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DIAGNOSTICS

Normalization of Spinal Cord Displacement With the Straight Leg Raise and Resolution of Sciatica in Patients With Lumbar Intervertebral Disc Herniation

A 1.5-year Follow-up Study

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Study Design. A controlled radiologic follow-up study.

Objective. The aim of this study was to ascertain whether changes in cord excursion with straight leg raise test (SLR) at 1.5-year follow-up time accompany changes in clinical symptoms.

Summary of Background Data. Lumbar intervertebral disc herniation (LIDH) is known to be a key cause of sciatica. Previously, we found that a significant limitation of neural displacement (66.6%) was evident with the SLR on the symptomatic side of patients with subacute single level posterolateral LIDH.

Methods. Fourteen patients with significant sciatic symptoms due to a subacute single-level posterolateral LIDH were reassessed clinically and radiologically at 1.5 years follow-up with a 1.5T MRI scanner. Displacement of the conus medullaris during the unilateral and bilateral SLR was quantified reliably with a randomized procedure and compared between SLRs and to data from baseline. Multivariate regression models and backward variable selection method were employed to identify variables more strongly associated with a decrease in low back pain (LBP) and radicular symptoms.

Results. Compared with previously presented baseline values, the data showed a significant increase in neural sliding in all the quantified maneuvers ($P \leq 0.01$), and particularly of 2.52 mm ($P \leq 0.001$) with the symptomatic SLR.

Increase in neural sliding correlated significantly with decrease of both radicular symptoms (Pearson = -0.719, $P \leq 0.001$) and LBP (Pearson = -0.693, $P \leq 0.001$). Multivariate regression models and backward variable selection method confirmed the improvement of neural sliding effects ($P \leq 0.004$) as the main variable being associated with improvement of self-reported clinical symptoms.

Conclusion. To our knowledge, these are the first noninvasive data to objectively support the association between increase in magnitude of neural adaptive movement and resolution of both radicular and LBP symptoms in *in vivo* and structurally intact human subjects.

Key words: intervertebral disc herniation, low back pain, radiculopathy, spinal cord, straight leg raise.

Level of Evidence: 2

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Sciatica is defined as pain radiating from the buttock distally in the lower limb in the distribution of the sciatic nerve. Even though lumbar intervertebral disc herniation (LIDH) can be asymptomatic,[1,2] it remains the leading cause of sciatica, being responsible for 85% to 90% of cases.[3,4] The segments L4–5 and L5-S1 are the most commonly affected,[1,2] which is highly relevant to sciatica on account of the related nerve roots being contiguous the sciatic nerve.

The straight leg raise test (SLR) is a standard physical test employed worldwide in diagnosis of sciatica due to LIDH. In isolation, the test is insufficient to make a diagnosis and shows high sensitivity with heterogeneous specificity.[5–7] This necessitates that novel in-depth knowledge of the neural biomechanics underpinning the SLR is provided in order to better aid interpretation of the test.

Using previously published methods of measurement of spinal cord displacement with the SLR, Rade *et al*[8] established normal multiplanar spinal cord movement with the SLR showing that the direction of such displacement can be predicted following rules of Euclidean geometry applied to Euclidean vectors. It is apparent that the conus medullaris consistently moves in a caudal direction, although less than the nerve roots in their intervertebral foramen, primarily due to direct transmission of forces through the lumbosacral nerve roots and associated dura mater.[9–13] Moreover, significant limitation of neural movement with the symptomatic SLR was found to occur in subacute patients on active sick leave due to single-level posterolateral LIDH. Specifically, the SLR on the symptomatic side produced less conus movement compared with the same SLR on the contralateral asymptomatic side (0.76 *vs*. 2.33 mm) and with previous studies on asymptomatic subjects with the same methods (3.5 mm).[14] These findings clarified the SLR as a useful tool in assessment of neuromechanical impairment in patients with sciatica from the nerve root.

Knowing that nerve root excursion has been shown to be impaired in patients with LIDH during intraoperative investigations[15] and this reduction also appears to be expressed in the conus medullaris in patients with LIDH, we have now followed up the same patients in our previous study[14] over 1.5 years to ascertain whether changes in cord excursion accompany changes in clinical symptoms. The purpose was to investigate whether there is a relationship between symptomatology and reduction of neural movement in patients with symptomatic radiculopathy and to see if that relationship remains intact in people who recover.

MATERIALS AND METHODS

Subjects and Clinical Follow-up Procedure

At baseline, study volunteers were collected from patients referred from primary health care centers and occupational doctors' offices to Kuopio University Hospital (KUH) Spine Centre (approximately 2500 referrals per year) for a specialist's consultation regarding severe low back pain (LBP). Of those, patients with subacute (3–8 weeks) sciatic symptoms with no known confounding factors (summarized in Table 1; exclusion criteria) were collected from the preliminary data available at referral and invited for clinical evaluation by a spine specialist (JP). A thorough clinical evaluation was performed for exclusion and inclusion criteria (Table 1), and to confirm that all patients were on active sick leave due to disabling LBP. As data from symptomatic SLRs were compared with contralateral, asymptomatic, SLR and normal cases previously published,[9–11] the contralateral SLR was assessed to be fully asymptomatic and the LIDH only single-level with strictly posterolateral direction impinging on only one nerve root (Figure 1). Moreover, as the amount of conus displacement with unilateral and bilateral SLRs has been shown to be significantly correlated with amount of hip flexion during SLRs,[12] patients selected for the study were required to present with an abnormal SLR between 45° and 70° of hip flexion. This was in order to allow for comparison of conus medullaris displacement with normal data now available in the literature, in which the same methods with the SLR and measurement of conus displacement were used.[9–11] An additional reason not to include acute patients was that acute patients possibly would not be able to tolerate an SLR position for the whole duration of the MR 3D spc scanning sequence (4 minutes and 14 seconds for each maneuver) without producing pain-mediated movement artefacts, as well as ethical concerns.

TABLE 1. Exclusion and Inclusion Criteria at Baseline

Exclusion Criteria
• Multisegmental or posterocentral LIDH verified to exist at MRI • Incomplete and/or painful knee extension • Incomplete and/or painful hip range of motion • History of previous lumbar surgeries • Other joint involvement, such as arthritis or already recognized metabolic bone disease • No clear signs of sciatic radiculopathy in anamnesis and at clinical examination • Clinical and/or radiological signs of lumbar spinal stenosis Presence of pacemakers and ferromagnetic implants • Sciatic radiculopathy with SLR abnormal over 70° or under 45° of hip flexion
Inclusion Criteria
Subjects with sciatica with segmental posterolateral LIDH verified to exist at MRI. • Subjects' consent to participate • No present exclusion criteria at the time of testing • Patient on sick leave due to heavy and disabling low back pain with proven radiculopathy • SLR "abnormal" at 45°–70° of hip flexion

