European Journal of Orthopaedic Surgery & Traumatology (2019) 29:17–23
https://doi.org/10.1007/s00590-018-2276-x

ORIGINAL ARTICLE • SPINE - SPONDYLOLISTHESIS

Evaluation of foraminal cross-sectional area in lumbar spondylolisthesis using kinematic MRI

Permsak Paholpak[1,2] · Alexander Nazareth[1] · Yusuf A. Khan[3] · Sameer U. Khan[3] · Faisal Ansari[3] · Koji Tamai[1,4] · Zorica Buser[1] · Jeffrey C. Wang[1]

Received: 2 April 2018 / Accepted: 24 June 2018 / Published online: 27 July 2018

Abstract

Purpose To evaluate the kinematic change of cross-sectional area of lumbar intervertebral foramen in degenerative lumbar spondylolisthesis patients using multi-positional MRI.

Methods Multi-positional MRI was performed on 31 patients diagnosed with single or multilevel degenerative lumbar spondylolisthesis and 31 control patients without degenerative lumbar spondylolisthesis. Foraminal area (FA) was measured at the lumbar spondylolisthesis level in degenerative lumbar spondylolisthesis group and at L3-4, L4-5, and L5-S1 level in the control group. FA was measured bilaterally in neutral, flexion, and extension positions. The difference in FA between the groups was analyzed using Mann–Whitney *U* test, and the difference between positions within groups was analyzed using Wilcoxon signed-rank test.

Results Degenerative lumbar spondylolisthesis group showed significantly smaller FA on both sides and on average in all three positions compared to the control group ($p < 0.05$ all). From neutral to flexion position, the change in FA was significantly smaller in the degenerative lumbar spondylolisthesis group than in the control group on both sides and on average ($p < 0.005$ all). In degenerative lumbar spondylolisthesis group, the FA showed no significant change from neutral to flexion, but showed significant change from neutral to extension ($p < 0.005$ all).

Conclusions FA in the degenerative lumbar spondylolisthesis group was smaller than in the control group. There was no difference in FA in degenerative lumbar spondylolisthesis group from neutral to flexion, only from neutral to extension. Patients with degenerative lumbar spondylolisthesis have a higher chance of developing foraminal stenosis.

Keywords Degenerative spondylolisthesis · Lumbar spondylolisthesis · Foramina area · Foraminal stenosis · Degenerative lumbar · Multi-positional MRI

Introduction

Degenerative lumbar spondylolisthesis is a disorder that results in spinal instability from progressive degeneration of the facet joints, intervertebral disks, and ligamentous structures [1–3]. It is defined as the anterior sublaxation of one vertebra in relation to the adjacent caudal vertebra and occurs most commonly at L4 to L5 level [4, 5]. Degenerative spondylolisthesis may be asymptomatic or can be present with axial or radicular pain and is common in the aging population. Prevalence of degenerative spondylolisthesis has been reported to range from 5–7% in general population [1, 2].

Lumbar intervertebral foraminal stenosis is a common cause of lumbar radiculopathy in patients with degenerative disease. Previous studies have found intervertebral foraminal

✉ Zorica Buser
zbuser@usc.edu

1 Department of Orthopaedic Surgery, Keck School of Medicine, University of Southern California, 1450 Biggy Street, NRT-2509N, Mail Code: 9601, Los Angeles, CA 90033, USA

2 Department of Orthopaedics, Faculty of Medicine, Khon Kaen University, Khon Kaen, Thailand

3 AiM Radiology Medical Group, Bellflower, USA

4 Department of Orthopedics, Osaka City University Graduate School of Medicine, Osaka, Japan

area to be dependent on spine position, with a significant decrease in extension and increase in flexion position [6–14]. However, these studies examined foraminal area changes in healthy patients using cadaveric specimens [3, 4, 15], computed tomography (CT), magnetic resonance imaging (MRI) [5–7], or three-dimensional reconstructed models from CT or MRI [8–10]. Multi-positional MRI of the lumbar spine offers weight-bearing and multi-positional imaging which may be superior to previous imaging modalities in detecting dynamic changes in foraminal area. A recent multi-positional MRI study of 45 patients with low back pain or radicular symptoms investigated changes in the dimensions of lumbar foraminal area (FA) in weight-bearing neutral, flexion, and extension positions. They found that FA changed significantly with different positions, and the decrease in size was due to the migration of disk bulge and angular motion [11].

