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The Lumbar Spine as a Dynamic Structure Depicted in Upright MRI

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Abstract: Spinal canal stenosis is a dynamic phenomenon that becomes apparent during spinal loading. Current diagnostic procedures have considerable short comings in diagnosing the disease to full extend, as they are performed in supine situation. Upright MRI imaging might overcome this diagnostic gap.

This study investigated the lumbar neuroforamenal diameter, spinal canal diameter, vertebral body translation, and vertebral body angles in 3 different body positions using upright MRI imaging.

Fifteen subjects were enrolled in this study. A dynamic MRI in 3 different body positions (at 0° supine, 80° upright, and 80° upright + hyperlordosis posture) was taken using a 0.25 T open-configuration scanner equipped with a rotatable examination bed allowing a true standing MRI.

The mean diameter of the neuroforamen at L5/S1 in 0° position was 8.4 mm on the right and 8.8 mm on the left, in 80° position 7.3 mm on the right and 7.2 mm on the left, and in 80° position with hyperlordosis 6.6 mm ($P < 0.05$) on the right and 6.1 mm on the left ($P < 0.001$).

The mean area of the neuroforamen at L5/S1 in 0° position was 103.5 mm^2 on the right and 105.0 mm^2 on the left, in 80° position 92.5 mm^2 on the right and 94.8 mm^2 on the left, and in 80° position with hyperlordosis 81.9 mm^2 on the right and 90.2 mm^2 on the left.

The mean volume of the spinal canal at the L5/S1 level in 0° position was 9770 mm^3, in 80° position 10600 mm^3, and in 80° position with hyperlordosis 9414 mm^3.

The mean intervertebral translation at level L5/S1 was 8.3 mm in 0° position, 9.9 mm in 80° position, and 10.1 mm in the 80° position with hyperlordosis.

The lordosis angle at level L5/S1 was 49.4° in 0° position, 55.8° in 80° position, and 64.7 mm in the 80° position with hyperlordosis.

Spinal canal stenosis is subject to a dynamic process, that can be displayed in upright MRI imaging. The range of anomalies is clinically relevant and dynamic positioning of the patient during MRI can provide essential diagnostic information which are not attainable with other methods.

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Abbreviations: CT = computed tomography, MRI = magnetic resonance tomography.

INTRODUCTION

Degenerative spondylolisthesis is a spinal pathology frequently diagnosed in the elderly.[1] The progressive loss of height in a motion segment coupled with subluxation of the facet joints leads to changes in biomechanical forces and hypertrophy of the ligamentum flavum and spondylophyte formation around the facet joints. Together the combination of a loss of height in the intervertebral space and the apposition of osseous and ligamentary structures result in progressive compression of the nerves passing through affected canals. This compression can be exacerbated by bulging-disc syndrome and spondylophytes in the vertebral endplates. The clinical symptoms are low back and radicular lower-limb pain and intermittent spinal claudication. This cascade of anatomical and pathological anomalies most frequently occur in the lower lumbar region, especially segments L3/4, L4/5, and L5/S1.[2,3] If conservative therapy fails, operative treatment, that is, segment decompression has to be considered. However, a satisfactory surgical outcome requires the indication for a specific surgical intervention preceded by differentiated diagnostics and accurate identification of the motion segment in question. Today, diagnosis of neuroforaminal stenosis or spinal stenosis relies on radiologic upright imaging on 2 levels as well as magnetic resonance tomography (MRI). As an alternative to MRI, computed tomography (CT) in combination with a myelography can be performed, however, due to its invasiveness and radiation exposure, MRI has become the diagnostic gold standard.[4,5] CT myelography however is still performed in patients unable to undergo MRI. A drawback of conventional MRI imaging is the fact that images are taken in supine position and can therefore not directly display aforementioned dynamic anomalies.[6,7] The dynamics in spinal-column width in patients suffering spinal canal stenosis while moving from a supine to a standing position were illustrated by Zander and Lander.[8] This phenomenon correlates well with clinical findings in these patients, as they frequently report decreased pain, when changing from standing to supine position. However, gravity's effect on neuroforamen in the presence of degenerative spondylolysis in the lower lumbar region has attracted little attention, so far. Many radiologic images (both CT and MRI) of patients suffering from stenosis of the spinal canal fail to reveal any pathology.[9,10] This fact underlines the need for additional diagnostic procedures, that enable us to visualize these effects. The possibility of dynamic radiological examinations with the upright MRI can close this diagnostic gap. However, data revealing dynamic anatomic changes in response to a load are scarce. Previous