Of those, 42 patients with proven typical clinical findings for unilateral radiculopathy due to LIDH and matching the inclusion criteria were referred for diagnostic MRI with standard T1 and T2 sagittal sequences and T2 axial sequences. Upon confirmation of single-level posterolateral L4–5 or L5-S1 LIDH by a medical radiologist (JM, RV), patients were included in the experimental protocol. Importantly, both diagnostic MRI and experimental MRI protocols were conducted within a week of the clinical assessment in order to minimize possible confounding factors including physiologic healing processes that can occur with time. The eligible subjects who declined to participate (from both the initial 186 and the 42 referred to MRI) made their decision upon knowledge that the scanning time will be available outside regular working hours of the Radiology department of KUH

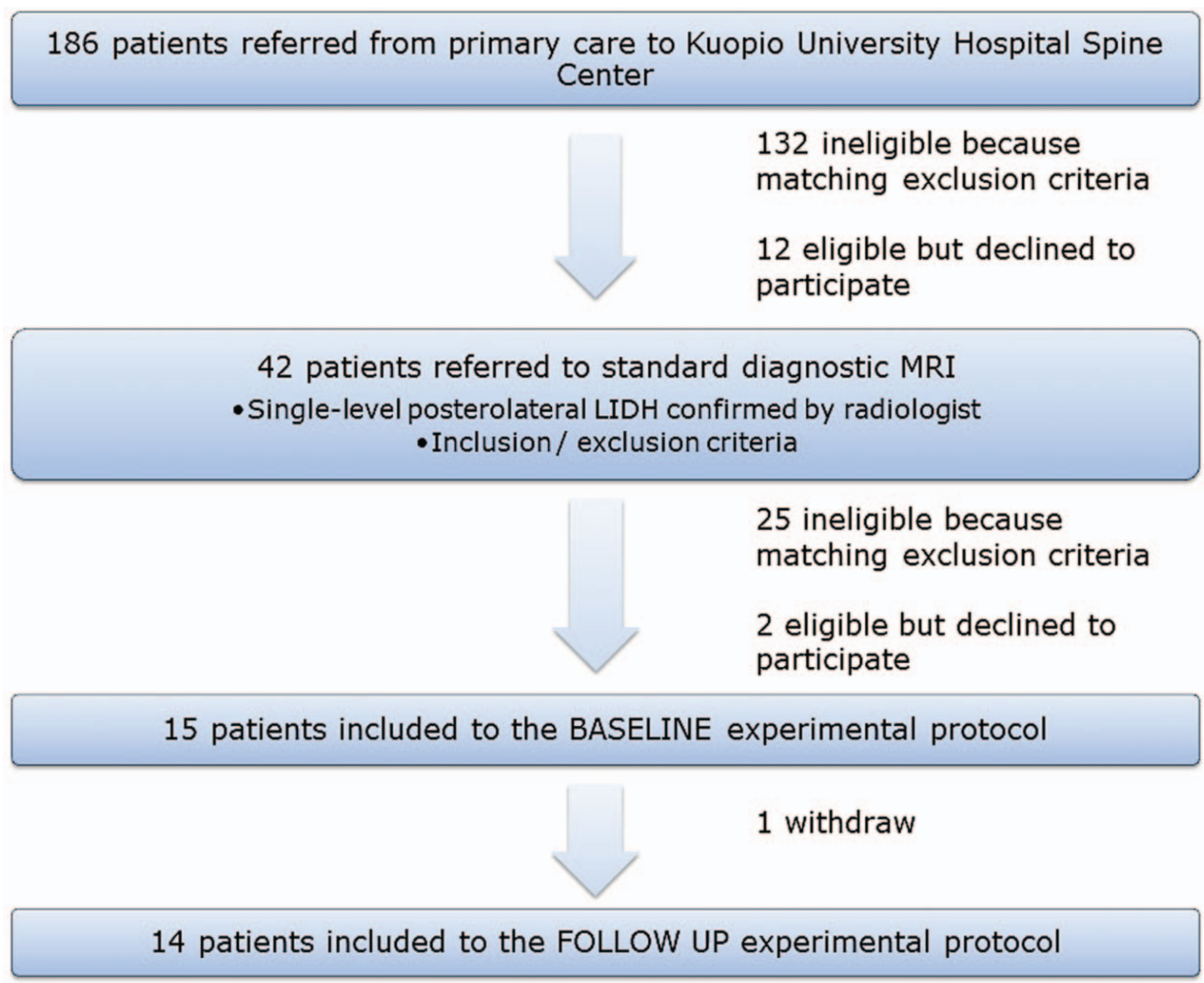

Figure 1. Flow chart showing the patients selection process.

(late in the evening or weekends) and that the whole scanning protocol along with patients' preparation and information process will last for at least 1.5 hours. Also, one patient withdrew from the study at follow-up due to change in place of residence outside the country. A flow chart showing the patients selection process is presented in Figure 2A,B. Finally, 15 symptomatic volunteers ranged from 23 to 58 years [mean age 36.87 ± 9.26 years, height 178.6 ± 8.6 cm, body mass index (BMI) 26.09 ± 3.78, visual analog scale (VAS) 63.93 ± 6.19], and who met all the inclusion criteria (Table 1) were included in the study.

On follow-up, patients were readmitted for a follow-up visit to a spine specialist (JP) after 1.5 years from the baseline (BL) measurements. Clinical history was taken with a special focus on whether patients still experienced pain and radicular symptoms. A clinical examination for back pain including neurological assessment (SLR, reflexes, skin sensation, motor strength) for the lower extremity was performed. In order to assess changes relative to the previously, LIDH diagnostic lumbar MRI was taken before the experimental protocol. The scans were analyzed by a medical musculoskeletal radiologist (RV) and a spine specialist (JP). The entire follow-up procedure was completed within the same day. Characteristics of the tested sample are summarized in Table 2.

All aspects of work that involved human patients was conducted with the ethical approval of the Research Ethical Committee of KUH, approval number 79/2012. All tested subjects signed an informed consent form and the study was performed in accordance with the Declaration of Helsinki.

EXPERIMENTAL PROTOCOL

Devices

The experimental protocol was identical to our previous studies.[9–11,14] Patients were positioned supine in a 1.5T magnetic resonance scanner (Siemens Magnetom Aera, Erlangen, Germany). The imaging area was centered on the lower part of the imaging area to T12-L2 anatomic region. The subjects were scanned using a 32-channel spine matrix coil.[14]

Different scanning sequences for planning and for measurement purposes were used:

(1) Planning: T2-weighted turbo spin echo sequence (TR 3530 ms, TE 96 ms, 17 slices, slice thickness 3 mm,

Figure 2. Passive unilateral SLR (**A**) and bilateral SLR (**B**) with subject lying supine in the magnetic resonance scanner. Adapted with permission from Rade *et al*.[11]

FOV 300 mm, in plane resolution 0.8 x 0.8 mm, flip angle 150°). Sagittal slices were aligned with the spinal cord to allow better identification of the conus medullaris.

