Part 3: Developing Methods of In Vivo MRI Measurement of Spinal Cord Displacement in the Thoracolumbar Region of Asymptomatic Subjects With Unilateral and Bilateral Straight Leg Raise Tests

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**Study Design.** Controlled radiological study.
**Objective.** Verify (1) whether conus medullaris displacement varies with the range of hip flexion and (2) whether the acquired data support the “principle of linear dependence.”

**Summary of Background Data.** We have previously quantified normal displacement of the conus with unilateral and bilateral straight leg raise (SLR) and have described the “principle of linear dependence.” However, we have since effected methodological advances that have produced data that surpass previous studies.

**Methods.** Ten asymptomatic volunteers were scanned with a 1.5-T magnetic resonance scanner using T2-weighted spc 3-dimensional scanning sequences and a device that permits greater ranges of SLR. Displacement of the conus medullaris during the unilateral and bilateral SLRs was quantified reliably with a randomized procedure.

**Results.** Pearson correlations were higher than 0.99 for both intra- and interobserver reliability and the observed power was 1 for each tested maneuver. The conus displaced caudally in the spinal canal by 3.54 ± 0.87 mm (µ ± SD) with unilateral (P ≤ 0.001) and 7.42 ± 2.09 mm with bilateral SLR (P ≤ 0.001).

**Conclusion.** To the authors’ knowledge, these are the first data on noninvasive, in vivo, normative measurement of spinal cord displacement with the SLR test at 60° of hip flexion. Conus medullaris displacement increased with hip flexion angle, while maintaining the relationship between magnitude of conus displacement and number of nerve roots involved into the movement, supporting the “principle of linear dependence.” The use of T2-weighted spc 3-dimensional sequence allows for better reliability testing, which is important for future clinical utility.

**Key words:** nerve, nerve root, spinal cord, sciatica, radiculopathy, low back pain, LBP, straight leg raise, SLR.

**Level of Evidence:** 5

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The straight leg raise (SLR) test is the most widely used, consistent, and accepted physical test for nerve root tension signs designed to aid the diagnosis of low back pain and sciatica.1–3

Following the notion that the SLR tests movement and mechanosensitivity of the L4, L5, and S1 nerve roots by applying caudally directed tensile forces to the neural tissue, several researchers have investigated neural displacement in response to this maneuver.1,2,4–9 In the literature, there is disparity on the magnitude of this displacement, but there is consensus on the direction, namely caudal,1,2,4–11

Shacklock12 has proposed that bilateral SLR would produce more caudal displacement of the spinal cord than the unilateral SLR. Rade et al.10,11 quantified the displacement of the conus medullaris in response to unilateral and bilateral SLRs in asymptomatic volunteers using magnetic resonance imaging (MRI). This was done following the notion that if any movement occurred, because of the neural continuum, it would be via sliding of, and direct transmission of forces through, the lumbosacral nerve roots and the adjacent dura to the spinal cord.
They reliably and consistently showed that the conus medullaris displaces caudally by $2.33 \pm 1.2$ mm ($\mu \pm SD$) with the unilateral SLR and $4.58 \pm 1.48$ mm with the bilateral SLR, approximating a linear dependency between magnitude of conus displacement and number of nerve roots involved. It was therefore hypothesized that, at certain times, the conus might be directly proportional to the sliding of the L5 and S1 neural roots, consistent with the “principle of linear dependence.”10,11

However, to test their hypothesis in in vivo and structurally intact asymptomatic human subjects, some limitations emerged with the use of MRI, with the architecture of the device limiting the subject’s hip flexion to 50° upon performance of an SLR.

Another limiting aspect of those studies is that the sample consisted of only male volunteers. Even if, to the author’s knowledge, there is no published evidence that supports the existence of sex-related differences in L4, L5, and S1 nerve root and conus medullaris, it would be of interest to construct a set of normative data including also female volunteers prior to the commencement of clinical investigations.

As in the literature, the bulk of nerve root excursion has been shown to occur between 60° and 75° of hip flexion1,2,4,5,9,13,14 it is probable that a greater amount of caudal displacement would be reported if greater hip flexion angles were achieved.