To the best of our knowledge, there are no published studies investigating dynamic changes in FA in patients with degenerative lumbar spondylolisthesis compared to controls using multi-positional MRI.

Materials and methods

Study populations

Lumbar multi-positional MRI images of 840 patients referred for symptomatic back pain between November 2014 and August 2016 were evaluated. The inclusion criteria for degenerative lumbar spondylolisthesis groups were (a) lumbar spondylolisthesis at least at one level L3-4, L4-5, or L5-S1, and (b) bilateral lumbar intervertebral foramen with clear, identifiable borders in all three positions. The exclusion criteria were (a) infection, (b) trauma, (c) congenital anomaly, (d) tumor, and (e) inflammatory diseases of the spine. Thirty-one patients with degenerative lumbar spondylolisthesis (18 females, age 55 ± 9.71 year) and 31 control patients (18 females, age 40.35 ± 13.24) were included in this study.

Multi-positional MRI protocol

MRI of the spine was performed using a 0.6-Tesla MRI machine (Upright Multi-Position, Fonar Corp., New York, NY, USA). Two horizontal orientated, opposing magnetic doughnuts placed 18 inches apart were used, allowing scanning of the patient sitting in an upright, axially loaded position. The image protocol included T1- (TR 671 ms, TE 17 ms, thickness 4.0 mm, field of view 30 cm, matrix 256 × 224, number of excitations 2) and T2- (TR 3000 ms, TE 140 ms, thickness 4.0 mm, field of view 30 cm, matrix 256 × 224, number of excitations 2) weighted sagittal fast spin-echo images that were obtained using a flexible surface coil. All patients were scanned with multi-positional MRI in flexion (30°), neutral, and extension (20°) positions.

FA measurement

The FA was measured at the spondylolisthesis level and at L3-4, L4-5, and L5-S1 in the control group on parasagittal T2-weighted image using eRAD PACS viewer version 7.2.38.0 (South Carolina, USA). The superior and inferior borders of FA were defined as adjacent superior and inferior vertebral pedicles, respectively. The anterior boundary was defined as the posterior–inferior margin of the superior vertebral body, the posterior intervertebral disk, and the posterior–superior margin of the inferior vertebral body. The posterior boundary was defined as the ligamentum flavum and the superior and inferior articular facets (Fig. 1). All cross-sectional measurements of FA were taken at the pedicular level in three positions: flexion, neutral, and extension. Two experienced spine surgeons independently assessed the cross-sectional area of FA twice for intra- and inter-observer reliability analysis.

Spondylolisthesis grading and stability

Lumbar spondylolisthesis was evaluated using MRI image in the neutral position based on the Meyerding classification: Grade 1, less than 25% slip; Grade 2, 25–50% slip; Grade 3, 50–75% slip; and Grade 4, 75–100% slip [12]. Lumbar segmental instability was defined as anterior or posterior translation of more than 3 mm s and sagittal rotation of more than 10° at each segment in multi-positional MRI [13, 14].

Statistical analysis

The sample size of 30 was calculated to be needed to detect differences in FA between three positions using power of 0.8, α of 0.05, and effect size of 0.5. Intraclass correlation coefficients (ICCs) were used to determine intra- and inter-observer reliability for two examiners. The difference in size of FA between flexion–neutral, extension–neutral, flexion–extension positions, and between the left and right side was analyzed by using Wilcoxon signed- rank test. Mann–Whitney U test was used to analyze the difference in FA between the spondylolisthesis and the control group in all positions. All statistical analyses were performed using SPSS software (version 23; SPSS, Chicago, IL, USA).