(2) Measurement: T2-weighted spc 3D-sequence (TR 1800 ms, TE 128 ms, slice thickness 1 mm, sagittal scan, FOV 300 mm, phase encoding direction proximal to caudal, in plane resolution 0.6 x 0.6 mm, flip angle 160°).

Coronal, axial, and sagittal slices (slice thickness 0.5–1 mm, approximately 70 slices in each plane) were reconstructed from the native T2-weighted spc 3D-sequence sagittal scans using the MPR program available in Sectra PACS workstation (Sectra Workstation IDS7, version 19.1.10.3584–2017–Sectra AB, Sweden).

Subject Positioning and Test Movements

We explored if a difference had occurred between the decreased conus medullaris movement found on the baseline study[14] and the current follow-up study. The patients were tested on four different positions with the amount of hip flexion having been determined by pre-scan SLR tests on the symptomatic and asymptomatic side: neutral (*i.e.*, lying supine in the anatomic position), SLR on the previously symptomatic side (SYM SLR), SLR on the asymptomatic or contralateral side (ASYM SLR), and bilateral SLR (Figure 2).

Throughout the whole study, four investigators performed the maneuvers in a random order to avoid possible series effects. Each movement was performed twice for evaluation of reproducibility. Before the measurements, the maximum achievable hip flexion within MRI device [54.6 ± 3.7° (mean ± SD)] was measured with an oil-filled precision goniometer placed on the anterior surface of the distal third of the tibia and recorded. Importantly, in order for the conus displacement to be regarded as a dependent variable, inside the MRI scanner, patients were tested at the same degree of hip flexion on baseline and follow-up. The head and neck were aligned and positioned in a neutral position with a standard cushion for baseline and follow-up so that cervical flexion was always avoided. Ankle position during SLR performance was kept in a neutral position.

Conus Medullaris Displacement Measurement

Both measurements and image reconstructions protocols have remained constant throughout the current line of research[8–14]: First, the tip was initially identified on the coronal slices and its position concurrently verified on the axial and sagittal slices using the crosshair and localizer tools available in Sectra PACS workstation. Particular care was taken to identify the origin of filum terminale so as to confirm the location of the tip of the conus (Figure 3). After the exact location of the tip of the medullar cone was identified, it was then projected at the center of the adjacent vertebral body by using the crosshair and localizer tools available in Sectra PACS program (Sectra Workstation IDS7, version 15.1.8.5-2013 – Sectra AB, Sweden). As previously described,[9–11,14] the distance between the mark on the vertebral body and the anatomical reference point represented by the upper intervertebral surface of the adjacent vertebra was measured on the coronal slices and data compared between different maneuvers.

From native experimental scans, reconstructions and measurements were performed twice without previous knowledge of the maneuver being analyzed. A duration

TABLE 2. Subject Demographics

Subject	Sex	Age, y	Height, cm	Weight, kg	Increment in SLR SYM in Clinical Settings (Degrees of HF)	Increase in Neural Sliding, mm	Improvement VAS LBP, mm	Improvement VAS Radicular, mm	Herniation Type at FU	Therapy
1	M	23	189	88	0	2.28	70	60	Extruded*	Conservative
2	M	32	180	78	30	2.58	80	70	None	Conservative
3	F	36	173	73	40	2.68	80	35	Bulging*	Surgical
4	M	40	171	100	30	1.62	70	80	Bulging*	Conservative
5	M	42	188	95	5	1.67	50	50	Extruded*	Surgical
6	M	45	188	118	20	3.72	10	15	None	Conservative
7	F	35	163	79	10	1.93	70	30	None	Conservative
8	M	58	185	80	5	1.43	55	40	Extruded*	Conservative
9	M	46	186	90	20	1.90	40	40	None	Conservative
10	M	41	185	92	30	5.52	70	70	Extruded*	Conservative
11	F	33	173	69	25	3.00	30	45	None	Conservative
12	F	24	164	73	30	2.70	60	50	None	Surgical
13	M	26	182	72	45	2.18	60	35	Bulging*	Conservative
14	M	32	174	71	30	2.22	40	75	Bulging*	Conservative

Subject number 9 withdrew from the study.

**Interestingly, and regardless of the type of therapy, on follow-up, eight patients still had LIDH-related findings in their new diagnostic MRI-scans (four bulging discs and four extruded discs).*

BL indicates baseline; FU, follow-up; HF, hip flexion; Increment in SLR SYM in clinical settings, difference in degrees of hip flexion during straight leg raise test performed on the previously symptomatic limb in clinical settings on baseline and follow-up; LBP, low back pain; VAS, visual analog scale.

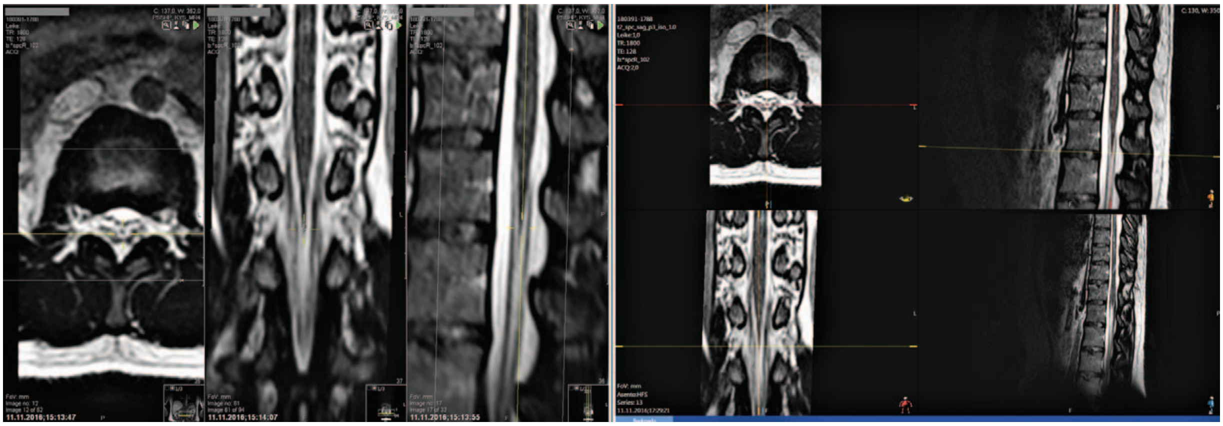

Figure 3. Marking process. Two observers independently assessed the conus displacement by first identifying the tip of the conus. The tip was initially identified on the coronal slices and its position concurrently verified on the axial and sagittal slices using the crosshair and localizer tools available in Sectra PACS workstation and MPR extension.

of 3 months occurred between each measurement in order to allow for more reliable evaluation of intra- and interobserver reliability. Every step in the reconstruction, conus identification, and measurement process was done independently between two observers (MR and JM) with the same image-viewing program in Sectra PACS workstation (Sectra Workstation IDS7, version 19.1.10.3584 - 2017 – Sectra AB, Sweden).

