



# Association of paraspinal muscle water–fat MRI-based measurements with isometric strength measurements

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## Abstract

**Objectives** Chemical shift encoding-based water–fat MRI derived proton density fat fraction (PDFF) of the paraspinal muscles has been emerging as a surrogate marker in subjects with sarcopenia, lower back pain, injuries and neuromuscular disorders. The present study investigates the performance of paraspinal muscle PDFF and cross-sectional area (CSA) in predicting isometric muscle strength.

**Methods** Twenty-six healthy subjects (57.7% women; age:  $30 \pm 6$  years) underwent 3T axial MRI of the lumbar spine using a six-echo 3D spoiled gradient echo sequence for chemical shift encoding-based water–fat separation. Erector spinae and psoas muscles were segmented bilaterally from L2 level to L5 level to determine CSA and PDFF. Muscle flexion and extension maximum isometric torque values [Nm] at the back were measured with an isokinetic dynamometer.

**Results** Significant correlations between CSA and muscle strength measurements were observed for erector spinae muscle CSA ( $r = 0.40$ ;  $p = 0.044$ ) and psoas muscle CSA ( $r = 0.61$ ;  $p = 0.001$ ) with relative flexion strength. Erector spinae muscle PDFF correlated significantly with relative muscle strength (extension:  $r = -0.51$ ;  $p = 0.008$ ; flexion:  $r = -0.54$ ;  $p = 0.005$ ). Erector spinae muscle PDFF, but not CSA, remained a statistically significant ( $p < 0.05$ ) predictor of relative extensor strength in multivariate regression models ( $R^2_{\text{adj}} = 0.34$ ;  $p = 0.002$ ).

**Conclusions** PDFF measurements improved the prediction of paraspinal muscle strength beyond CSA. Therefore, chemical shift encoding-based water–fat MRI may be used to detect subtle changes in the paraspinal muscle composition.

## Key Points

- We investigated the association of paraspinal muscle fat fraction based on chemical shift encoding-based water–fat MRI with isometric strength measurements in healthy subjects.
- Erector spinae muscle PDFF correlated significantly with relative muscle strength.
- PDFF measurements improved prediction of paraspinal muscle strength beyond CSA.

**Keywords** Magnetic resonance imaging · Paraspinal muscle · Muscle strength

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## Abbreviations

BMI	Body mass index
CSA	Cross-sectional area
ESL	Left erector spinae muscles
ESR	Right erector spinae muscles
IPAQ	International Physical Activity Questionnaire
LBP	Lower back pain
MFI	Muscle fat infiltration
MVIC	Maximum voluntary isometric contraction
NMD	Neuromuscular diseases
PDFF	Proton density fat fraction
PL	Left psoas muscle

PR	Right psoas muscle
RMSCV	Root mean square coefficients of variation
ROIs	Regions of interest

## Introduction

The paraspinal muscles are important postural muscles stabilizing the spine and playing a crucial role in daily mobility such as rising from a chair, walking and keeping balance [1]. There is increasing interest in paraspinal muscle composition as a potential prognostic and diagnostic marker for spine health as integrity, structure and functionality of paraspinal muscle tissue is affected by systemic as well as local influencing factors. Exercise [2–5], aging [6, 7] and sarcopenia [8], metabolic diseases including diabetes mellitus [9], musculoskeletal disorders including lower back pain (LBP) [10–13], injuries [14], osteoarthritis [15], and intervertebral disc disease [16] as well as neuromuscular diseases (NMD) [17, 18] have been shown to cause transformation of muscle tissue.

Therefore, magnetic resonance imaging (MRI) as a non-invasive way to assess structure and composition of paraspinal muscle tissue is recently becoming popular to characterize diseases, response to injuries or changes due to mechanical stress [19, 20]. MRI is used to examine cross-sectional area (CSA), volume, fatty infiltration and edema of paraspinal muscle. Most of the population-based studies that investigate pathoanatomical features of the spine use conventional T<sub>1</sub>-weighted or T<sub>2</sub>-weighted MRI [21]. The determination of proton density fat fraction (PDFF) derived from chemical shift encoding-based water–fat imaging is a promising technique to obtain robust, spatially resolved quantitative values with excellent agreement with spectroscopy [13] and histology [22].

Assessment of paraspinal muscle degeneration (fatty infiltration and atrophy) using mostly T<sub>1</sub>-weighted and T<sub>2</sub>-weighted MRI has been performed in several clinical studies including healthy volunteers [6, 7], patients with LBP [10–13], whiplash associated disorders [14] and NMD [17, 18, 23]. In a healthy cohort, women showed significantly more paraspinal muscle fat infiltration (MFI) than men, indicating a gender-dependent difference in the muscle tissue composition [6, 7, 24]. A shrinking of paraspinal muscle mass has been observed to be associated with aging; however, the association of CSA and age is still the subject of discussions [6, 25–28]. Paraspinal muscles are more affected by an aging-related increase in MFI than lower extremity muscles [7]. Therefore, paraspinal muscles seem to be more susceptible to age-related changes than other muscles. MFI is significantly higher in patients with LBP compared to a healthy cohort [10–13, 29]. Patients suffering from lumbar spine pathologies also show higher MFI with increasing age [29].