Results

From 840 patients, 54 (6.4%) patients with degenerative lumbar spondylolisthesis were identified. After applying inclusion and exclusion criteria, thirty-one degenerative

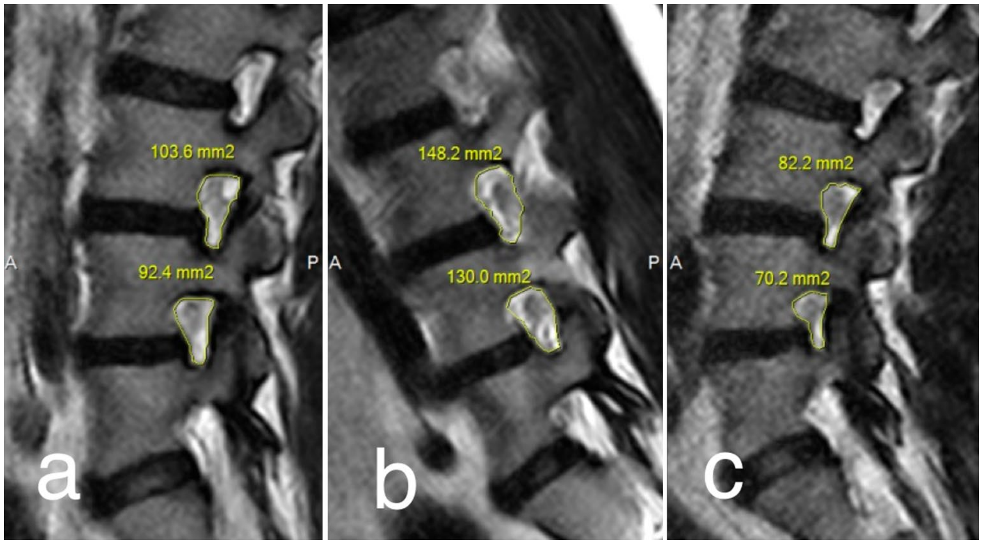

Fig. 1 Foraminal area cross-sectional diameter (FA) measured on parasagittal T2 images in neutral (**a**), flexion (**b**), and extension (**c**) postures

lumbar spondylolisthesis patients were analyzed. Thirty-one control patients without lumbar spondylolisthesis were selected from the database. Patients in degenerative lumbar spondylolisthesis group were significantly older compared to the control group ($p < 0.001$). In the degenerative lumbar spondylolisthesis group, only one patient had multilevel degenerative lumbar spondylolisthesis group at L4-5 and L5-S1 levels. Degenerative lumbar spondylolisthesis was present at L3-4 (9.3%), L4-5 (53.1%), and L5-S1(37.5%). Twenty-seven spondylolisthesis segments were Meyerding grade 1 slip, and five (15.63%) segments were Meyerding grade 2 slip. There was no lumbar segment instability in degenerative lumbar spondylolisthesis or control group. The CONSORT diagram is shown in Fig. 2. The ICC values for intra- and inter-observer FA measurement were excellent in (0.865 for intra-observer, and 0.812 for inter-observer).

Both groups showed that the average FA was larger in flexion and smaller in extension when compared to the average FA in neutral position (Table 1). Degenerative lumbar spondylolisthesis group showed significantly smaller FA on both sides and on average in all three positions compared to the control group. The average FA difference, for both sides, from neutral to flexion position was significantly smaller in the degenerative lumbar spondylolisthesis group compared to the control group ($p = 0.001$). No significant differences were found between the groups from neutral to extension position.

No significant difference between the groups was found for average FA in all three positions at L3-L4 (Table 2). At L4-5 and L5-S1, average FA in flexion and extension positions was significantly smaller in the degenerative lumbar spondylolisthesis group compared to the control group. From neutral to flexion position, only right side of FA at L3-4 segment in degenerative lumbar spondylolisthesis group showed significantly less FA change than the control group ($p = 0.008$, Table 2). At L4-5 segment, the FA on the left side and average FA showed smaller changes in degenerative lumbar spondylolisthesis group compared to control ($p < 0.001$ left, and 0.001 for the average value). At L5-S1 segment, there was no significant difference between the two groups. There were no significant differences in FA on both sides and on average between the degenerative