Of particular interest is (1) whether the magnitude of conus medullaris displacement increases with more hip flexion, resembling more accurately the common clinical SLR and (2) whether the “principle of linear dependence” would be substantiated at greater amounts of hip flexion.

In addition, attempts will be made to improve the measurement methodology with the aid of 3-dimensional (3D) MRI scanning, so as to investigate whether the methodology itself could be improved in terms of clinical feasibility and better values with inter- and intrarater reliability testing.

**MATERIALS AND METHODS**

**Subjects**

Following the results of a pilot study and because of the dimensions of the scanner (Siemens Magnetom Aera 1.5T, Erlangen, Germany), the authors calculated that subjects taller than 183 cm were needed to allow performance of the SLR in the scanner, permitting at least 60° of unrestricted hip flexion.

A total of 11 volunteers were recruited and screened for eligibility, one of whom met the exclusion criteria (Table 1) and was thus excluded from the study. Ten asymptomatic volunteers ranged from 20 to 32 years (mean age 25.1 ± 3.9 yrs), height 186.7 ± 2.9 cm, BMI 24.22 ± 3.92, and were included in the study.

Asymptomatic volunteers were chosen to make use of the normal situation providing normative measurements and avoid potentially confounding variables such as local impairments or neural dysfunctions that may occur in a symptomatic population.

<table>
<thead>
<tr>
<th>TABLE 1. Exclusion and Inclusion Criteria</th>
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<tbody>
<tr>
<td>Exclusion criteria</td>
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<tr>
<td>Subjects currently experiencing painful symptoms in the tested area</td>
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<tr>
<td>Incomplete and/or painful knee extension</td>
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<tr>
<td>Incomplete and/or painful hip range of motion</td>
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<td>History of known neurological disorders of the tested extremity</td>
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<td>History of diagnosed lumbar intervertebral disc herniation</td>
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<td>History of previous abdominal or lumbar surgeries</td>
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<td>Other joint involvement, like arthritis or already recognized metabolic bone disease</td>
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<tr>
<td>Subjects with any known arthrogenic, muscular or neurogenic dysfunctions in the lumbar spine area which, on provocative physical testing, gave positive signs and/or pain into the lower limb</td>
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<tr>
<td>Presence of pacemakers and ferromagnetic implants</td>
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<tr>
<td>Inclusion criteria</td>
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<tr>
<td>Subjects assessed to be asymptomatic</td>
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<tr>
<td>Subjects’ consent to participation by signing the consent form</td>
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<tr>
<td>No present exclusion criteria at the time of testing</td>
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Summary of exclusion criteria: All the volunteers were screened to be asymptomatic and to have a pain-free and complete range of bilateral movement in the hip, knee, and ankle joints and did not match the exclusion criteria.

All tested subjects signed an informed consent form and the study was approved by the institutional ethics committee. The study was performed in accordance with the Declaration of Helsinki.

**Devices**

The tested subjects were lying in the supine position into the 1.5-T magnetic resonance (MR) scanner (Siemens Magnetom Aera). The imaging area was centered approximately 3 cm proximally from the xiphoid process of the sternum and the coronal images centered at the lower part of the imaging area to T12–L2 anatomic region. The volunteers were scanned using a 32-channel spine matrix coil.

Different scanning sequences for planning and for measurement were used.

1. Planning: T2-weighted turbo spin echo sequence (repetition time 3530 ms, echo time 96 ms, 17 slices, slice thickness 3 mm, field of view 300 mm, in plane resolution $0.8 \times 0.8$ 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 (repetition time 1800 ms, echo time 128 ms, slice-thickness 1 mm, sagittal scan, field of view 300 mm, phase encoding direction proximal to caudal, in plane resolution $0.6 \times 0.6$ mm, flip angle 160°).
Coronal, axial, and sagittal slices (slice thickness 1 mm, approximately 70 slices in each plane) were reconstructed from the native T2-weighted spine 3D-sequence sagittal scans using the MPR program available in Sectra PACS workstation (Sectra Workstation IDS7, version 15.1.8.5-2013, Sectra AB, Sweden).