In an effort to provide more conservative and reliable data, all the presented metric *values were truncated* to the next *lowest* decimal value (*i.e.*, 3.55 = 3.5).

Statistical Methods

We analyzed the data to detect possible statistically significant differences in medullar cone position between the reference and tested maneuvers in follow-up measurements, comparing those to baseline measurements and normal data from previous experiments. A two-tailed hypothesis that the conus would displace in response to SLRs *versus* no change was tested. Intraclass correlation coefficients between the displacements found in two scans of the same maneuvers performed on each subject was calculated as well as for inter- and intraobserver reliability using Cohen kappa statistics.

Having found a strong correlation between the measures from different scans of the same maneuvers performed on each subject on follow-up, as well as high correlations between different measurements performed by different observers on those scans, it was decided to average all the available measurements when presenting the mean values and their standard deviations, in order to present the results as accurately and conservatively as possible. Confidence intervals (95% CI) were estimated for the effect estimates. The effect size was calculated dividing the mean value by the Cohen *d* value, as suggested by Lakens.[16] The observed power was calculated on the data using *t*-distribution, while the minimum number of subjects needed to achieve statistically significant results was calculated from the collected data. Shapiro-Wilk test was used to test the assumption of normality of continuous variables. After finding that continuous variables were normally distributed, and considering repetitiveness of the measurements, paired Student *t* test was used to test the significance of medullar displacement with SLR maneuvers in relation to the position found in the reference scans in both baseline and follow-up.

Linear regression models were applied with backward variable selection to find multivariate associations between response variable magnitude of clinical symptoms (VAS for radicular pain and for LBP) and covariates sex (male/female), age, height, weight, herniation type (extruded/sequester), degrees of hip flexion during clinical SLR, and amount of neural displacement in the spinal canal.

Statistical analysis was performed using R Program (R Foundation for Statistical Computing, Vienna, Austria), Version 2.15.2 (2012). The significance level was set at $P < 0.05$.

RESULTS

During the 1.5-year follow-up time, 11 patients were treated conservatively and 3 operatively. Of these patients, eight still had LIDH-related findings in their new diagnostic MRI-scans (four bulging discs and four extruded discs) (Table 2).

At 1.5-year follow-up, the conus medullaris displaced caudally with the asymptomatic SLR by 3.13 ± 1.1 mm (mean $\pm$ SD), $P \leq 0.001$; 3.23 ± 1.25 mm with the symptomatic SLR $P \leq 0.001$; and 4.90 ± 1.73 mm with the bilateral SLR, $P \leq 0.001$. This translates into an increase in neural sliding in all the quantified maneuvers, and particularly of 2.52 mm ($P \leq 0.001$) with the symptomatic SLR. Also, an increase of 0.82 mm ($P = 0.006$) was observed with asymptomatic (contralateral) SLR, and 1.64 mm ($P \leq 0.001$) with the bilateral SLR. Comparison between symptomatic and asymptomatic SLR in those followed-up over the 1.5 years did not show statistically significant difference ($P = 0.573$), being now regarded as normal (Figure 4A–F).

We found a strong correlation between magnitude of symptoms and reduction of neural sliding, such that improvement of neural sliding strongly correlated with a

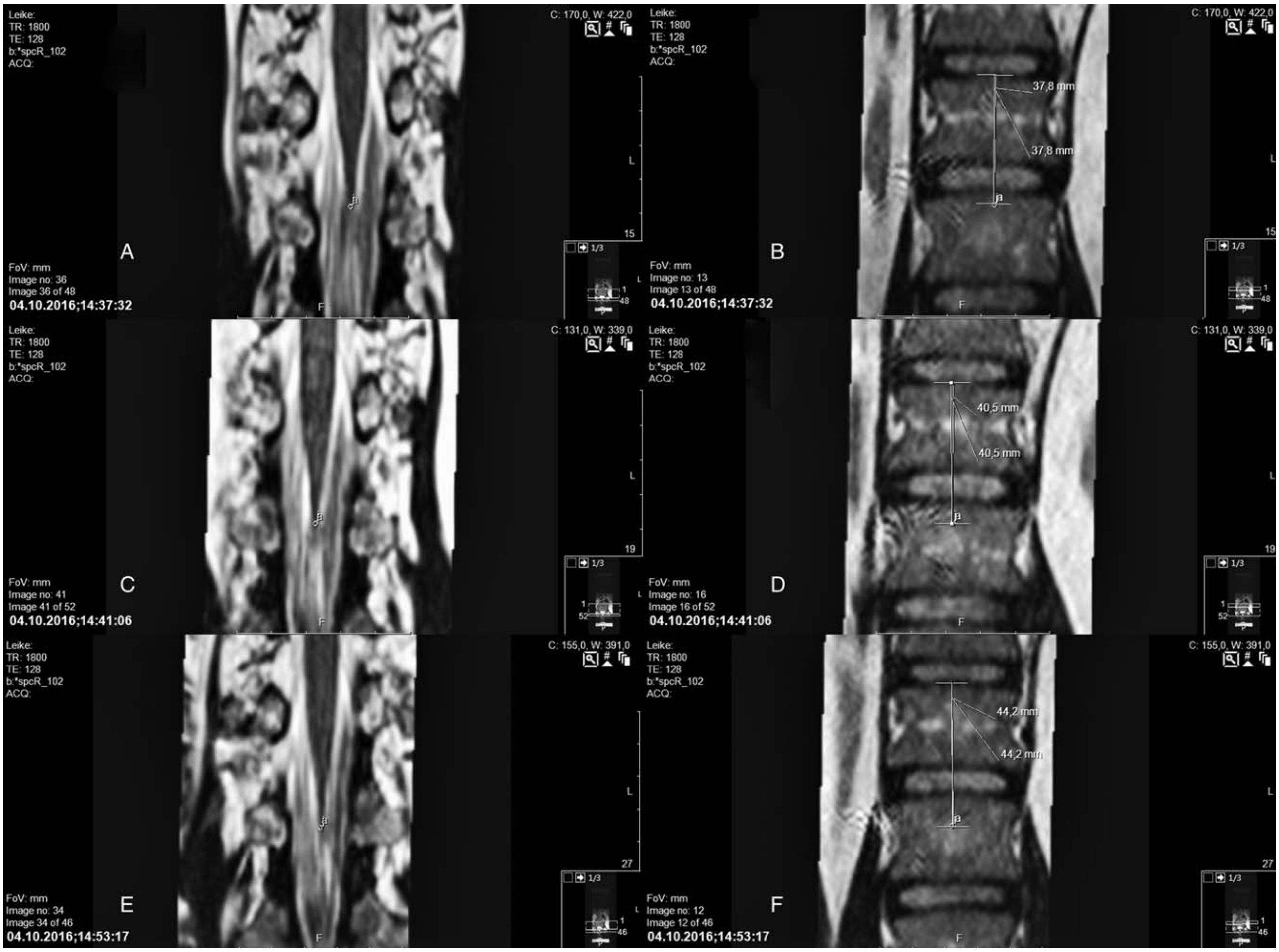

Figure 4. Magnetic resonance scans. Coronal slices of the thoracolumbar region of a sample subject during (**A**) reference scan, (**C**) unilateral SLR, (**E**) bilateral SLR are presented. The apex of the conus medullaris is marked. The vertical distances from the upper vertebral endplate of the adjacent vertebral body are marked and presented in **B** (distance between medullar cone and upper intervertebral surface of the adjacent vertebra of adjacent vertebra = 37.8 mm), **D** (distance between medullar cone and upper intervertebral surface of the adjacent vertebra of adjacent vertebra = 40.5 mm), and **F** (distance between medullar cone and upper intervertebral surface of the adjacent vertebra of adjacent vertebra = 44.2 mm). Unprocessed original images from a single patient are presented here. Measurements from both examiners are shown to demonstrate a significant level of inter-rater reproducibility.