Increased paraspinal MFI is associated with muscle weakness [30], poorer function [1] and limitations of movement [31], postulating that muscle tissue composition in addition to mass may be responsible for muscle weakness. It is speculated that poorer muscle quality determined by increased MFI affects muscle function when noncontractile tissue replaces muscles fibers [6, 7]. However, the association of MFI and muscle strength has never been accurately investigated in the paraspinal region in a comparable way to previous work performed in the thigh region [32]. The lack of muscle strength measurements in the paraspinal region might be related to the relatively difficult assessment of paraspinal muscle strength. A handheld dynamometry is a reliable instrument in muscle strength testing [33], but has limitations, especially when testing the paraspinal muscles [7]. Dahlqvist et al used the static back extension endurance test, which did not correlate with CSA or lumbar fat fraction [7]; however, the endurance test is highly susceptible to the subject's motivation and effort [34]. The usage of objective muscle isometric strength measurement devices such as an isokinetic dynamometer that allows a robust assessment of the muscle strength of individual functional muscle groups is still needed to investigate the influence of MFI on paraspinal muscle function.

Therefore, the aim of this study was to investigate whether paraspinal muscle PDFF improves the prediction of muscle strength beyond CSA. The present study investigated the association of paraspinal muscle fat fraction with isometric strength measurements in healthy volunteers using an isokinetic dynamometer and chemical shift encoding-based water–fat MRI.

## Materials and methods

### Subjects

Twenty-six healthy subjects (57.7% women; age: 30 ± 6 years) were recruited for this study. Body mass index (BMI) between 20 and 33 kg/m<sup>2</sup> was defined as an inclusion criterion to obtain a rather broad BMI range in the study population (BMI of study population: mean ± SD of 27.0 ± 2.7 kg/m<sup>2</sup>; range: 22.2–32.4 kg/m<sup>2</sup>). Completing the International Physical Activity Questionnaire (IPAQ-sf) ensured that all recruited subjects had a moderate level of physical activity (referring to IPAQ-sf scoring protocol: 600–1,500 MET-min/week) and no history of high-performance sports [35, 36]. Based on T2W Dixon TSE images and physical examination before the muscle strength measurements, only subjects with a physiological spine anatomy were included. It was ensured that the subjects' spine were aligned and did not show any qualitatively detectable anatomy variations or spine pathologies such as scoliosis. Exclusion criteria were vertebral fractures, NMD

and MRI contraindications. All subjects gave written informed consent on MRI examination and biometrical strength measurements. The study was approved by the local institutional Committee on Human Research.

## MRI measurements

All subjects underwent MRI on a 3T system (Ingenia, Philips Healthcare, Best, The Netherlands) using a whole-body coil, the built-in 12-channel posterior coil and a 16-channel anterior coil, which was placed on top of the abdomen. Subjects were positioned head-first in a supine position. An axially-prescribed six-echo 3D spoiled gradient echo sequence was used for chemical shift encoding-based water–fat separation covering the lumbar spine. The sequence acquired the six echoes in a single TR using non-flyback (bipolar) read-out gradients and the following imaging parameters: TR/TE<sub>min</sub>/ΔTE = 6.4/1.1/0.8 ms, field of view (FOV) = 220 × 401 × 252 mm<sup>3</sup>, voxel size = 3.2 × 2.0 × 4.0 mm<sup>3</sup>, frequency encoding direction = L/R, no SENSE, scan time = 1 min 25 s. A saturation slab with a thickness of 80 mm was used to minimize artefacts from breathing motion. A flip angle of 3° was used to minimize T<sub>1</sub>-bias effects [37].

The gradient echo imaging data was processed online using the vendor's routines as described here: The multi-echo mDIXON algorithm performs a phase error correction followed by a complex-based water–fat decomposition using a pre-calibrated seven-peak fat spectrum and a single T<sub>2</sub>\* to model the signal variation with echo time. The imaging-based PDFF maps were computed as the ratio of the fat signal over the sum of fat and water signals.

## MR image segmentation

Segmentation of the paraspinal muscles was performed by drawing regions of interest (ROIs) on each slice of the PDFF maps using the open-source software MITK (German Cancer Research Center, Division of Medical and Biological Informatics, Medical Imaging Interaction Toolkit) by a radiologist. The following four muscle compartments were separately segmented from the upper endplate level of L2 to the lower endplate level of L5: right and left erector spinae muscles (ESR/ESL), and right and left psoas muscles (PR/PL). The ROIs were placed at the muscle contour to allow the determination of muscle CSA, avoiding the accidental inclusion of subcutaneous fat or the muscle fat-interface. Representative PDFF maps of one subject with corresponding segmentation masks of ESR and ESL muscles as well as PR and PL muscles are shown in Fig. 1. CSA and PDFF of each muscle were extracted. Right and left CSA and PDFF were averaged, respectively.

## Reproducibility of PDFF measurements

**Short-term intra-reader reproducibility:** Four subjects (25% women) were randomly selected from the study population. Erector spinae and psoas muscles were segmented twice by a radiologist as outlined above. Intra-reader reproducibility error was expressed as root mean square absolute precision error in percent (absolute units) according to Gluer et al [38]. It amounted to 0.72% for PDFF of the erector spinae muscles and 0.05% for PDFF of the psoas muscles.

**Short-term inter-reader reproducibility:** Erector spinae and psoas muscles were segmented in the same four subjects once by two radiologists. Inter-reader reproducibility was 0.64% for PDFF of the erector spinae muscles and 0.46% for PDFF of the psoas muscles.