**Conus Medullaris Displacement Measurement**

The displacement of the conus medullaris relative to the upper endplate of the adjacent vertebra during the unilateral passive right, left, and bilateral SLRs was quantified and compared with the position of the conus in the neutral (anatomic) position (Figure 1A—F).

Measurements were taken twice by the main author, with 2 months between each measurement, and once by coauthor (J.M.) to allow for evaluation of intra- and interobserver reproducibility.

The 2 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. Particular care was taken to identify the origin of filum terminale so as to confirm the localization of the tip of the conus.

The mark on tip of the conus was then precisely projected at the center of the adjacent vertebral body by using the crosshair and localizer tools available in Sectra PACS program. As in Rade et al, the distance between the mark on the vertebral body and the anatomical reference point represented by the upper vertebral endplate was measured on the coronal slices. The measurements were made using Sectra PACS program (Sectra Workstation IDS7, version 15.1.8.5-2013, Sectra AB, Sweden).

All the presented metric values were truncated to the next lowest decimal integer (3.55 = 3.5) to provide more conservative and reliable data.

**Subject Positioning and Tested Movements**

The volunteers were scanned in the following positions in random order and the passive SLR combinations were performed as follows:

- Neutral: subjects lying in the supine position and relaxed in the anatomic position.
- Right SLR: right SLR to maximum hip flexion allowed by the scanner, holding the lower limb still, with the knee extended and the ankle in a plantargrade position (0° of dorsiflexion), (Figure 2).
- Left SLR as with the right.
- Bilateral SLR: as with the unilateral SLR. Two investigators were required for this in which subjects’ legs were raised, one by one, starting from the right, left, or both legs together in a random order (Figure 2A, B).

Because of the MR device architecture with a tube with diameter of 70 cm, 60° (μ 59.6°) of hip flexion was achieved.
Hip flexion was measured with an oil-filled precision goniometer placed on the anterior surface of the distal third of the tibia. This method has been shown to have good intraobserver repeatability during the performance of the SLR and was considered safe to be operated in the MR scanning room, security zone IV.

Each movement was performed twice for evaluation of reproducibility. Three investigators performed the maneuvers in random order to avoid possible series effects.

Each subject’s cervical spine was always placed in a neutral position so as to avoid producing any positional effects in the spinal cord.

Statistical Methods
The purpose of the data analysis was to detect any statistically significant differences in conus medullaris position between the reference position and the tested maneuvers, right, left, and bilateral SLRs.

A 2-tailed hypothesis that the conus would displace in response to SLR versus no change was tested.

The Pearson correlation between the 2 scans of the same maneuvers performed on each subject was calculated as well as for inter- and intraobserver reliability.

Having found strong correlations between the measures from the different scans of the same maneuvers performed on each subject, 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, to present the results as more accurately and conservatively as possible.

The Student t test was used to test the significance of conus medullaris displacement during the SLR in relation to the position found in the reference scans. The alpha level was set at $P < 0.05$.

The Observed Power was calculated on the data using $t$ distribution, whereas the minimum number of subjects needed to extract statistically significant results was calculated from the collected data. Statistical analysis was performed using R Program (R Foundation for Statistical Computing, Vienna, Austria), Version 2.15.2 (2012).

RESULTS
The number of subjects required to obtain statistically significant results ($P < 0.05$) compared with the reference position is 3 for both unilateral (2.71) and bilateral (2.87) SLRs.

When compared with the position in the neutral (anatomic) position, the conus medullaris displaced caudally in the spinal canal by $3.52 \pm 0.77$ mm ($\mu \pm SD$) with the right SLR ($P \leq 0.001$) and $3.57 \pm 1.14$ mm with the left SLR ($P \leq 0.001$), presenting an average of $3.54 \pm 0.87$ mm for unilateral SLR (Figure 3).

In response to bilateral SLR, the conus medullaris displaced by $7.42 \pm 2.09$ mm, showing statistical significance when compared with the reference position ($P \leq 0.001$), as well as with magnitudes of displacement achieved with unilateral SLR ($P \leq 0.001$) (Figure 4).