Fig. 2 The CONSORT diagram

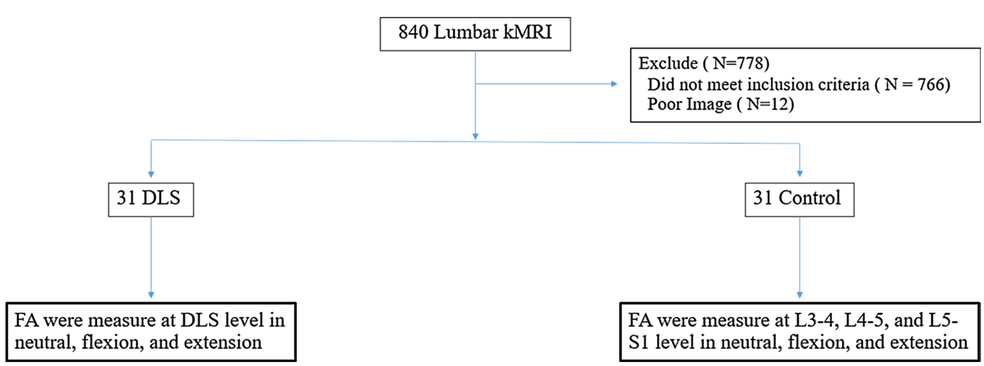

Table 1 Difference of cross-sectional area of foraminal area between spondylolisthesis and control group

			Overall (number of segment)		
			DLS (32)	Control (93)	*p*-value
Neutral	FA	Rt	99.83 ± 31.66	117.20 ± 27.14	0.012*
		Lt	100.58 ± 30.91	118.74 ± 27.23	0.003†
		Ave	100.21 ± 29.71	117.97 ± 25.83	0.006†
Flexion	FA	Rt	101.56 ± 37.77	128.40 ± 30.72	< 0.001†
		Lt	103.84 ± 35.78	131.85 ± 30.96	< 0.001†
		Ave	102.70 ± 34.80	130.12 ± 29.48	< 0.001†
Extension	FA	Rt	80.28 ± 30.06	100.52 ± 25.71	< 0.001†
		Lt	86.52 ± 26.88	102.09 ± 25.05	0.005*
		Ave	83.40 ± 26.92	101.36 ± 23.86	0.001†
N–F	FA	Rt	− 1.73 ± 19.85	− 11.20 ± 9.26	0.003†
		Lt	− 3.26 ± 21.51	− 13.11 ± 11.07	0.003†
		Ave	− 2.49 ± 17.61	− 12.15 ± 8.97	0.001†
N–E	FA	Rt	19.55 ± 24.06	16.69 ± 10.52	0.698
		Lt	14.06 ± 23.89	16.64 ± 13.33	0.125
		Ave	16.80 ± 22.67	16.61 ± 9.70	0.382

DLS degenerative lumbar spondylolisthesis, *FA* foraminal area (mm^2), *N* neutral, *F* flexion, *E* extension

*is statistically significant difference ($p < 0.05$)

†is statistically significant difference ($p < 0.005$)

lumbar spondylolisthesis and the control group from neutral to extension position.

For degenerative lumbar spondylolisthesis group at all levels, there was no significant difference in the FA size between neutral and flexion positions (Table 3). Degenerative lumbar spondylolisthesis group at all levels and L4-5 showed significantly larger FA in neutral position when compared to the extension position on both left and right side and average. At L5-S1, right side of FA was significant larger in neutral position when compared to the extension position. For control group, there was significantly larger FA in flexion position, and smaller FA in extension compared to the neutral position overall, L3-4, L4-5, and L5-S1 segment. The percentage change in FA (referenced to neutral position) between neutral–flexion and neutral–extension positions is shown in Table 4.

Discussion

Results from the current study demonstrate that in both lumbar spondylolisthesis and non-spondylolisthesis patients dynamic changes in foraminal cross-sectional area exist between neutral, flexion and extension positions. Previous studies have found similar results in which neural foraminal area was found to be position dependent [3, 5]. However, these studies have not examined the effect of specific lumbar pathology including degenerative spondylolisthesis on dynamic foraminal area. In the current study, patients with lumbar spondylolisthesis had significantly smaller foraminal cross-sectional area compared to control patients. Foramina area of the lumbar spine is a positional-dependent parameter, and dynamic foraminal stenosis may contribute to the development of radiculopathy and stenosis in patients with degenerative spondylolisthesis [5, 11].

Previous studies have reported that FA was larger in flexion position and smaller in extension position in patients without spondylolisthesis [3, 5, 16]. Similarly, our results showed that FA cross-sectional area in both DLS group and control group increased in flexion and decreased in extension position. The etiology of dynamic foraminal area change is likely multifactorial. Recent multi-positional MRI study by Singh et al. [11] reported a significant correlation between the changes in FA in flexion/extension, changes in the disk bulge from flexion to extension, and angular motion or disk bulge migration, suggesting that in the extension the disk protrudes posteriorly into the neural foramen, decreasing total FA and compressing exiting nerve roots.