investigations of spinal canal imaging under a load are mostly cadaver studies.[11,12] There is a paucity of in vivo data on structural changes in the lumbar spine, and those that do exist only address specific anatomic structures. Just one study has examined dynamic changes in the spinal canal.[13]

The aim of this study was therefore the radiological evaluation of the diameter of the lumbar neuroforamen, the diameter of the spinal canal, the translation of the vertebral bodies, and the angle of the vertebral bodies, that is, of L5/S1 in 3 different positions.

MATERIALS AND METHODS

Fifteen subjects with chronic back pain were enrolled in this study. All were scheduled for *transforaminal lumbar interbody fusion* (*TLIF*) L5/S1 after having been diagnosed with degenerative spondylolisthesis L5/S1 via conventional X-ray, segment infiltration, and probatory corset. Exclusion criteria were previous surgical interventions and any malignancies.

A dynamic MRI in 3 different body positions (at $0°$ supine, $80°$ upright, and $80°$ upright + hyperlordosis posture) was taken using a 0.25 T open-configuration scanner (G-Scan, Esaote, Genoa, Italy) equipped with a rotatable examination bed allowing a true standing MRI (Figure 1A and B). Gradient supports ± 20 mT/m with a slew rate of 25 mT/m/ms. Phased array dedicated receiving coils were used. Sagittal MR examinations included a 2D FSE T2 sequence (TR = 3350 ms, TE = 120 ms, FOV = 310×310 mm^2, M = 224×208, TH = 4 mm, TA = 5′28″) and a 3D HYCE (balanced steady state sequence, TR = 10 ms, TE = 5 ms, FOV = $290 \times 290 \times 100$ mm^3, M = $232 \times 206 \times 28$, TA = 5′29″).

Images taken during these different positions were quantitatively evaluated by measuring the diameter of the neuroforamen and that of the spinal canal at the level of L5/S1.

The Medical Image Viewer Impax, Agfa HealthCare was used for standardized reorientation of the images (Figure 2). This was done to avoid measurement errors due to partial volume effects caused by differences in the patients' positioning.

In the sagittal view, the slice was oriented along the ground plate of L5. In the axial view the slice was oriented alongside the middle of the vertebral body and spinal process. Comparative measurements of the spinal canal volume, spinal canal diameter, the neuroforaminal diameter and its area were taken in all the prescribed patient positions.

Moreover, intervertebral body translation and the lordosis angle were calculated (Figure 3).

Statistical Evaluation

For statistical evaluation we employed SPSS for Mac (version 22, SPSS, Inc., Chicago, Il). An one-way analysis of variance[14] was used to assess statistical differences. The post hoc Bonferroni test was used to identify differences between each position. The level of significance was set at $P < 0.05$.

RESULTS

The mean diameter of the neuroforamen at L5/S1 in $0°$ position was 8.4 ± 1.6 mm on the right and 8.8 ± 1.8 mm on the left, in $80°$ position 7.3 ± 1.4 mm on the right and 7.2 ± 1.8 mm on the left, and in $80°$ position with hyperlordosis 6.6 ± 1.5 mm ($P < 0.05$) on the right and 6.1 ± 1.6 mm on the left ($P < 0.001$) (Figure 4A + B).

The mean area of the neuroforamen at L5/S1 in $0°$ position was 103.5 ± 22.2 mm^2 on the right and 105.0 ± 25.8 mm^2 on the left, in $80°$ position 92.5 ± 27.9 mm^2 on the right and 94.8 ± 38.1 mm^2 on the left, and in $80°$ position with hyperlordosis 81.9 ± 28.5 mm^2 on the right and 90.2 ± 31.1 mm^2 on the left.