The Pearson correlations, as well as observed ranges and results for the Observed Power, are presented in Table 2.

DISCUSSION
We investigated in vivo spinal cord displacement in the thoracolumbar vertebral canal during the clinically applied unilateral SLR on each side and bilateral SLR in asymptomatic
subjects to (1) obtain normative data for a better understanding of mechanical behavior of the neural tissues of this clinically important region, (2) verify whether the “principle of linear dependence” described earlier is supported evidentially at greater angles of hip flexion showed, and (3) verify whether previous methods of measurement could be improved with the aid of 3D MRI scanning.

The results showed that caudal displacement of the conus medullaris at a 60° SLR was definitely greater than our previously reported results for a 50° SLR. This is in agreement with the literature on cadaver investigations, in which bulk of nerve root excursion is shown to occur between 60° and 75° of hip flexion.

Following the results presented in the literature, it seems probable that even greater amounts of conus medullaris displacement would occur with more hip flexion. Although there is agreement that the L5 and S1 nerve roots displace in the caudal direction with the SLR, there is significant variation in the magnitude between studies. In the present study, the average caudal displacement with the unilateral (3.54 ± 0.87 mm) and bilateral (7.42 ± 2.09 mm) SLRs seems to be in agreement with other studies and falls within a reasonable range of excursion (<10 mm). The lack of statistical significance (P = 0.844) in cord displacement between left and right SLRs indicates that the conus displaced a similar amount and direction in response to each unilateral SLR. The P value is equivalent to what was presented earlier.

As previously reported, the results showed that caudal displacement of the conus medullaris was significantly greater with the bilateral SLR compared with the unilateral SLR, suggesting that the amount of conus medullaris displacement may be cumulative between the two.

The fact that the displacement was virtually double with bilateral SLR may indicate that (1) a linear dependency between the magnitude of cord movement and number of nerve roots involved and (2) this relationship is maintained at greater angles of hip flexion. At least in the current circumstances, an explanatory mechanism may be that traction applied to twice the number of nerve roots produced proportionally more cord movement. Furthermore, because of the neural continuum, the authors speculate that this movement might be directly proportional to the sliding of the L5 and

![Figure 3. Conus medullaris caudal displacement with unilateral straight leg raise (SLR) test. Mean value and standard deviations of measurements are presented. Note the lack of statistical significance between left and right SLRs, indicating that a similar amount of neural displacement took place on each side. Values are expressed as negative to indicate the caudal direction of the displacement.](image)

![Figure 4. Conus medullaris displacement with unilateral and bilateral straight leg raises (SLRs). Mean value and standard deviations of measurements are presented. Values are expressed as negative to indicate caudal displacement. Note: Compared with the unilateral SLR, the magnitude of conus displacement was almost double the bilateral SLR, approximating a linear dependency between the conus movement and the number of nerve roots involved.](image)
S1 neural roots in response to unilateral and bilateral SLRs. This seems to support the “principle of linear dependence” in which the magnitude of conus medullaris displacement is proportional to the displacement of L5 and S1 nerve roots and dependent on the number of nerve roots involved in the movement (i.e., unilateral and bilateral SLRs).

Compared to previous methods in which coronal slices were obtained to measure the spinal cord displacement into the vertebral canal,\textsuperscript{10,11} attempts were made to improve the methods with the aid of 3D MRI scanning. In previous investigations,\textsuperscript{10,11} only 3-mm-thick coronal slices were used to identify the conus medullaris, which could have allowed the conus medullaris to fall between the slices, thus being visually represented as a partial volume. The use of 3D scanning in this investigation allowed \textit{ad hoc} reconstruction of 1-mm slices in the desired planes, offering the investigators easier identification of the tip of the conus medullaris and simultaneous confirmation of its position in the other planes.

Further improvement of the previously presented methodology is represented by the circumstance in which the whole marking and measurement procedure could be verified in real time using the remaining 2 scanning planes, axial and sagittal, improving the precision of the measurement while reducing the time needed to perform the analysis.