In degenerative lumbar spondylolisthesis patients, our study found that the FA of the overall segments and at L3-4, L4-5, and L5-S1 was significant smaller than in the control group in all three positions. Furthermore, the overall degenerative lumbar spondylolisthesis segments did not show significant increase in FA cross-sectional area from neutral to flexion, and significantly less than the control group. But the FA showed a significant decrease in extension and showed no significant difference in FA change compared to the control group. In the control group, FA significantly increased from neutral to flexion and significantly decreased from neutral to extension. These findings suggest that in degenerative lumbar spondylolisthesis patients the FA was narrower in neutral and extension position and did not show significant changes in flexion when compared to the controls. This may be explained by disk degeneration, facet hypertrophy, hypertrophic ligamentum flavum, and bony spurs commonly found in degenerative lumbar spondylolisthesis, which can reduce foraminal area [17–19] and that degenerative spines may fail to show significant position-dependent changes in FA [6]. When focusing on each segment in degenerative lumbar spondylolisthesis group, L3-4 level did not show significant difference in FA compared to the control group, and only the right side and the average value at L4-5 and L5-S1 level showed significantly smaller FA in spondylolisthesis group.

This study results are relevant clinically because FA stenosis in degenerative lumbar spondylolisthesis might be underdiagnosed in the standard MRI, and surgical treatment without adequate decompression may lead to less favorable clinical outcomes. And even in flexion position, the FA area in degenerative lumbar spondylolisthesis

Table 2 Difference of cross-sectional area of foraminal area between spondylolisthesis and control group at each spinal level

			L3-4			L4-5			L5-S1		
			DLS (3)	Control (31)	*p*-value	DLS (17)	Control (31)	*p*-value	DLS (12)	Control (31)	*p*-value
Neutral	FA	Rt	117.53 ± 28.78	126.22 ± 27.78	0.785	100.19 ± 33.73	114.72 ± 26.18	0.149	94.90 ± 30.11	110.66 ± 25.83	0.147
		Lt	114.33 ± 24.51	127.24 ± 24.59	0.524	105.54 ± 31.52	115.18 ± 24.86	0.236	90.13 ± 30.50	113.80 ± 30.63	0.055
		Ave	115.93 ± 26.63	126.73 ± 25.23	0.693	102.86 ± 30.54	114.95 ± 24.36	0.192	92.51 ± 29.33	112.23 ± 26.32	0.076
Flexion	FA	Rt	119.10 ± 30.40	139.52 ± 32.31	0.288	101.91 ± 40.32	125.73 ± 29.14	0.026*	96.68 ± 37.11	119.97 ± 28.16	0.037*
		Lt	130.30 ± 40.56	142.45 ± 30.06	0.976	103.99 ± 36.10	130.52 ± 27.91	0.011	97.01 ± 34.23	122.57 ± 32.40	0.058
		Ave	124.70 ± 35.34	140.99 ± 30.15	0.738	102.95 ± 35.41	128.12 ± 27.31	0.009*	96.85 ± 34.55	121.27 ± 28.34	0.030*
Extension	FA	Rt	111.20 ± 41.92	106.97 ± 28.26	0.485	75.55 ± 27.73	97.10 ± 24.24	0.003†	79.27 ± 28.49	97.48 ± 24.00	0.045*
		Lt	113.07 ± 46.96	111.54 ± 21.86	0.606	85.69 ± 24.46	97.50 ± 23.68	0.113	81.05 ± 23.33	97.25 ± 27.33	0.101
		Ave	112.13 ± 44.34	109.25 ± 24.08	0.564	80.62 ± 23.91	97.30 ± 22.68	0.015*	80.16 ± 24.57	97.54 ± 23.58	0.048*
N–F	FA	Rt	− 1.57 ± 1.67	− 13.30 ± 11.60	0.008*	− 1.72 ± 21.44	− 11.00 ± 8.78	0.129	− 1.78 ± 21.02	−9.31 ± 6.56	0.113
		Lt	− 15.97 ± 17.95	− 15.22 ± 14.67	0.832	1.55 ± 18.10	− 15.34 ± 9.86	< 0.001†	−6.88 ± 25.96	−8.76 ± 5.82	0.745
		Ave	− 8.77 ± 9.78	− 14.26 ± 12.36	0.564	−0.09 ± 15	− 13.17 ± 7.38	0.001†	−4.33 ± 22.48	−9.04 ± 4.86	0.279
N–E	FA	Rt	6.33 ± 13.15	19.25 ± 11.39	0.073	24.64 ± 27.63	17.63 ± 10.48	0.360	15.63 ± 19.63	13.18 ± 8.90	0.448
		Lt	1.27 ± 23.29	15.70 ± 11.70	0.288	19.84 ± 25.99	17.68 ± 15.33	0.779	9.07 ± 20.11	16.55 ± 13.07	0.101
		Ave	3.80 ± 17.95	17.48 ± 8.80	0.172	22.24 ± 25.03	17.65 ± 11.69	0.635	12.35 ± 19.09	14.69 ± 8.31	0.208

