature,
11 however, to date, studies applying this method are lacking. Further, there is also a need for
12 more clinical studies investigating changes in muscular function in individuals with
13 musculoskeletal disorders.

14

15 **Conclusion**

16 MfMRI is a relatively new and innovative technique that is well-suited for examining normal
17 and abnormal patterns of muscle activation within individuals during exercise. It has the
18 advantage to non-invasively evaluate muscle activity of deep or closely adjacent and
19 overlying muscles. Although the cost-effectiveness of using mfMRI for patient assessment
20 and plan of care is currently unknown, this technique, alone or in conjunction with other non-
21 invasive methods, may provide a powerful means for improving the assessment and
22 management of patients with a range of musculoskeletal conditions.

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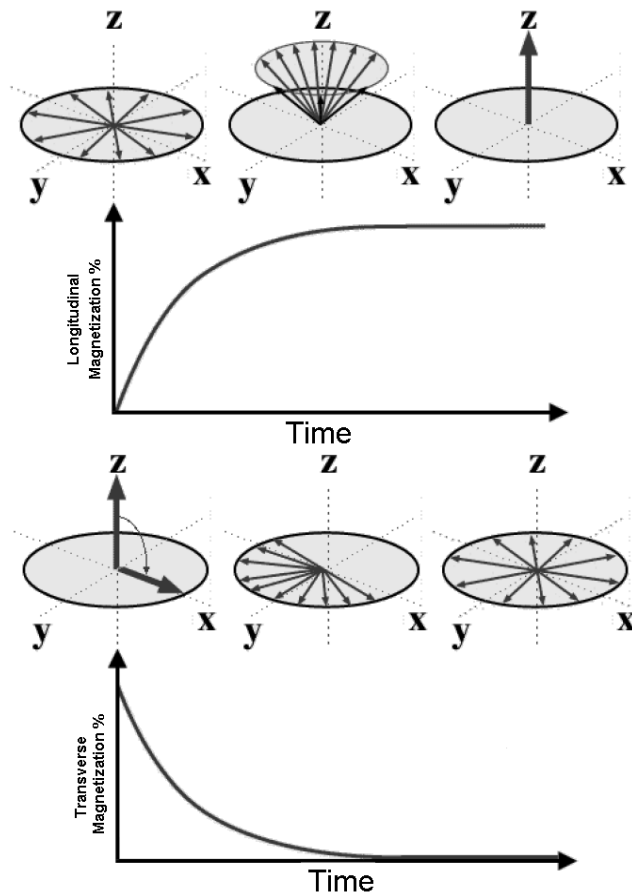
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2 **Figures**

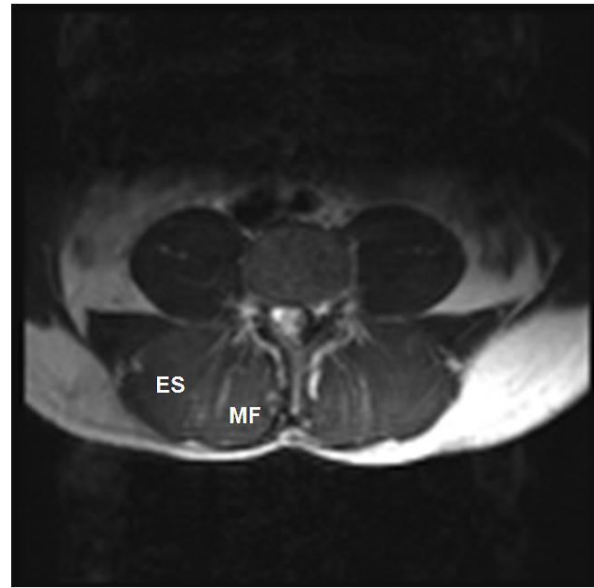
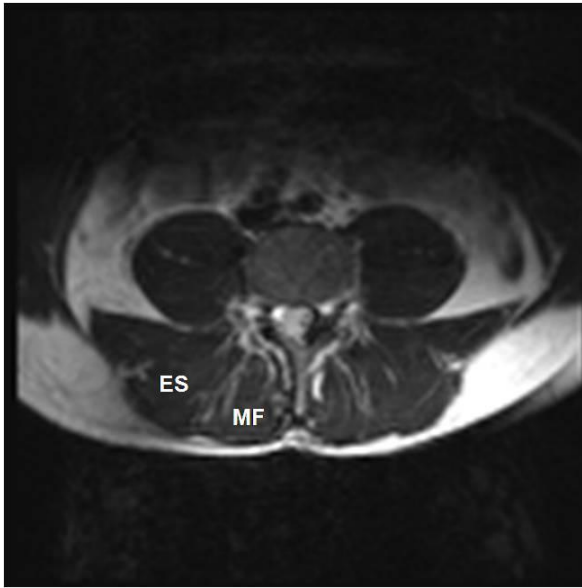


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4 **Figure 1** Definitions of T1- and T2 relaxation. T1, or the longitudinal relaxation time,
5 characterizes the rate at which the longitudinal component (Z-axis) of the magnetization
6 vector recovers and is defined as the time (in milliseconds) it takes for the longitudinal
7 magnetization to reach 63% of its final value. T2, or transverse relaxation time, characterizes
8 the rate at which the magnetization vector decays in the transverse or XY plane. T2 is defined
9 as the time (in milliseconds) it takes for the transverse signal to reach 37% (1/e) of its initial
10 value.

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2 **Figure 2:** Illustration of a T2 weighted image at rest (A) and following exercise (B) (TR: 2500
3 ms; TE: 16 equidistant echoes ranging from 10.1 to 161.6 ms; 128 x 128 matrix and 256 mm
4 FOV). There is an increased signal intensity (=brighter) for the m. multifidus (MF) and the m.
5 erector spinae (ES). Although the changes in signal intensity are subtly visible, they are
6 quantifiable using the calculation of T2 values.