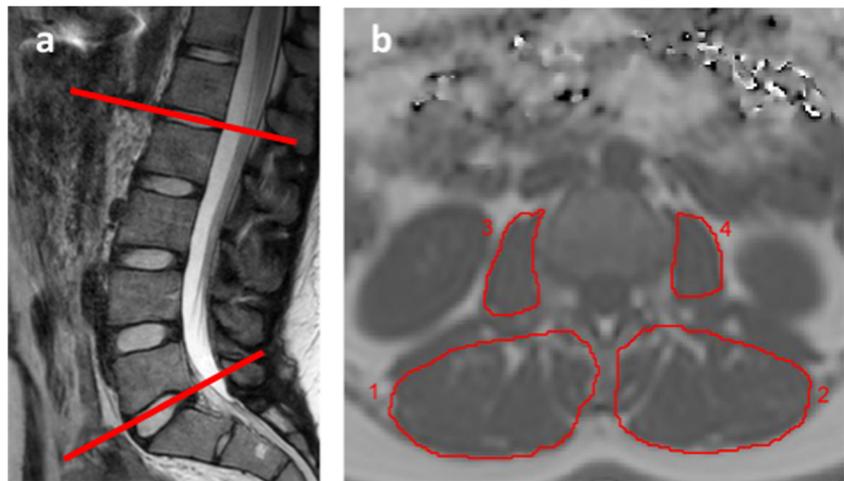
**Long-term reproducibility:** Four additional healthy subjects (25% women; age: 27 ± 1 years; BMI: 26.8 ± 1.5 kg/m<sup>2</sup>) were recruited and scanned at baseline and 4-week follow-up to assess the long-term reproducibility error of the PDFF measurements in erector spinae and psoas muscles. The segmentation procedure was performed by one radiologist. Long-term reproducibility error amounted 0.38% for PDFF of the erector spinae muscles and 0.70% for PDFF of the psoas muscles.

## Isometric muscle strength measurements

There were two dates for measuring the isometric muscle strength of back extensors with different objectives: The aim of the first visit was to become familiar with the measuring procedure and to provide training in activating the maximum isometric strength. To ensure the reproducibility of strength measurement, each subject did at least five and up to eight repetitions with maximum voluntary isometric contraction (MVIC) with 3 min breaks in-between. The second appointment was the final measuring visit to collect the MVIC data, which the present analysis is based on. There were at least 2 days of rest between the two visits and subjects were instructed to come totally recovered (no physical activity for 2 days before) to the measurements, which always took place between 10:00 a.m. and 2:00 p.m. Each visit started with a standardized warm-up: 10 min on a cycling ergometer (70–80 rpm) to activate the cardiovascular system were followed by 30–45 s of holding the plank-position statically as well as doing 10–15 sit-ups for muscular pre-activation of trunk muscles.

Afterwards the subjects were placed in an isokinetic rotational dynamometer (IsoMed Back Module, D&R Ferstl GmbH) that was calibrated exactly on each individual body dimension. Subjects were seated in an upright sitting position with a hip angle of 90° and were fixed by

**Fig. 1** (a) Sagittal view of lumbar spine (T<sub>2</sub>-weighted Dixon sequence). Segmentation was performed from the upper endplate level of L2 to the lower endplate level of L5. (b) Representative PDFF map with manually segmented muscle compartments. 1: right erector spinae muscles, 2: left erector spinae muscles, 3: right psoas muscle, 4: left psoas muscle



a hip belt and two adjustable straps, one for fixing the upper body, the other one for fixing the legs. The setup for MVIC measurements is shown in Fig. 2. In the fixed position, the subjects' task was to flex or extend the upper body with the individual maximum contraction of trunk muscles against the measuring pad on the front-/backside of the body. MVIC of each direction of movement (flexion/extension) was collected three times with 3 min of recovery in-between and the highest value of the muscle flexion and extension maximum isometric torque [Nm] was taken for the data analysis. The starting direction of the movement was randomized. The force transducers were located in the measuring pads to transfer the measured value of maximum isometric torque to the software proEMG. The measured absolute flexion and extension MVICs were adjusted to the BMI to obtain relative values.

**Fig. 2** Setup for isometric muscle strength measurements



### Reproducibility of muscle strength measurements

Roth et al [39] proofed test-retest reliability of isometric (and isokinetic) torque measurements in trunk flexion/extension using the back module of the IsoMed 2000 (D&R Ferstl) with  $n = 15$  at four different dates and stated an absolute reliability providing stable repeatability in the isometric (as well as isokinetic) condition. That result is consistent with the present verification of reproducibility by testing  $n = 3$  (33.3% women; mean age =  $29 \pm 6$  years) beforehand the two measurement visits. The three subjects performed the measurements on three consecutive days between 10:00 a.m. and 2:00 p.m. The reproducibility expressed as root mean square absolute precision error in Nm (absolute units) and as root mean square coefficients of variation (RMSCV) in percent (relative units) according to Gluer et al [38] was: 5.8 Nm and 2.8% for extension, 4.2 Nm and 3.2% for flexion, respectively.

**Table 1** Spearman correlation coefficients *r* for muscle strength measurements versus muscle PDFF and CSA

		Erector spinae muscle PDFF	psoas muscle PDFF	erector spinae muscle CSA	psoas muscle CSA
relative extension muscle strength	<i>r</i>	-0.51	n.s.	n.s.	n.s.
	<i>p</i> -value	<b>0.008</b>	0.904	0.440	0.291
relative flexion muscle strength	<i>r</i>	-0.54	n.s.	0.40	0.61
	<i>p</i> -value	<b>0.005</b>	0.628	<b>0.044</b>	<b>0.001</b>

Bold type denotes  $p < 0.05$  (statistically significant)

## Statistical analysis

Statistical analysis was performed using SPSS (SPSS Inc., Chicago, IL, USA). All tests were done using a two-sided 0.05 level of significance.

Parameters were presented as mean and standard deviation (SD). The Kolmogorov-Smirnov test indicated for the majority of parameters no normal distribution. Therefore, CSA and PDFF between males and females were compared using the Wilcoxon-Mann-Whitney test. Correlations were evaluated with the Spearman correlation coefficient *r*. Multivariate regression models were used to determine significant predictors of relative extension and flexion strength. Potential predictors (CSA and PDFF of the erector spinae and psoas muscles) were included in the regression models if the level of significance was  $p < 0.05$ .