decrease of radicular symptoms [{VAS at baseline 64.6 ± 9.7 mm (mean ± STD) and VAS at follow-up 15.0 ± 15.2 mm}, Pearson correlation = -0.72, $P \leq 0.001$] and LBP (VAS at baseline 75.0 ± 7.3 mm, and VAS at follow-up 18.9 ± 19.4 mm, Pearson = -0.693, $P \leq 0.001$) (Figure 5A–C).

Multivariable linear regression models indicated significant association between herniation type (sequestered, extruded), increase of hip flexion amount with SLR, and improvement of neural displacement with improvement of clinical symptoms (Table 3).

Backward variable selection method of data analysis indicated improvement of neural sliding ($P = 0.004$) and degrees of hip flexion with symptomatic SLR ($P = 0.025$) as the main variables associated with improvement of self-reported painful symptoms at follow-up for radicular pain. Likewise, reduction of self-reported LBP was associated with improvement of neural sliding ($P = 0.006$) but not with degrees of hip flexion measured with symptomatic SLR ($P = 0.057$).

Overall, there was a significant increase in neural sliding (symptomatic, asymptomatic, and bilateral SLRs) in association with a decrease of symptoms during the follow-up period. The number of subjects required to produce statistically significant results on comparison between baseline and follow-up data ($P < 0.05$) was only four for the symptomatic SLR. Intraclass correlation coefficients proved higher than 0.99 for both inter and intraobserver reliability as well as results reproducibility for each tested maneuver. Observed power was 1 for each tested maneuver (Table 4).

DISCUSSION

Here, we show noninvasively with MRI in patients with posterolateral LIDH who demonstrated reduction in conus medullaris displacement with the SLR that an improvement of conus movement was strongly associated with resolution

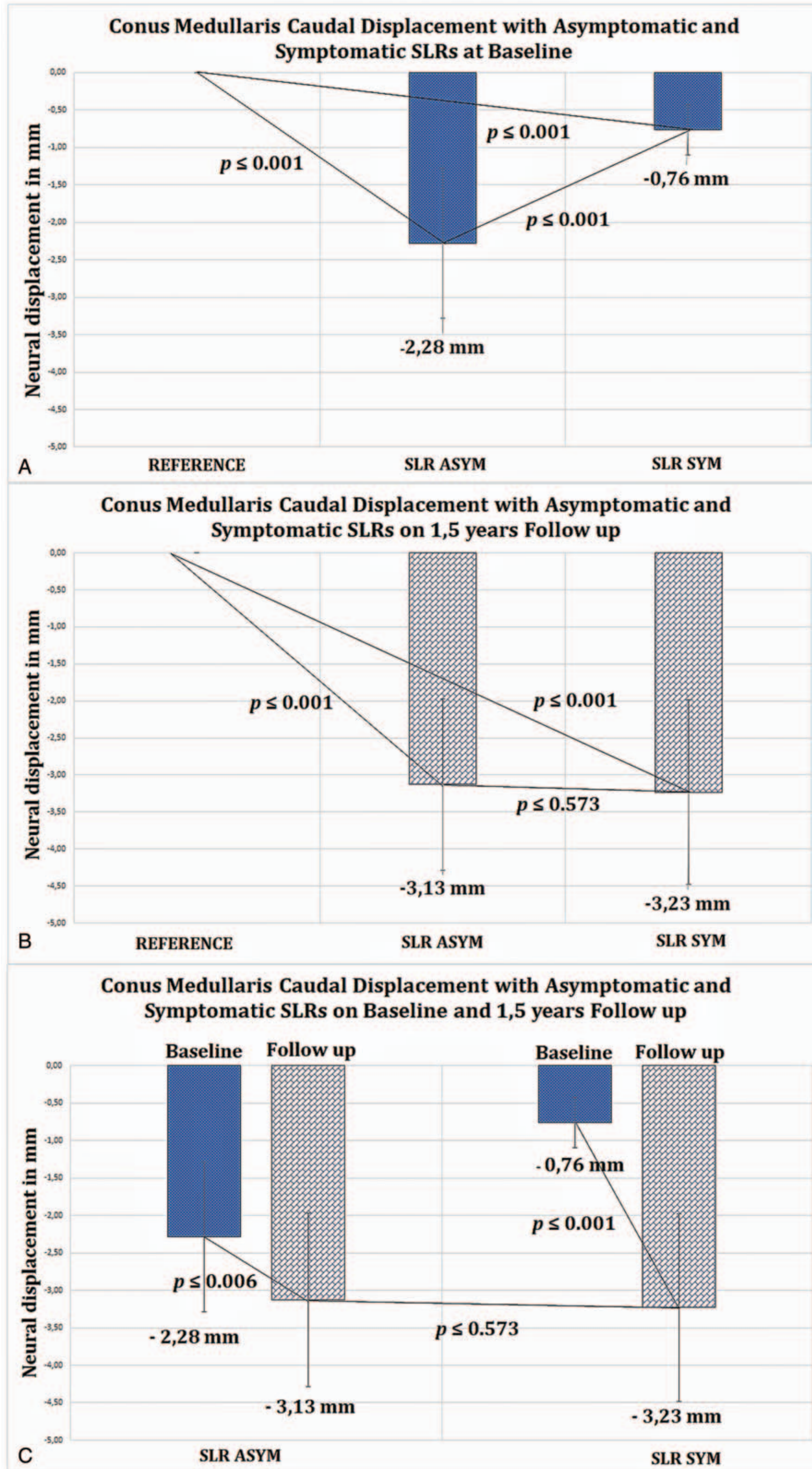

Figure 5. Conus medullaris caudal displacement with unilateral SLR test performed on the asymptomatic (ASYM) and previously symptomatic (SYM) side (**A–C**). A significant reduction of neural movement in patients with symptomatic radiculopathy can be seen at baseline (dark blue columns) with improvement in neural excursion at follow-up time (light blue columns) (**A**). This improvement is statistically significant and consistent (**C**). Mean value and standard deviations of measurements are presented. The reference value (0.0 mm) is represented by measurements taken in anatomical (neutral) position, while baseline scans refer to measurements taken in SLR 1.5 years before the follow-up time, when subjects were on active sick leave because of heavy sciatic symptoms due to single-level posterolateral LIDH. Values are expressed as negative to indicate the caudal direction of the displacement. **Note: A color image accompanies the online version of this article.**

of radicular symptoms and LBP during the 1.5 years follow-up time ($P \leq 0.001$).