The mean volume of the spinal canal at the L5/S1 level in $0°$ position was 9770 ± 3900 mm^3, in $80°$ position 10600 ± 3900 mm^3, and in $80°$ position with hyperlordosis 9414 ± 4700 mm^3.

The mean intervertebral translation at level L5/S1 was 8.3 ± 4.4 mm in $0°$ position, 9.9 ± 4.9 mm in $80°$ position and 10.1 ± 5.1 mm in the $80°$ position with hyperlordosis.

The lordosis angle at level L5/S1 was $49.4 \pm 11.3°$ in $0°$ position, $55.8 \pm 13.3°$ in $80°$ position, and 64.7 mm $\pm 16.3°$ in the $80°$ position with hyperlordosis.

DISCUSSION

The main findings of the present study are that significant narrowing of the neuroforaminal diameter develops during the change from a lying to standing position or to a standing position with hyperlordosis. This effect can be displayed in a
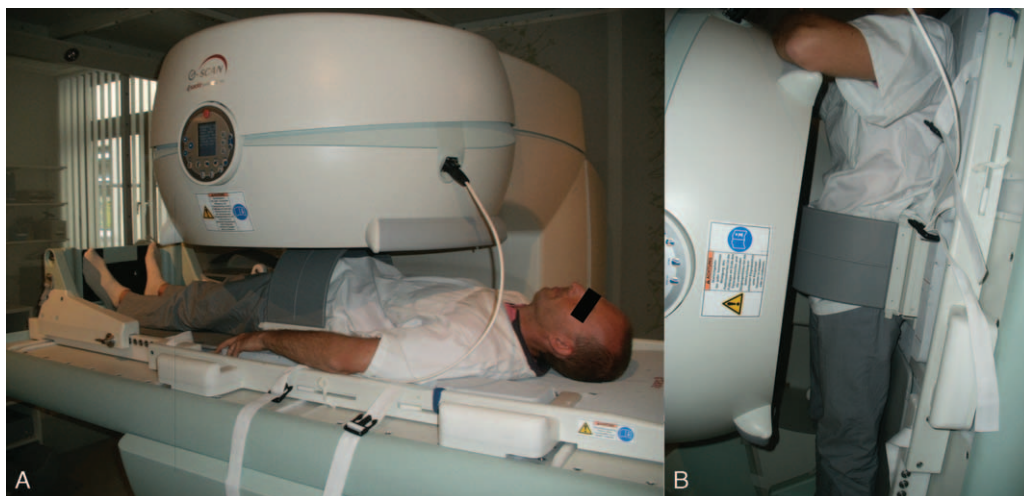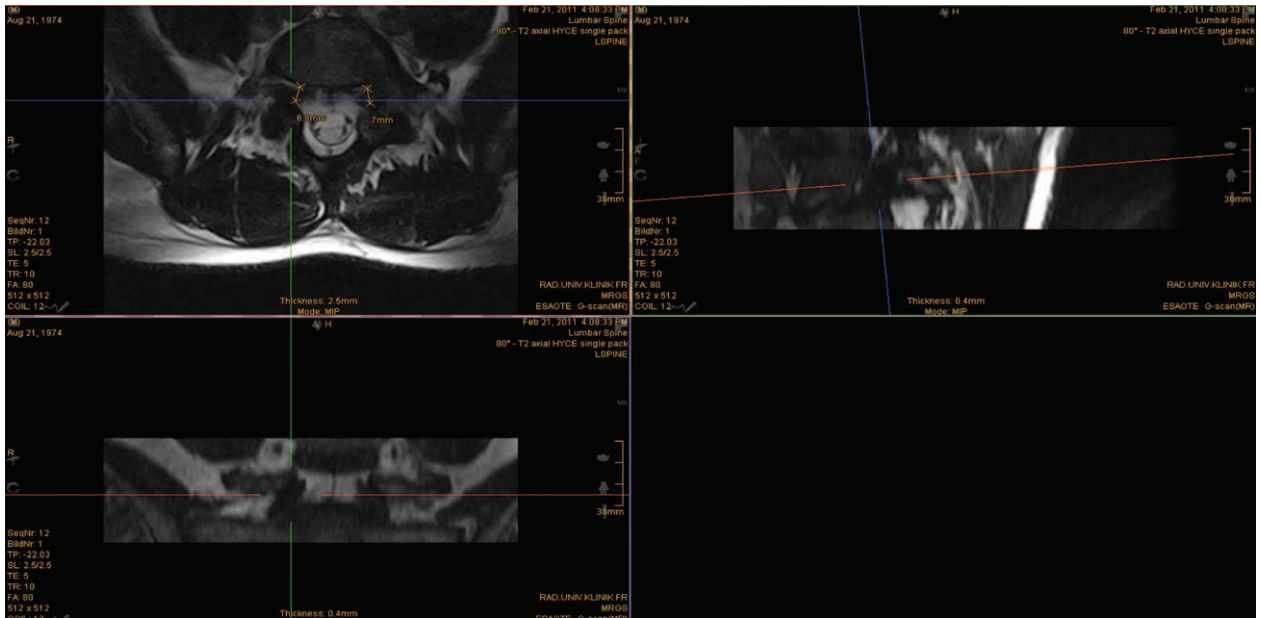