## Results

CSA was significantly ( $p < 0.05$ ) greater in males compared to females in the erector spinae ( $33.18 \pm 8.65 \text{ cm}^2$  vs.  $23.09 \pm 5.64 \text{ cm}^2$ ;  $p = 0.004$ ) and psoas muscles ( $17.83 \pm 5.61 \text{ cm}^2$  vs.  $8.19 \pm 3.07 \text{ cm}^2$ ;  $p < 0.001$ ). PDFF was lower in males than females in the erector spinae ( $8.91 \pm 2.10\%$  vs.  $11.64 \pm 2.93\%$ ;  $p = 0.009$ ) and psoas muscles ( $4.88 \pm 1.09\%$  vs.  $5.27 \pm 1.83\%$ ;  $p = 0.446$ ). Males had greater relative muscle strength than females for flexion ( $6.33 \pm 1.28 \text{ Nm}^3/\text{kg}$  vs.  $3.51 \pm 1.06 \text{ Nm}^3/\text{kg}$ ;  $p < 0.001$ ) and extension ( $7.81 \pm 1.96 \text{ Nm}^3/\text{kg}$  vs.  $6.41 \pm 1.70 \text{ Nm}^3/\text{kg}$ ;  $p = 0.097$ ).

PDFF of the erector spinae and psoas muscles showed no significant correlation with age and BMI ( $p > 0.05$ ). CSA of the erector spinae muscles correlated significantly with BMI ( $r = 0.46$ ;  $p = 0.019$ ) but not with age ( $p > 0.05$ ). CSA of the psoas muscles did not correlate significantly either with BMI and or with age ( $p > 0.05$ ).

CSA of the erector spinae muscles correlated significantly with CSA of the psoas muscles ( $r = 0.84$ ;  $p < 0.001$ ), while PDFF of the erector spinae and psoas muscles showed no significant correlation ( $p > 0.05$ ). Relative extension strength correlated with relative flexion strength ( $r = 0.44$ ;  $p = 0.025$ ).

Spearman correlation coefficients *r* for PDFF and CSA values versus muscle strength measurements are shown in Table 1. Erector spinae CSA and relative extension strength showed no significant correlations ( $p > 0.05$ ) (Fig. 3a). Significant correlations between CSA and muscle strength measurements were observed for erector spinae muscle CSA and psoas muscle CSA with relative flexion strength (CSA of erector spinae muscles:  $r = 0.40$ ;  $p = 0.044$  (Fig. 3b); CSA of psoas muscle:  $r = 0.61$ ;  $p = 0.001$ ). Erector spinae muscle PDFF correlated significantly with relative muscle strength (extension:  $r = -0.51$ ;  $p = 0.008$  (Fig. 4a); flexion:  $r = -0.54$ ;  $p = 0.005$  (Fig. 4b)). Psoas PDFF showed no significant correlations with muscle strength measurements ( $p > 0.05$ ).

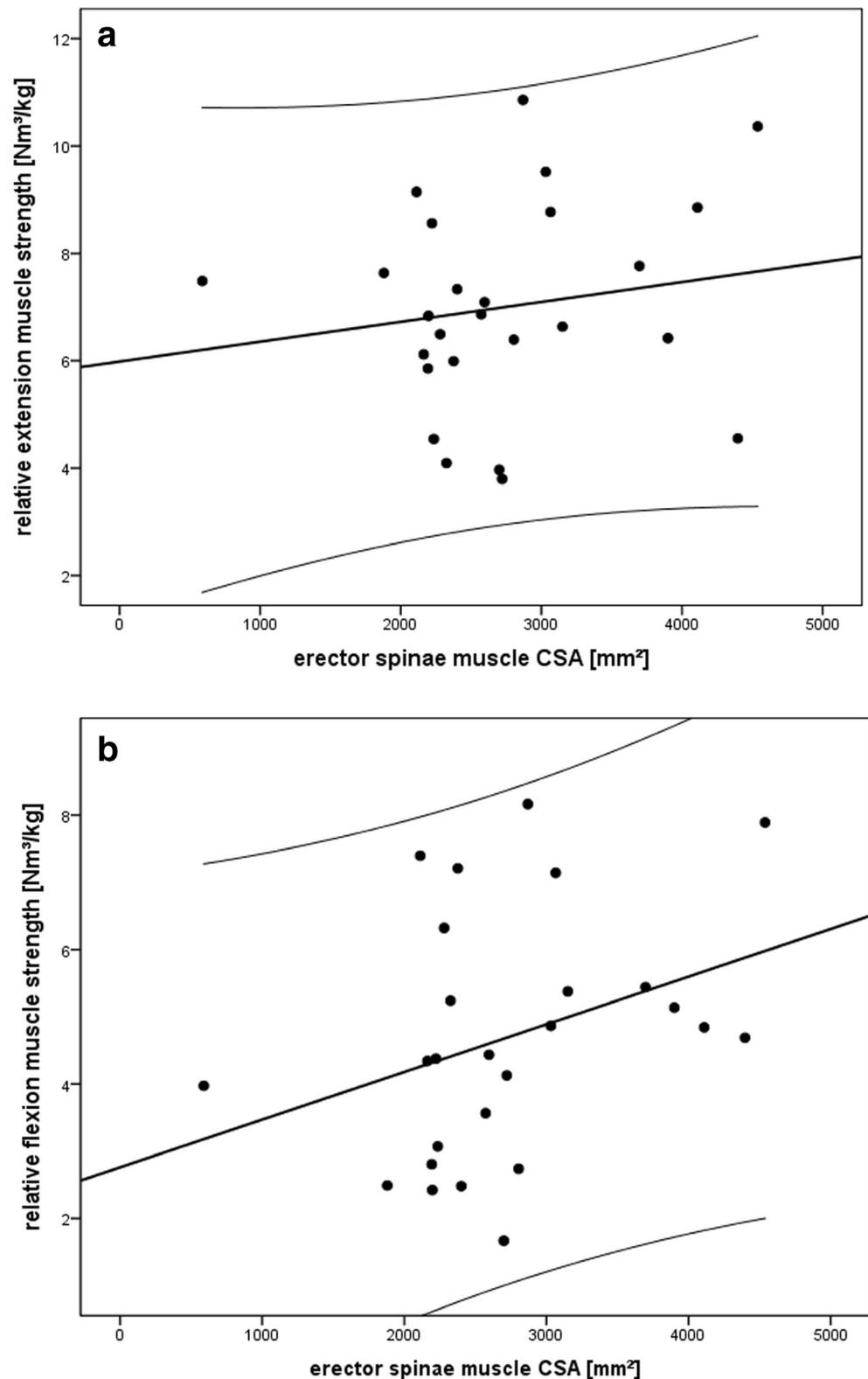
Erector spinae muscle PDFF remained the only statistically significant ( $p < 0.05$ ) predictor of relative extensor strength in multivariate regression models ( $R^2_{\text{adj}} = 0.34$ ;  $p = 0.002$ ), while psoas muscle PDFF and both erector spinae and psoas muscles CSA showed no significant contribution ( $p > 0.05$ ). Only psoas muscle CSA was included on statistically significant level in the multivariate regression model for the prediction of relative flexion strength ( $R^2_{\text{adj}} = 0.24$ ;  $p = 0.010$ ).