DLS degenerative lumbar spondylolisthesis, *FA* foraminal area (mm^2), *N* neutral, *F* flexion, *E* extension

*is statistically significant difference ($p < 0.05$)

† is statistically significant difference ($p < 0.005$)

Table 3 Statistically significant difference between neutral and flexion and neutral and extension position in both spondylolisthesis and control group

			p-value		
			FA right	FA left	FA average
Spondylolisthesis	Neutral–Flexion	Overall DLS (32)	0.701	0.390	0.438
		L3-4 (3)	0.285	0.285	0.285
		L4-5 (17)	0.813	0.831	0.925
		L5-S1 (12)	0.638	0.347	0.530
	Neutral–Extension	Overall DLS	< 0.001†	0.004†	< 0.001†
		L3-4 (3)	1	1	1
		L4-5 (17)	0.003†	0.005*	0.003†
		L5-S1 (12)	0.010*	0.110	0.099
Control	Neutral–Flexion	Overall (93)	< 0.001†	< 0.001†	< 0.001†
		L3-4 (31)	< 0.001†	< 0.001†	< 0.001†
		L4-5 (31)	< 0.001†	< 0.001†	< 0.001†
		L5-S1 (31)	< 0.001†	< 0.001†	< 0.001†
	Neutral–Extension	Overall (93)	< 0.001†	< 0.001†	< 0.001†
		L3-4 (31)	< 0.001†	< 0.001†	< 0.001†
		L4-5 (31)	< 0.001†	< 0.001†	< 0.001†
		L5-S1 (31)	< 0.001†	< 0.001†	< 0.001†

DLS degenerative lumbar spondylolisthesis, *FA* foraminal area (mm^2), *N* neutral, *F* flexion, *E* extension

*is statistically significant difference ($p < 0.05$)

†is statistically significant difference ($p < 0.005$)

Table 4 Percent change of FA from neutral to flexion and extension (neutral position is the reference position)

	Right (number of segments)			Left (number of segments)			Average (number of segments)		
	DLS (32)	Control (93)	*p*-value	DLS (32)	Control (93)	*p*-value	DLS (32)	Control (93)	*p*-value
N–F	− 1.92 ± 21.27	− 9.60 ± 7.22	0.013†	− 5.26 ± 29.16	− 11.26 ± 9.21	0.013†	− 3.07 ± 21.91	− 10.32 ± 6.94	0.004†
N–E	17.92 ± 20.42	14.18 ± 8.34	0.365	11.04 ± 20.12	13.84 ± 10.02	0.302	14.73 ± 18.64	14.02 ± 7.35	0.782

DLS degenerative lumbar spondylolisthesis, *FA* foraminal area (mm^2), *N* neutral, *F* flexion, *E* extension

*is statistically significant difference ($p < 0.05$)

†is statistically significant difference ($p < 0.005$)

patients was not as wide as in the control patients. Additionally, the multi-positional MRI can provide the weight-bearing multi-positional images and the correlations of these positional changes with soft tissue pathology such as ligamentum flavum hypertrophy, degenerative disk disease, and facet joint osteoarthritis [20–22].

This study has several limitations: (a) retrospective nature, (b) there were not enough patients for certain segments to detect differences between two group, (c) due to our strict imaging inclusion criteria, we were not able to match for age, (d) all patients had back pain and we did not have an asymptomatic control group, and (e) the lack of patient medical records. Lumbar foramina are dumb-bell shaped, and the dimension of the foramen depends on the exact position of the MRI section [23]. Only patients whose intervertebral foramen was clearly visible and measured bilaterally in all three positions in the same coronal plane were included in the study. However, this tight criterion reduced our sample size and power.