FIGURE 1. (A + B) Dynamic MRI in supine ($0°$) and weight bearing ($80°$) positions with a volunteer.
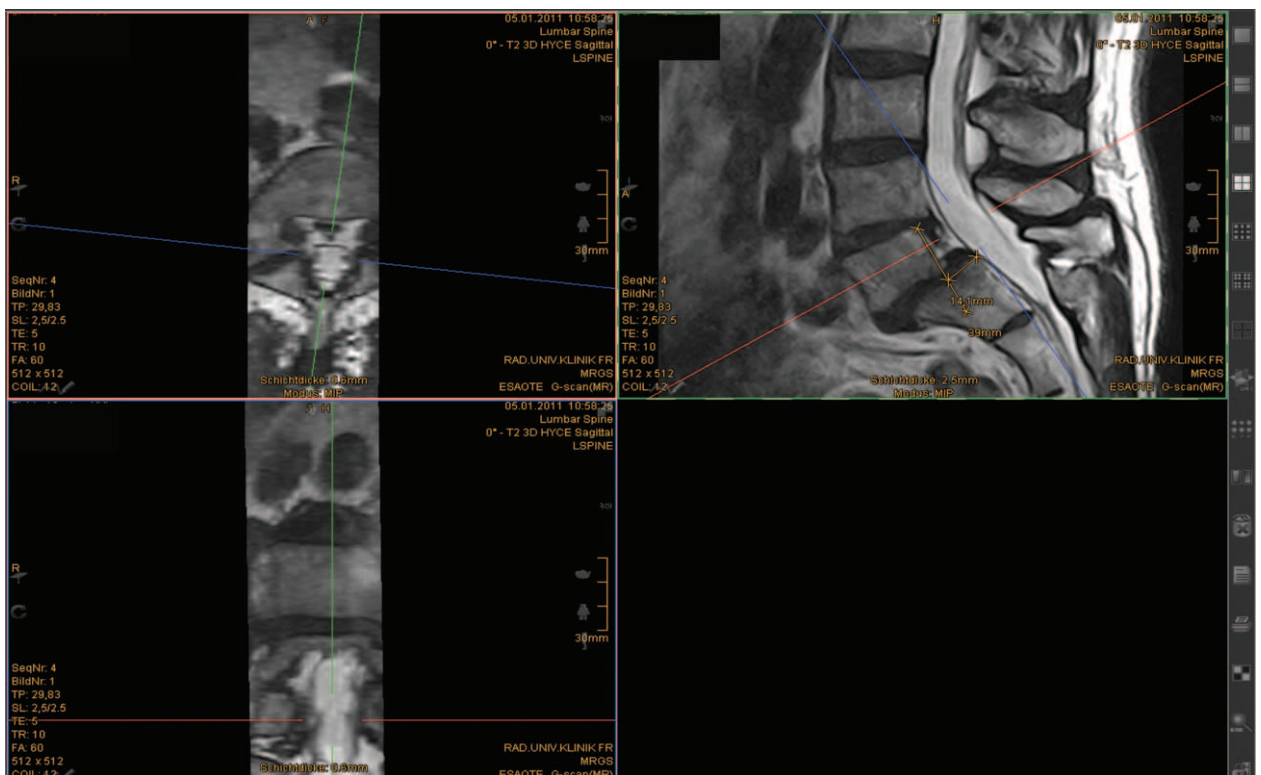
FIGURE 2. Measurement of the neuroforaminal diameter L5/S1 in weight bearing (80°) position with standardized reorientation of the images.