## Discussion

The present study showed that paraspinal muscle PDFF is a parameter significantly correlating with relative paraspinal muscle strength in healthy subjects. PDFF measurements improved the prediction of paraspinal muscle strength beyond muscle CSA. The present findings support the assumption that MFI in paraspinal muscles has a direct influence on paraspinal muscle functionality.

We observed that males had significantly greater CSA in erector spinae and psoas muscles, respectively. Males had significantly greater extension and flexion strength, whereas females had higher PDFF in erector spinae and psoas muscles, respectively. These findings are in accordance with current literature results, showing gender differences in muscle CSA [6], relating gender differences in muscle strength to differences in muscle fiber characteristics with males having primarily larger fibers [40] and showing greater MFI in female than male paraspinal muscles [6, 7].

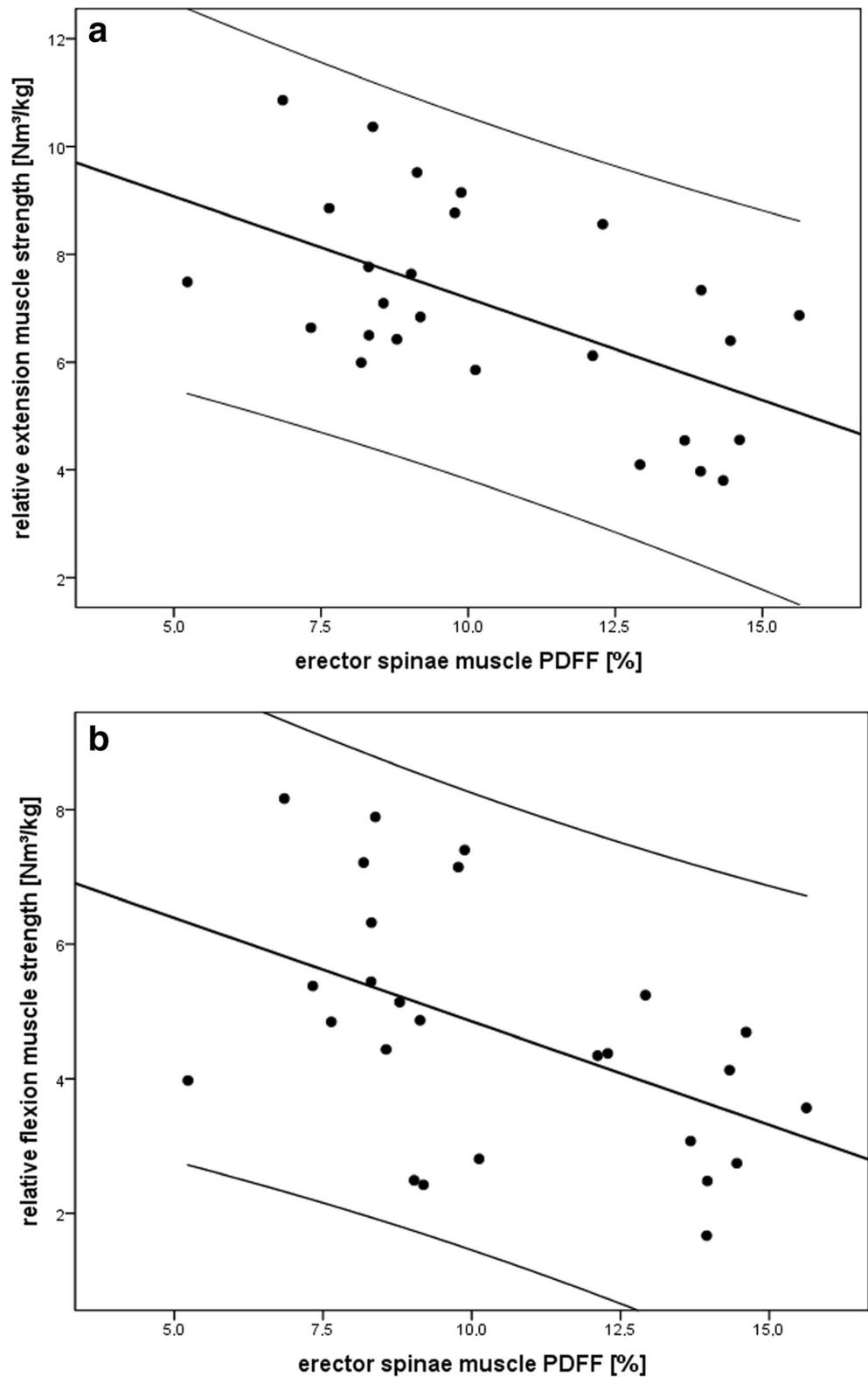
**Fig. 3** Plot of erector spinae muscle CSA versus relative extension (a) and flexion (b) muscle strength