The improvement in neural adaptive movement correlated significantly (inverse correlation) with the decrease, and resolution, of radicular symptoms in the ipsilateral limb (Pearson correlation = -0.72) as well as LBP symptoms (Pearson = -0.69) (Figure 6A,B). Backward variable selection method indicated an improvement of neural sliding effects ($P = 0.004$) and degrees of hip flexion with symptomatic SLR ($P = 0.025$) as the main variables being associated with

TABLE 3. Association Between Different Variables and Painful Symptoms at Follow-up

Parameter	Estimate	Std. Error	Df	*t*	*P*	95% Confidence Interval	
						Lower Bound	Upper Bound
Estimates of Fixed Effects for VAS Low Back Pain							
Sex (male = 0, female = 1)	20.476	14.268	19	1.435	0.168	−9.388	50.341
Age, yrs	0.754	0.481	19	1.567	0.134	−0.253	1.760
Height, cm	1.422	0.708	19	2.008	0.059	−0.060	2.904
Weight, kg	0.717	0.351	19	2.040	0.055	−0.018	1.452
Herniation type (extruded = 0, sequester = 1)	−23.740	8.724	19	−2.721	0.014	−41.999	−5.481
Therapy (surgical = 0, conservative = 1)	−6.360	12.208	19	−0.521	0.608	−31.911	19.192
SLR hip flexion, degrees	−1.290	0.488	19	−2.643	0.016	−2.312	−0.269
Neural displacement, mm	10.541	3.455	19	3.051	0.007	3.309	17.774
Estimates of Fixed Effects for VAS Radicular Pain							
Sex (male = 0, female = 1)	8.502	13.258	19	0.641	0.529	−19.248	36.252
Age, yrs	0.797	0.447	19	1.785	0.090	−0.138	1.733
Height, cm	0.601	0.658	19	0.913	0.373	−0.776	1.978
Weight, kg	0.442	0.326	19	1.353	0.192	−0.242	1.125
Herniation type (extruded = 0, sequester = 1)	−15.581	8.106	19	−1.922	0.070	−32.548	1.385
Therapy (surgical = 0, conservative = 1)	−5.243	11.344	19	−0.462	0.649	−28.986	18.499
SLR hip flexion, degrees	−1.299	0.454	19	−2.865	0.010	−2.249	−0.350
Neural displacement, mm	8.450	3.211	19	2.632	0.016	1.729	15.170

Df indicates degrees of freedom; Std.Error, standard error; VAS, visual analog scale.

TABLE 4. Reproducibility Values and Observed Power of Conus Medullaris Displacement with SLRs

	Range, mm		Pearson Correlations					
	Min	Max	Results Reproducibility	Intraobserver	Interobserver	Number of Subjects Tested	Number of Subjects Needed for Significant Results Compared with Baseline Data	Observed Power
Asymptomatic SLR	−1.9	−5.6	0.985	1	0.999	14	13	0.839
Symptomatic SLR	−2.1	−7	0.994	0.999	0.999	14	4	1
Bilateral SLR	−2.5	−7.9	0.995	0.999	0.998	14	8	0.985
Reference scan		0.999	1	0.999	14			

SLR indicates straight leg raise test.

improvement of self-reported painful symptoms at follow-up for radicular pain. Likewise, reduction of self-reported LBP symptoms was shown to be associated with improvement of neural sliding effects ($P = 0.006$). A connection between degrees of hip flexion with SLR and amount of neural movement has already been shown in earlier work on asymptomatic subjects.[12] In addition, Kobayashi *et al*[15,17] have shown intraoperatively both reduction in nerve root excursion in the lumbar intervertebral foramen with the SLR and a decrease in blood flow in the symptomatic nerve root. Later, Takamori *et al*[18] showed that these ischemic changes cause a transient disruption of compound muscular action potentials (CMAPs) occurring at the same degree of hip flexion known to be symptomatic with SLR at clinical evaluation. All of these findings integrate well into our results presented here.

The data on the amount of conus movement at follow-up became similar to those from our previous studies on asymptomatic subjects,[9–11] indicating that neural adaptive movements have adjusted toward normal along with resolution of sciatic symptoms during the follow-up time. The lack of statistical significance between left and right SLRs on follow-up indicates that a similar amount of neural displacement took place on each side, being regarded as normal.

In investigation of neurodynamic tests, it is important to make distinctions between key variables: (1) excursion of the neural tissues *per se* relative to their neighboring structures, (2) the range of movement (ROM) of the limb with the neurodynamic test, and (3) reproduction of patient's clinical symptoms. Alterations in neurodynamic test ROM and patient pain responses (*e.g.*, clinical pain) can differ in patient groups from their normal counterparts, which is used in diagnosis.[19–21] However, complicating matters is the fact that in these studies also shows that only using ROM and patient pain response produces variable diagnostic efficacy ratings (sensitivity 0.4–0.93, specificity 0.13–0.93).[22] Furthermore, nerve excursion and its variations between individuals have not been studied in relation to the ROM of neurodynamic tests. As such, the neurodynamic test cannot yet be considered a direct indication of neuropathy, radiculopathy, or amount of neural excursion.

However, even though the neurodynamic test may not indicate exactly and quantify the amount of neural sliding, there exist studies that show differences in longitudinal excursion of peripheral nerve between asymptomatic and symptomatic groups.[23] For instance, in carpal tunnel syndrome (CTS), it is shown that the median nerve slides less in patients with CTS (8.3 mm) compared with normal (11.2 mm).[24] Differences have also been established in tibial nerve sliding between healthy controls (2.18 mm) and diabetes patients (0.83 mm).[25] In lumbar radiculopathy patients with LIHD, Kobayashi *et al*[17] showed that the L5 nerve root moved on average 0.5 mm with the SLR, and after surgical removal of LIHD, excursion returned to an average of 3.8 mm.

The above literature is consistent with the current study that approached the problem from a different direction, not to ascertain the patient symptom responses or ROM value of the SLR in diagnosis, but to ask the question: in what way might (or might not) alterations in neural excursion be associated with symptomatology over time in a sample of LBP and radiculopathy patients? That we know of, this is the first demonstration of contemporaneous changes in symptomatology and mechanical function of neural tissues in the spine.