Despite these limitations, in the current multi-positional MRI study we were able to detect subtle position-dependent changes and differences in foraminal cross-sectional area between degenerative lumbar spondylolisthesis and control patients. We believe that this information may be helpful in evaluating and making treatment decision in degenerative lumbar spondylolisthesis patients, particularly those with foraminal stenosis.

Conclusion

FA increased from neutral to flexion and decreased from neutral to extension in both degenerative lumbar spondylolisthesis and control group. In degenerative lumbar spondylolisthesis group, FA was smaller in all positions. Our results suggest that degenerative lumbar spondylolisthesis patients had a higher chance of developing foraminal stenosis than non-spondylolisthesis patients and that the FA will not increase with flexion position.

Acknowledgments The study was supported by departmental funds. Authors would like to thank AiM Radiology Medical Group, especially to Aziza Qadir MD for the help in overseeing the upload of multipositional MRI images into the database.

Disclosures Disclosures outside of submitted work: ZB—Xenco Medical (consultancy), AO Spine (consultancy); JCW—Royalties—Biomet, Seaspine, Amedica, DePuy Synthes; Investments/Options—Fziomed, Promethean, Paradigm Spine, Benvenue, Nexgen, Vertiflex, Electrocore, Surgitech, Expanding Orthopedics, Osprey, Bone Biologics, Pearldiver; Board of Directors—North American Spine Society (non-financial, reimbursement for travel for board meetings, courses etc.), North American Spine Foundation (non-financial), AO Foundation (financial, $20,000 honorariums for board positions, plus travel for board meetings), Cervical Spine Research Society (non-financial, reimbursement for travel for board meetings); Editorial Boards—Spine, JAAOS, The Spine Journal, Clinical Spine Surgery, Global Spine Journal; Fellowship Funding (paid to institution): AO Foundation. Yusuf A. Khan, Sameer U. Khan—family relationships (a family member owner of kMRI imaging center).

Compliance with ethical standards

Conflict of interest No conflict of interest for the current study.