Increasing MFI in paraspinal muscles has been investigated during aging [6, 7], LBP [10–13], whiplash-associated disorders [14] and NMD [17, 18, 23]. Hence, paraspinal MFI is increasingly seen as a surrogate marker for paraspinal muscle

health. MFI is associated with muscle weakness [30] and poorer functionality [1], in accordance with the assumption that in addition to paraspinal muscle mass the quality of the contractile muscle tissue plays an important role for stability and

**Fig. 4** Plot of erector spinae muscle PDFF versus relative extension (a) and flexion (b) muscle strength



functionality of the postural trunk muscles [7]. However, the direct impact of the replacement of contractile muscle fibers by noncontractile fatty tissue on paraspinal muscle functionality represented by muscle strength has not yet been properly

investigated, due to the relatively difficult objective, independent assessment of the paraspinal muscles in strength measurements [7]. Using an isokinetic rotational dynamometer, the present study allows the direct assessment of the association

of MFI and muscle strength of paraspinal muscles. Thereby paraspinal PDFF correlated significantly with relative extension and flexion strength, whereas CSA only correlated significantly with relative flexion strength. The relative superiority of PDFF over CSA for the prediction of paraspinal muscle extension strength is in accordance with previous studies performed in the thigh region that show a negative correlation between PDFF and muscle strength [8, 41–43] and report that muscle fat fraction rather than muscle size is correlated with knee extensor strength [44]. As PDFF is significantly correlated with relative spine extension strength as well as relative spine flexion strength, PDFF seems to be a general predictor for muscle strength. The observed correlation coefficients were moderate and may be explained by the diverse muscle components contributing to the spine extension and flexion. Muscle interaction for spine movement seems to be highly complex with erector spinae muscles not only being involved in spine extension and rotation but also spine flexion, known as the lumbar erector spinae flexion-relaxation phenomenon [45].

Determination of paraspinal MFI in the present study was based on chemical shift encoding-based water–fat MRI and is therefore one of few studies using quantitative MRI to determine the fat content of paraspinal muscles rather than conventional qualitative sequences that have been used most of the time [21]. PDFF determination based on chemical shift encoding-based water–fat MRI is a more robust and reliable technique to assess fat content than the post-acquisitional semi-quantitative analysis of conventional sequences. The superiority of PDFF compared to CSA in predicting muscle strength underlines the importance of MRI in the examination of the lumbar spine muscle region as other imaging modalities do not allow such an insight into muscle morphology. An early detection of disruptive factors on muscle integrity and muscle biomechanical functionality might be useful to early arrange counteracting individual interventions such as changes in lifestyle, adjusted training or appropriate therapeutics. Chemical shift encoding-based water–fat MRI is a fast method that can be added to a routinely performed MRI in patients with diseases affecting the spine region and is therefore a far more time efficient way to assess muscle strength than using a rarely available isokinetic dynamometer.

The present study has some limitations. Firstly, PDFF determination of erector spinae muscles was based on measurements in a ROI over a muscle group. The segmentation masks grouped the lumbar erector spinae muscles, consisting of multifidus, longissimus thoracis and iliocostalis lumborum muscle. Therefore, both inter- and intramuscular fat contribute to the obtained PDFF values. However, the erector spinae muscles act as one functional unit not allowing determination of the contribution of the individual muscles to muscle strength. Furthermore, the amount of intermuscular fat in the present cohort was marginal and no remarkable interindividual difference was observed.

Secondly, the performed muscle strength measurement might not only examine the targeted muscle groups. Although using an isokinetic dynamometer particularly built to measure muscle strength of the back extension and flexion, the body movements are a result of different antagonizing muscles. The major muscles for back extension are the erector spinae muscles, whereas the psoas muscle has an important effect on back flexion. However, as the psoas muscle is the main hip flexor of the body, its influence on inclination of the lumbar spine is less prominent and therefore could explain why psoas muscle PDFF was not significantly correlation with muscle strength during back movement. PDFF measurements of abdominal muscles as the main muscle contributor for flexion were not possible due to breathing artefacts in the free-breathing MRI acquisition that was carried out.

Thirdly, only young subjects with relatively low muscle PDFF were examined in the study. Therefore, the study lacks the evaluation of fat content in aging muscles, which might correlate differently due to other factors influencing muscle strength in aging muscles. However, despite the small variance in fat fraction between the subjects, a significant correlation between PDFF and muscle strength could be observed. The association of PDFF and muscle strength even in muscles with relatively low fat content suggests that small changes in muscle fat content already have a detectable impact on muscle biomechanical functionality.