Also, the higher correlation values reported for both intra- and interobserver reliability testing achieved in this investigation indicate improvement in that may have positive effects on the clinical feasibility of this radiological feature.

CONCLUSIONS

The presented results showed larger amounts of conus medullaris displacement with unilateral and bilateral SLRs to $60^\circ$ hip flexion compared with $50^\circ$.

As previously reported,\textsuperscript{10,11} caudal displacement of the conus medullaris was significantly greater (slightly more than double) with the bilateral SLR compared with the unilateral SLR.

Hence, in addition to the $50^\circ$ SLR, it seems that the “principle of linear dependence” presented by Rade \textit{et al}\textsuperscript{10,11} is valid also at $60^\circ$ and that our proposals given earlier seem valid also when including female subjects and when the conus medullaris displacement is quantified with the use of 3D MR scanning sequences.

With these results, the authors expect that the sliding of neural structures in the vertebral canal may indeed present a protective mechanism that preserves the spinal cord and neural roots from excessive strain. If this were true, the preservation of free vertical sliding of the neural structures in the vertebral canal, along with the associated meninges, might indeed be a \textit{conditio sine qua non} for maintaining an asymptomatic spine. Therefore, possibilities relating to measurement of such displacement may have future diagnostic value.

The authors believe to have presented an improved set of normative data that include also female volunteers and that can now be used for future clinical comparisons.

This study provides conclusive evidence that the spinal cord displaces caudally with the lumbar nerve roots during both the clinically applied unilateral and bilateral SLRs. Moreover, the high correlation values presented in this study show that these medullar cone movements are significant, consistent, and reproducible, which both supports and adds to previous work.\textsuperscript{10,11}

These relevant studies offer standardized measurements and improved research methodology on which further studies in diagnosis and treatment of lumbar disc protrusion and radiculopathy with the SLR can be based. In particular, relationships between cord and nerve root movement warrant further investigation.

### Key Points

- The results show that caudal displacement of the conus medullaris depends on flexion angle: $60^\circ$ of hip flexion during the SLR induces larger displacement than the SLR to $50^\circ$.
- The conus medullaris displacement with bilateral SLR was again virtually double that of the unilateral SLR, indicating that a linear

### TABLE 2. Reproducibility Values and Observed Power of Conus Medullaris Displacement With Unilateral and Bilateral SLRs

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<thead>
<tr>
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<th>Min</th>
<th>Max</th>
<th>Results Reproducibility</th>
<th>Pearson Correlations</th>
<th>Number of Subjects Tested</th>
<th>Number of Subjects Needed for Significant Results</th>
<th>Observed Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right SLR</td>
<td>2.3</td>
<td>4.9</td>
<td>0.990</td>
<td>0.999</td>
<td>0.998</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>Left SLR</td>
<td>2.1</td>
<td>5.4</td>
<td>0.996</td>
<td>0.999</td>
<td>0.998</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>Bilateral SLR</td>
<td>3.7</td>
<td>11</td>
<td>0.979</td>
<td>0.999</td>
<td>0.977</td>
<td>10</td>
<td>3</td>
</tr>
<tr>
<td>Reference scan</td>
<td></td>
<td></td>
<td>0.995</td>
<td>0.999</td>
<td>0.998</td>
<td>10</td>
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SLR indicates straight leg raise.
dependency exists between the magnitude of cord movement and the number of nerve roots through which distal tension is applied. This confirms that the “principle of linear dependence” is also valid at 60° SLR compared with the previously described SLR to 50°.

- The measurement methodology previously described was improved on with the aid of 3D MRI scanning.
- To the authors’ knowledge, these are the first data on noninvasive, in vivo, normative measurement of spinal cord displacement with the SLR test at 60° of hip flexion. This study provides conclusive evidence that the spinal cord displaces distally with the lumbar nerve roots during both the clinically applied unilateral and bilateral SLRs.
- These relevant studies offer standardized measurements and improved research methodology on which further studies in diagnosis and treatment of lumbar disc protrusion and radiculopathy with the SLR can be based. In particular, the relation between cord and nerve root movement provides a useful tool.

References