Different treatments (conservative and surgical) were chosen for the patients during the follow-up time (11 conservative and 3 operative), all of which coexisted with 76.8% improvement of radicular pain and 74.8% decrease of LBP from baseline data. However, with eight of the patients, remnants of LIDH (*i.e.*, extrusions or bulging discs) could still be seen in the follow-up diagnostic MRI. Hence, even though this indicates that if LIDH was still visible on the follow-up MRI, this may not correlate with the patient's symptoms (Figure 7), adding one possible

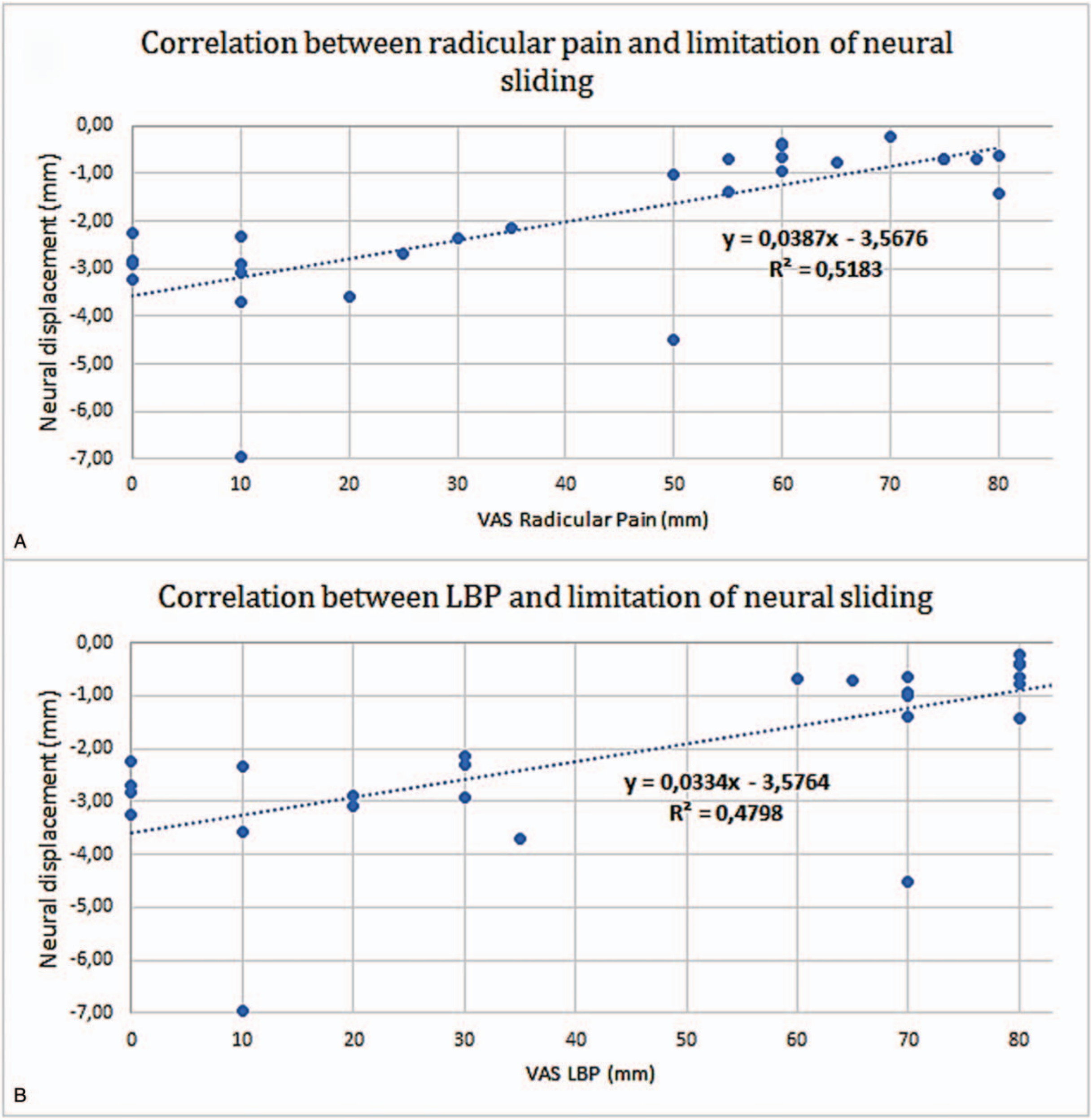

Figure 6. Correlogram showing association between (**A**) increase of neural sliding effects and decrease of self-reported radicular pain, (**B**) increase of neural sliding effects and decrease of self-reported low back pain (LBP) symptoms. Note that plots include both baseline and follow-up measurements taken on symptomatic sides.

explanation to the known dilemma on lack of association between radiological findings and clinical findings. The data presented here support the notion that amount of neural displacement may be associated with symptomatic radiculopathy and LBP, and that quantification of neural adaptive movements may be employed to evaluate such relationships in the future, rather than only utilizing plain descriptive assessment of anatomical structures occupying the spinal recesses or compression of nerve roots. In the event that further study is performed in more centers and with larger and broader samples, explanations for factors that produce an asymptomatic spine might in the future include normal neural tissue movement. Furthermore, this might contribute to why some LIDH are asymptomatic.[26,27] Clinically, this means that noninvasive measurement of these mechanisms may have important benefits, which could in the future be used to identify functional neurodynamic impairments in relation to (1) prognosis, (2) predictive aspects of clinical evaluation and determination of specific clinical pathways for intervention, (3) investigation of physicals effects of possible interventions such as surgery, (4) mobilization of nerve roots and different types of rehabilitation,[28,29] and (5) before surgery, establishment of the need, or lack thereof, to address neural mobility issues intraoperatively or as part of rehabilitation. Moreover, the current MRI measure could be used in concert with surgical and conservative interventions