In the future, studies examining patients with NMD or LBP need to be performed to objectively investigate the association of PDFF with muscle strength in muscles with higher fat fractions. Additionally, training effects on muscle PDFF and muscle strength could be examined in a longitudinal study scanning subjects before and after training. To implement PDFF determination during clinical routine a fast and robust way of automatic muscle segmentation has to be developed.

In conclusion, water–fat MRI measurements of the paraspinal muscles correlates with muscle strength and may be advantageous compared to muscle CSA measurements. Assessment of paraspinal MFI using MRI may be important to detect muscular changes at the beginning of a disease process, thus allowing an early therapy initiation.

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## Compliance with ethical standards

**Guarantor** The scientific guarantor of this publication is Thomas Baum, MD.

**Conflict of interest** The authors of this manuscript declare relationships with the following companies: Philips Healthcare.

**Statistics and biometry** No complex statistical methods were necessary for this paper.

**Informed consent** Written informed consent was obtained from all subjects in this study.

**Ethical approval** Institutional Review Board approval was obtained.

#### Methodology

- Prospective
- Cross-sectional study
- Performed at one institution

## References

- Hicks GE, Simonsick EM, Harris TB et al (2005) Cross-sectional associations between trunk muscle composition, back pain, and physical function in the health, aging and body composition study. *J Gerontol A Biol Sci Med Sci* 60:882–887
- Fisher MJ, Meyer RA, Adams GR, Foley JM, Potchen EJ (1990) Direct relationship between proton T2 and exercise intensity in skeletal muscle MR images. *Invest Radiol* 25:480–485
- Shellock FG, Fukunaga T, Mink JH, Edgerton VR (1991) Acute effects of exercise on MR imaging of skeletal muscle: concentric vs eccentric actions. *AJR Am J Roentgenol* 156:765–768
- Takahashi H, Kuno S, Miyamoto T et al (1994) Changes in magnetic resonance images in human skeletal muscle after eccentric exercise. *Eur J Appl Physiol Occup Physiol* 69:408–413
- Mendez-Villanueva A, Suarez-Arrones L, Rodas G et al (2016) MRI-Based Regional Muscle Use during Hamstring Strengthening Exercises in Elite Soccer Players. *PLoS One* 11: e0161356
- Crawford RJ, Filli L, Elliott JM et al (2016) Age- and Level-Dependence of Fatty Infiltration in Lumbar Paravertebral Muscles of Healthy Volunteers. *AJNR Am J Neuroradiol* 37:742–748
- Dahlqvist JR, Vissing CR, Hedermann G, Thomsen C, Vissing J (2017) Fat Replacement of Paraspinal Muscles with Aging in Healthy Adults. *Med Sci Sports Exerc* 49:595–601
- Heymsfield SB, Gonzalez MC, Lu J, Jia G, Zheng J (2015) Skeletal muscle mass and quality: evolution of modern measurement concepts in the context of sarcopenia. *Proc Nutr Soc* 74:355–366
- Karampinos DC, Baum T, Nardo L et al (2012) Characterization of the regional distribution of skeletal muscle adipose tissue in type 2 diabetes using chemical shift-based water/fat separation. *J Magn Reson Imaging* 35:899–907
- Kjaer P, Bendix T, Sorensen JS, Korsholm L, Leboeuf-Yde C (2007) Are MRI-defined fat infiltrations in the multifidus muscles associated with low back pain? *BMC Med* 5:2–2
- Teichtahl AJ, Urquhart DM, Wang Y et al (2015) Fat infiltration of paraspinal muscles is associated with low back pain, disability, and structural abnormalities in community-based adults. *Spine J* 15: 1593–1601
- D'Hooge R, Cagnie B, Crombez G, Vanderstraeten G, Dolphens M, Danneels L (2012) Increased intramuscular fatty infiltration without differences in lumbar muscle cross-sectional area during remission of unilateral recurrent low back pain. *Man Ther* 17:584–588
- Fischer MA, Nanz D, Shimakawa A et al (2013) Quantification of muscle fat in patients with low back pain: comparison of multi-echo MR imaging with single-voxel MR spectroscopy. *Radiology* 266: 555–563
- Elliott JM, Courtney DM, Rademaker A, Pinto D, Sterling MM, Parrish TB (2015) The Rapid and Progressive Degeneration of the Cervical Multifidus in Whiplash: An MRI Study of Fatty Infiltration. *Spine (Phila Pa 1976)* 40:E694–E700
- Maly MR, Calder KM, Macintyre NJ, Beattie KA (2013) Relationship of intermuscular fat volume in the thigh with knee extensor strength and physical performance in women at risk of or with knee osteoarthritis. *Arthritis Care Res (Hoboken)* 65:44–52
- Sun D, Liu P, Cheng J, Ma Z, Liu J, Qin T (2017) Correlation between intervertebral disc degeneration, paraspinal muscle atrophy, and lumbar facet joints degeneration in patients with lumbar disc herniation. *BMC Musculoskelet Disord* 18:167
- Janssen BH, Voet NBM, Nabuurs CI et al (2014) Distinct Disease Phases in Muscles of Facioscapulohumeral Dystrophy Patients Identified by MR Detected Fat Infiltration. *PLoS One* 9:e85416
- Dahlqvist JR, Vissing CR, Thomsen C, Vissing J (2014) Severe paraspinal muscle involvement in facioscapulohumeral muscular dystrophy. *Neurology* 83:1178–1183
- D'Aprile P, Tarantino A, Jinkins JR, Brindicci D (2007) The value of fat saturation sequences and contrast medium administration in MRI of degenerative disease of the posterior/perispinal elements of the lumbosacral spine. *Eur Radiol* 17:523–531
- Kumar Y, Hayashi D (2016) Role of magnetic resonance imaging in acute spinal trauma: a pictorial review. *BMC Musculoskelet Disord* 17:310
- Crawford RJ, Cornwall J, Abbott R, Elliott JM (2017) Manually defining regions of interest when quantifying paravertebral muscles fatty infiltration from axial magnetic resonance imaging: a proposed method for the lumbar spine with anatomical cross-reference. *BMC Musculoskelet Disord* 18:25
- Smith AC, Parrish TB, Abbott R et al (2014) Muscle-fat MRI: 1.5 Tesla and 3.0 Tesla versus histology. *Muscle Nerve* 50:170–176
- Hadar H, Gadoth N, Heifetz M (1983) Fatty replacement of lower paraspinal muscles: normal and neuromuscular disorders. *AJR Am J Roentgenol* 141:895–898
- Doherty TJ (2003) Invited review: Aging and sarcopenia. *J Appl Physiol* (1985) 95:1717–1727
- Fortin M, Macedo LG (2013) Multifidus and paraspinal muscle group cross-sectional areas of patients with low back pain and control patients: a systematic review with a focus on blinding. *Phys Ther* 93:873–888
- Fortin M, Videman T, Gibbons LE, Battie MC (2014) Paraspinal muscle morphology and composition: a 15-yr longitudinal magnetic resonance imaging study. *Med Sci Sports Exerc* 46:893–901
- Valentin S, Licka T, Elliott J (2015) Age and side-related morphometric MRI evaluation of trunk muscles in people without back pain. *Man Ther* 20:90–95
- Fortin M, Yuan Y, Battie MC (2013) Factors Associated With Paraspinal Muscle Asymmetry in Size and Composition in a General Population Sample of Men. *Phys Ther* 93:1540–1550
- Shahidi B, Parra CL, Berry DB et al (2017) Contribution of Lumbar Spine Pathology and Age to Paraspinal Muscle Size and Fatty Infiltration. *Spine (Phila Pa 1976)* 42:616–623
- Goodpaster BH, Carlson CL, Visser M et al (2001) Attenuation of skeletal muscle and strength in the elderly: The Health ABC Study. *J Appl Physiol* (1985) 90:2157–2165
- Goodpaster BH, Park SW, Harris TB et al (2006) The loss of skeletal muscle strength, mass, and quality in older adults: the health, aging and body composition study. *J Gerontol A Biol Sci Med Sci* 61:1059–1064
- Baum T, Inhuber S, Dieckmeyer M et al (2016) Association of quadriceps muscle fat with isometric strength measurements in healthy males using chemical shift encoding-based water-fat magnetic resonance imaging. *J Comput Assist Tomogr* 40:447–451
- Stark T, Walker B, Phillips JK, Fejer R, Beck R (2011) Hand-held dynamometry correlation with the gold standard isokinetic dynamometry: a systematic review. *Pm r* 3:472–479
- Moreau CE, Green BN, Johnson CD, Moreau SR (2001) Isometric back extension endurance tests: a review of the literature. *J Manipulative Physiol Ther* 24:110–122
- Guedes DP, Lopes CC, Guedes JERP (2005) Reprodutibilidade e validade do Questionário Internacional de Atividade Física em