upright MRI and should be included into diagnostics of chronic lower back pain.

Segmental instability in the spinal column is defined as an anterior–posterior translation of the opposing vertebrae by more than 3 mm,[15,16] whereby a translation exceeding 3 mm is considered pathological and is associated with lower back pain and sciatica.[17] Patients suffering from a degenerative spinal disease such as spondylolisthesis complain of worsening

FIGURE 3. Measurement of the intervertebral body translation L5/S1 in supine (0°) position with standardized reorientation of the images.
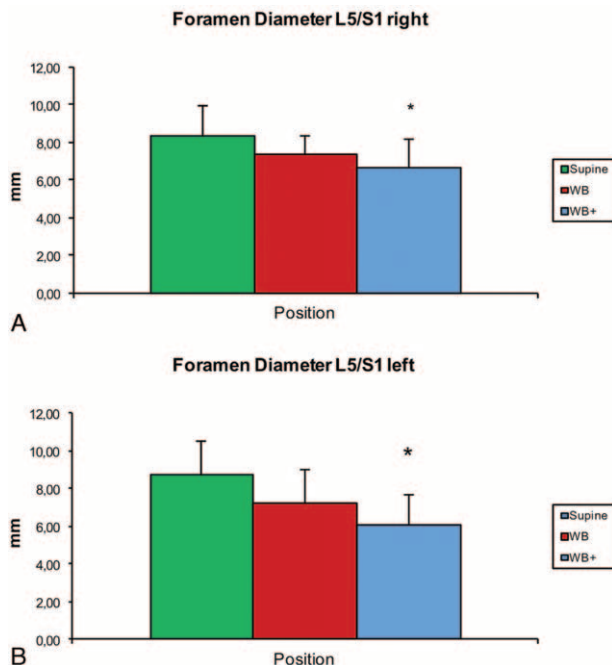
FIGURE 4. (A + B) Mean diameter and standard deviation (error bar) of the neuroforamen at L5/S1 in supine (0°), weight bearing (WB) and hyperlordosis (WB+) position ($^*P < 0.005$).

pain when standing for a long time or carrying a load; this is because of a worsening of an existing spondylolisthesis in an upright position. Nevertheless, the imaging procedures performed to visualize a known spinal anomaly such as MRI or CT are usually carried out with the patient in supine position. As lumbar lordosis is reduced in supine position, the patient's lumbar pain also tends to lessen. Our data confirm the surveillance that lumbar lordosis diminishes when moving from a standing to lying position. Radiologic imaging of the spinal column in an upright position enables functional assessment under an axial load.[18,19] Here too, our data confirm the assumption that an increasing axial load on the spinal column leads to a reduction in spinal canal volume and to progressive listhesis of the lumbar vertebrae. We were surprised to observe that changing from a supine position to an 80° upright stance triggered an initial expansion in the spinal canal at the L5/S1 level. A repeated change in position to an 80° upright stance in conjunction with lumbar hypomochlion, however, led to a reduction in spinal canal volume. This reveals that the pain experienced by patients with hyperlordotic spondylolisthesis can be aggravated by an increasing load on the facet joints, as well as by a worsening 360° restriction of the spinal canal.

Depending on its stage and the amount of pain it causes, treatment for spondylolisthesis can involve surgery. Bony decompression is clinical routine nowadays in patients suffering from a spinal canal stenosis caused by spondylolisthesis—an intervention designed to expand spinal canal volume. However, additional reposition of the vertebrae remains highly controversial.[20,21] A randomized, double-blind trial by Audat et al[20] examining clinically symptomatic patients suffering from Meyerding stage 1 and 2 spondylolisthesis demonstrated that the outcome of patients who had undergone fixation versus decompression in the affected motion segment were nearly identical, whether the sliding vertebrae had been repositioned or not.