References

1. Jacobsen S, Sonne-Holm S, Rovsing H, Monrad H, Gebuhr P (2007) Degenerative lumbar spondylolisthesis: an epidemiological perspective: the Copenhagen Osteoarthritis Study. Spine (Phila Pa 1976) 32(1):120–125. https://doi.org/10.1097/01.brs.0000250979.12398.96
2. Norton RP, Bianco K, Klifto C, Errico TJ, Bendo JA (2015) Degenerative spondylolisthesis: an analysis of the nationwide inpatient sample database. Spine (Phila Pa 1976) 40(15):1219–1227. https://doi.org/10.1097/brs.0000000000000987
3. Fujiwara A, An HS, Lim TH, Haughton VM (2001) Morphologic changes in the lumbar intervertebral foramen due to flexion–extension, lateral bending, and axial rotation: an in vitro anatomic and biomechanical study. Spine (Phila Pa 1976) 26(8):876–882
4. Hasegawa T, An HS, Haughton VM, Nowicki BH (1995) Lumbar foraminal stenosis: critical heights of the intervertebral discs and foramina. A cryomicrotome study in cadavera. J Bone Jt Surg Am 77(1):32–38
5. Inufusa A, An HS, Lim TH, Hasegawa T, Haughton VM, Nowicki BH (1996) Anatomic changes of the spinal canal and intervertebral foramen associated with flexion-extension movement. Spine (Phila Pa 1976) 21(21):2412–2420
6. Wildermuth S, Zanetti M, Duewell S, Schmid MR, Romanowski B, Benini A, Boni T, Hodler J (1998) Lumbar spine: quantitative and qualitative assessment of positional (upright flexion and extension) MR imaging and myelography. Radiology 207(2):391–398. https://doi.org/10.1148/radiology.207.2.9577486
7. Schmid MR, Stucki G, Duewell S, Wildermuth S, Romanowski B, Hodler J (1999) Changes in cross-sectional measurements of the spinal canal and intervertebral foramina as a function of body position: in vivo studies on an open-configuration MR system. AJR Am J Roentgenol 172(4):1095–1102. https://doi.org/10.2214/ajr.172.4.10587155
8. Zhong W, Driscoll SJ, Tsai TY, Wang S, Mao H, Cha TD, Wood KB, Li G (2015) In vivo dynamic changes of dimensions in the lumbar intervertebral foramen. Spine J 15(7):1653–1659. https://doi.org/10.1016/j.spinee.2015.03.015
9. Havey RM, Goodsitt J, Khayatzadeh S, Muriuki M, Potluri T, Voronov LI, Lomasney LM, Patwardhan AG (2015) Three-dimensional computed tomography-based specimen-specific kinematic model for ex vivo assessment of lumbar neuroforaminal space. Spine (Phila Pa 1976) 40(14):E814–E822. https://doi.org/10.1097/brs.0000000000000959
10. Senoo I, Espinoza Orias AA, An HS, Andersson GB, Park DK, Triano JJ, Inoue N (2014) In vivo 3-dimensional morphometric analysis of the lumbar foramen in healthy subjects. Spine (Phila Pa 1976) 39(16):E929–E935. https://doi.org/10.1097/brs.0000000000000399
11. Singh V, Montgomery SR, Aghdasi B, Inoue H, Wang JC, Daubs MD (2013) Factors affecting dynamic foraminal stenosis in the lumbar spine. Spine J 13(9):1080–1087. https://doi.org/10.1016/j.spinee.2013.03.041
12. Meyerding HW (1956) Spondylolisthesis; surgical fusion of lumbosacral portion of spinal column and interarticular facets; use of autogenous bone grafts for relief of disabling backache. J Int Coll Surg 26(5 Part 1):566–591
13. Fujiwara A, Lim TH, An HS, Tanaka N, Jeon CH, Andersson GB, Haughton VM (2000) The effect of disc degeneration and facet joint osteoarthritis on the segmental flexibility of the lumbar spine. Spine (Phila Pa 1976) 25(23):3036–3044
14. Fujiwara A, Tamai K, An HS, Kurihashi T, Lim TH, Yoshida H, Saotome K (2000) The relationship between disc degeneration, facet joint osteoarthritis, and stability of the degenerative lumbar spine. J Spinal Disord 13(5):444–450
15. Cinotti G, De Santis P, Nofroni I, Postacchini F (2002) Stenosis of lumbar intervertebral foramen: anatomic study on predisposing factors. Spine (Phila Pa 1976) 27(3):223–229
16. Panjabi MM, Takata K, Goel VK (1983) Kinematics of lumbar intervertebral foramen. Spine (Phila Pa 1976) 8(4):348–357
17. Miao J, Wang S, Wan Z, Park WM, Xia Q, Wood K, Li G (2013) Motion characteristics of the vertebral segments with lumbar degenerative spondylolisthesis in elderly patients. Eur Spine J 22(2):425–431. https://doi.org/10.1007/s00586-012-2428-3
18. Hu SS, Tribus CB, Diab M, Ghanayem AJ (2008) Spondylolisthesis and spondylolysis. J Bone Jt Surg Am 90(3):656–671
19. Jenis LG, An HS (2000) Spine update. Lumbar foraminal stenosis. Spine (Phila Pa 1976) 25(3):389–394
20. Do DH, Taghavi CE, Fong W, Kong MH, Morishita Y, Wang JC (2011) The relationship between degree of facet tropism and amount of dynamic disc bulge in lumbar spine of patients symptomatic for low back pain. Eur Spine J 20(1):71–78. https://doi.org/10.1007/s00586-010-1558-8
21. Lee SH, Daffner SD, Wang JC (2014) Does lumbar disk degeneration increase segmental mobility in vivo? Segmental motion analysis of the whole lumbar spine using kinetic MRI. J Spinal Disord Tech 27(2):111–116
22. Phan KH, Daubs MD, Kupperman AI, Scott TP, Wang JC (2015) Kinematic analysis of diseased and adjacent segments in degenerative lumbar spondylolisthesis. Spine J 15(2):230–237. https://doi.org/10.1016/j.spinee.2014.08.453
23. Stephens MM, Evans JH, O'Brien JP (1991) Lumbar intervertebral foramens. An in vitro study of their shape in relation to intervertebral disc pathology. Spine (Phila Pa 1976) 16(5):525–529