- adolescentes. *Revista Brasileira de Medicina do Esporte* 11:151–158
36. Kurtze N, Rangul V, Hustvedt BE (2008) Reliability and validity of the international physical activity questionnaire in the Nord-Trøndelag health study (HUNT) population of men. *BMC Med Res Methodol* 8:63
  37. Karampinos DC, Yu H, Shimakawa A, Link TM, Majumdar S (2011) T<sub>1</sub>-corrected fat quantification using chemical shift-based water/fat separation: application to skeletal muscle. *Magn Reson Med* 66:1312–1326
  38. Gluer CC, Blake G, Lu Y, Blunt BA, Jergas M, Genant HK (1995) Accurate assessment of precision errors: how to measure the reproducibility of bone densitometry techniques. *Osteoporos Int* 5:262–270
  39. Roth R, Donath L, Kurz E, Zahner L, Faude O (2017) Absolute and relative reliability of isokinetic and isometric trunk strength testing using the IsoMed-2000 dynamometer. *Phys Ther Sport* 24:26–31
  40. Miller AEJ, MacDougall JD, Tarnopolsky MA, Sale DG (1993) Gender differences in strength and muscle fiber characteristics. *Eur J Appl Physiol Occup Physiol* 66:254–262
  41. Horvath JJ, Austin SL, Case LE et al (2015) Correlation between quantitative whole-body muscle magnetic resonance imaging and clinical muscle weakness in pompe disease. *Muscle Nerve* 51:722–730
  42. Willis TA, Hollingsworth KG, Coombs A et al (2013) Quantitative Muscle MRI as an Assessment Tool for Monitoring Disease Progression in LGMD2I: A Multicentre Longitudinal Study. *PLoS One* 8:e70993
  43. Willis TA, Hollingsworth KG, Coombs A et al (2014) Quantitative Magnetic Resonance Imaging in Limb-Girdle Muscular Dystrophy 2I: A Multinational Cross-Sectional Study. *PLoS One* 9:e90377
  44. Kumar D, Karampinos DC, MacLeod TD et al (2014) Quadriceps intramuscular fat fraction rather than muscle size is associated with knee osteoarthritis. *Osteoarthritis Cartilage* 22:226–234
  45. Colloca CJ, Hinrichs RN (2005) The biomechanical and clinical significance of the lumbar erector spinae flexion-relaxation phenomenon: a review of literature. *J Manipulative Physiol Ther* 28: 623–631