Due to the more beneficial biomechanical relationships within the spinal motion segment created thereby, other authors recommend repositioning.[22,23] As a study comparing the sagittal alignment of the spinal column in patients presenting spondylolysis and spondylolisthesis with a normal control group's sagittal alignment revealed, patients with spondylolysis and spondylolisthesis present exacerbated lumbar lordosis, which in turn alters the biomechanics in the spinal column and facet joints.[22] Spondylolisthesis thus correlates negatively with spinal canal volume. Theoretically speaking, repositioning the sliding vertebrae in conjunction with spinal-cord decompression should create expansion in the spinal cord.

Considering other spinal column structures and their behavior in association with degenerative diseases, several experimental cadaver studies employing MRI and CT come to mind. These specifically examined the effect of a load on spinal-column structures and the related anatomical changes in the neuroforamen. These in vitro cadaver investigations demonstrated in lumbar spinal-column segments that a load on the spinal column caused by axial rotation, extension, or lateral deflection leads to the constriction of neural pathways that does not occur when there is no load.[24–28] Our data confirm this observation. This effect also applies to the diameter of the neuroforamen and its corresponding volume. Also apparent is that the effect of increasing constriction in the neuroforamen is much worse at L4/5 than at L5/S1 when changing from a supine to standing position.

Our investigation has demonstrated that the change from a supine to an 80° upright position results in worsening lumbar lordosis, which in turn exacerbates lumbar hypomochlion. A certain degree of lumbar lordosis is needed, as it enables impacts affecting the discs to be absorbed and deflected. Specifically, the effect of lordosis is that it creates increased pressure on the dorsal parts of the disc and thus to ventral displacement of gel-like elements such as the nucleus pulposus, thereby preventing the disc from slipping in a dorsal direction.[27,28]

Considering the spinal column's dorsal structures, it again becomes clear how relevant the change in position from a supine to upright position is. The shear forces occurring in an upright position are absorbed primarily by the facet joints,[29] whereas the facet joints absorb just 16% of the compression forces affecting the spinal column.[30]

Disc degeneration and the discs' accompanying loss of height can raise the facet joints' compression load up to 70%, eventually causing the facet joints to degenerate and leading to facet-joint arthrosis, which in turn plays a major role in constricting the adjacent neuroforamen.

LIMITATIONS

This study provides an investigation of the dynamic structures of the lumbar spine in 3 different body positions. In our point of view, the gathered information is essential to understand and evaluate the pathogenesis of degenerative diseases of the spine. Nevertheless, some limitations need to be recognized; at first, the number of investigated subjects is limited. However, the present study size is in line with previously reported investigations.[13,31,32] Moreover, we could demonstrate significant changes in the neuroforaminal diameter that allow to draw conclusions conclude to general public of. However, further investigations on intervertebral translation and the impact on positioning on the spinal canal volume should be carried out in a bigger population. Moreover, upright MRI was carried out in 80° not in 90°. The quasi full up-right position was chosen as the

overlordosis position was not possible in the full 90° upright position as we wanted the patients to stand naturally and not to be binded against the patients bed of the scanner. Last but not least, investigations were carried out at low field. Therefore spatial resolution is lower compared to the high-field environment. However, weight-bearing MRI of the spine is so far not possible at high-field. Moreover several studies could show that with careful adjustment of slice orientation and sequence design high accuracy during functional MRI of the musculoskeletal system can be achieved.[33–35]

CONCLUSION

Pathologies of the spinal column like spinal canal stenosis or (degenerative) spondylolisthesis are subject to dynamic processes that can be displayed in upright MRI by positioning the patient dynamically. The range of anomalies is clinically relevant, and dynamic positioning of the patient during upright MRI can provide essential diagnostic information to the physician that is not attainable with other methods. We consider upright MRI to be superior to supine MRI for diagnosing degenerative spinal cord diseases.

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