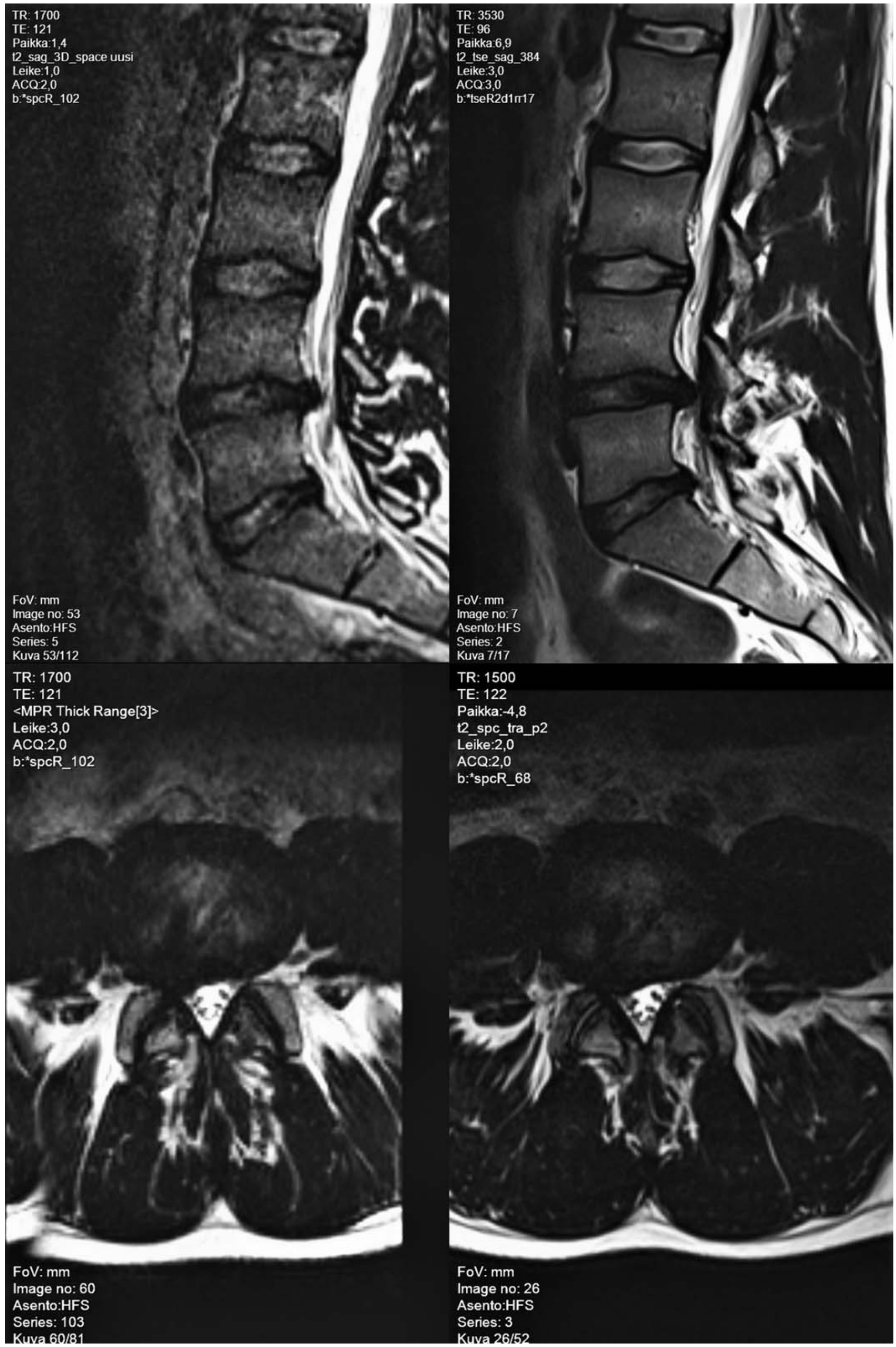

Figure 7. MRI T2 sagittal and T2 axial slices from baseline (BL, on left-side) and follow-up (FU, on right-side) showing L4-5 postero-lateral lumbar intervertebral disc herniation to the right side. Even if intervertebral disc bulging still exists, symptoms are absent (VAS Low back pain BL = 70 mm, FU = 0 mm, VAS radicular pain BL = 60 mm, FU = 0 mm) showing lack of correlation between conventional diagnostic images and clinical features.

aimed at reducing radicular symptoms, in order to observe this aspect of neural mobility as well as other proposed indicators such as the sedimentation sign investigated by Barz *et al*.[30] A goal might be to develop an algorithm with known sensitivity and specificity to predict presence of radicular symptoms, using one or more imaging measures.

In relation to mechanisms, an important consideration is the fact that the reduction in cord movement is an ‘‘effect’’ and not a ‘‘cause’’. It is likely that compression, ischemo-sensitivity and mechanosensitivity, and reduced nerve root movement from the disc protrusion are the causal mechanisms, and this restriction produced a failure of the nerve root to transmit forces to the cord with the SLR in our population. In other words, the limitation of neural movement seems to be related to impaired capacity of the nerve roots to transmit forces to the cord. After the follow-up time, our patient group showed significant decrease of pain symptoms, radicular and LBP, associated with restored neural sliding. Therefore with the present knowledge, it may be now possible to plan new diagnostic and treatment algorithms targeting the restoration of free neural sliding. With a better understanding to the underlying problem, identifying the right patient, and more focused treatment protocol, it is safe to assume we could address this large group of patients more effectively.

An important consideration relates to the fact that this study was designed to test for correlation between restriction of neural movement and clinical symptoms of sciatica and LBP, with interest being focused on mechanisms. The lack of association between type of therapies (conservative/surgical) and clinical outcomes seems to indicate that additional or unconsidered aspects may be important. However, the small number of subjects does limit the generalization of these data to the general population. In order to better discern differences in clinical outcomes as a function of type of treatment, and as a suggestion for further improvement on further studies, patients with surgical intervention shall be separated from the ones undergoing conservative treatment. Furthermore, multiple linear regression ideally benefits from several participants per variable examined, and consequently, further studies with larger number of participants (at least 10 subjects per variable being examined) are advised. Despite the highly significant *P* values achieved for key associations, it is worth acknowledging possible overfitting of variables for this sample size.

Through a selection process of 186 patients, we recruited patients with a similar type of LIDH and compression of the nerve root being the very similar in all patients. From these, we selected single-level posterolateral LIDH compressing one single nerve root (L4–5 or L5-S1) in order to provide comparable data. Even if the study sample was relatively small, the highly controlled settings and inclusion/exclusion criteria allowed for a very uniform sample with results showing large effect sizes and observed power. Also, high inter- and intraobserver, as well as reproducibility values show that the results were obtained in accurate circumstances and pertain to patients with posterolateral LIDH. The normative data from this line of research in neuroradiology have been replicated in cadavers with different methods by an independent research group[31] confirming that movements of the lumbosacral nerve roots with the unilateral and bilateral SLRs are consistent, reproducible, and, most likely, normal. Although keeping all of above in mind, we suggest that studies with larger samples and in other locations might yield more information on the generalizability of this study to a broader population of radiculopathy sufferers.

CONCLUSION

In this study, we found a concomitant improvement in reduced movement of the conus medullaris with the SLR and resolution of both radicular symptoms and LBP in patients with posterolateral LIDH during the 1.5 years follow-up. This suggests the possibility that the amount of neural displacement may be a variable relevant to symptomatic radiculopathy and LBP. These findings also substantiate the SLR test as a useful tool in assessment of neuromechanical impairment in patients with sciatica from the nerve root. To our knowledge, these are the first noninvasive data to objectively support an association between magnitude of neural adaptive movement and clinical symptoms in *in vivo* and structurally intact human subjects.

➢ Key Points

- ❑ In this study, we have shown a significant association between the improvement of neural adaptive (conus medullaris) movement during the SLR and resolution of both radicular and LBP symptoms in patients with posterolateral lumbar intervertebral disc herniation (LIDH) during 1.5 years follow-up time.
- ❑ With 8 of 14 patients, remnants of the previously herniated disc were still visible on MRI on follow-up, even if symptoms and magnitude of neural adaptive movements improved significantly.
- ❑ Following these data, we suggest that unrestricted neural movement may represent a crucial aspect of why patients are known to be asymptomatic even though a LIDH can still be seen on the MRI.

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