Kinetic Magnetic Resonance Imaging of the Cervical Spine: A Review of the Literature

Elizabeth L. Lord[1] Raed Alobaidan[1] Shinji Takahashi[2] Jeremiah R. Cohen[3] Christopher J. Wang[4] Benjamin J. Wang[4] Jeffrey C. Wang[4]

[1] Department of Orthopaedic Surgery, UCLA, Los Angeles, California, United States
[2] Department of Orthopaedic Surgery, Osaka City University, Osaka City, Osaka, Japan
[3] Department of Orthopaedic Surgery, David Geffen School of Medicine at UCLA, Los Angeles, California, United States
[4] USC Spine Center, Los Angeles, California, United States

Address for correspondence Elizabeth L. Lord, MD, Department of Orthopaedic Surgery, UCLA, CHS 76-143, 10833 Le Conte Avenue, Los Angeles, CA 90095, United States (e-mail: lord.elizabeth@gmail.com).

Global Spine J 2014;4:121–128.

Abstract

Study Design Literature review.
Objective The purpose of this study is to compile and review the body of literature related to kinetic magnetic resonance imaging (kMRI) of the cervical spine.
Methods A review of literature related to kMRI was performed using PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines.
Results We included 16 prospective and retrospective studies of symptomatic and asymptomatic patients who underwent kMRI of the cervical spine.
Conclusions Data suggest that kMRI is able to provide meaningful information regarding changes in the cervical spine in both normal and pathologic segments. A prospective study comparing magnetic resonance imaging and kMRI is needed to confirm clinically utility of this technology.

Keywords
- kinetic magnetic resonance imaging
- kinetic MRI
- kMRI
- MRI cervical spine
- dynamic magnetic resonance imaging
- positional magnetic resonance imagining

Introduction

Rationale

Kinetic magnetic resonance imaging (kMRI) is a novel imaging technique that combines the excellent soft tissue contrast and multiplanar capabilities of conventional magnetic resonance imaging (MRI) with "functional" or kinematic capabilities.[1] kMRI allows patients to be examined in multiple positions beyond the traditional position of supine and neutral (►**Fig 1**). Various techniques and positioning devices have been used to obtain these images of patients in positions of loading and weight bearing, upright and recumbent, and particularly flexion, neutral, extension, and axial rotation (►**Figs. 2** and **3**).[2–5] This noninvasive technique demonstrates mobility and in situ kinematics that may not be apparent with conventional static MRI.[2,6]

Objectives

The purpose of this study is to compile and review the body of literature related to kMRI of the cervical spine.

Materials and Methods

We performed a search in accordance with PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines for transparent reporting of systematic reviews and meta-analyses.[7] Medline was searched through February 2014 to identify studies related to kMRI of the cervical spine. Texts were selected if they met the following criteria: adult patients, kMRI defined as MRI in two or more positions, results relating the cervical spine only. Texts were excluded if they did not meet the inclusion criteria, were case reports, or focused on imaging or positioning techniques instead of

received
March 7, 2014
accepted after revision
March 19, 2014
published online
April 29, 2014

DOI http://dx.doi.org/10.1055/s-0034-1375563.
ISSN 2192-5682.

Fig. 1 Kinetic magnetic resonance imaging positioning. (A) Neutral. The patient is seated in an upright, weight-bearing position at 0 degrees. (B) Flexion. The patient is positioned with chin angled toward chest at 40 degrees of flexion. (C) Extension. The patient is positioned with chin angled upwards in −20 degrees of extension.[14]

clinical findings. Overall, 127 citations were identified, of which 16 fulfilled our criteria.

Results

Dynamic Changes in Neuroforaminal Size

Muhle et al prospectively examined 30 healthy volunteers to assess functional changes in neuroforaminal size during flexion, extension, and axial rotation. Volunteers were measured in 40, 30, 20, and10 degrees of flexion; neutral; −10, −20, and −30 degrees of extension; 20 and 40 degrees of axial rotation to the right and left in neutral. The foramen widened in flexion up to 31% compared with neutral and degreased up to 20% in extension. With 20 and 40 degrees of rotation, the ipsilateral foramen decreased in size by 15 and 23%, and the contralateral foramen increased by 9 and 20%.[8]

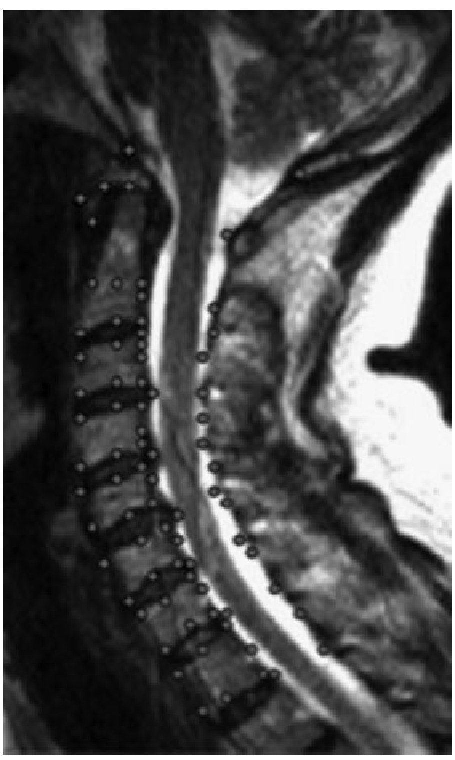

Fig. 2 A representative example of points marked for measurement.[15]

Length of Cervical Cord and Cross-Sectional Area of Cord

Kuwazawa et al prospectively examined the relationship between posture and the length of the cervical cord in 20 healthy volunteers. Subjects were studied in neutral, flexion, and extension in both supine and erect positions. The length of the cervical cord was defined as the length between a line that crosses the cord at the upper edge of the anterior and posterior arches of C1 to the continuation of the line of the lower end plate of C7. In both supine and upright series, the cervical cord was longer in flexion compared with neutral and extension at the anterior, middle, and posterior portions. The cord length varied between flexion, extension, and neutral.[6] In a separate study, Kuwazawa et al also examined the cross-sectional area of the cervical cord (ACSCC) in these same positions. In both supine and upright positions, the ACSCC was greater in extension compared with neutral and flexion at all levels. ACSCC was smaller in flexion than neutral or extension at all levels.[4]

Segmental Motion at Levels Adjacent to Disk Herniation

Daffner et al and Fei et al retrospectively reviewed kMRIs of 407 asymptomatic patients to assess for changes in segmental motion at levels adjacent to disk herniation. Translational motion, angular variation, disk height, and disk degeneration were assessed for each level from C2–3 to C7–T1. Levels above disk herniation had a 7.2% decrease in translational motion per millimeter of disk herniation and levels below did not change.

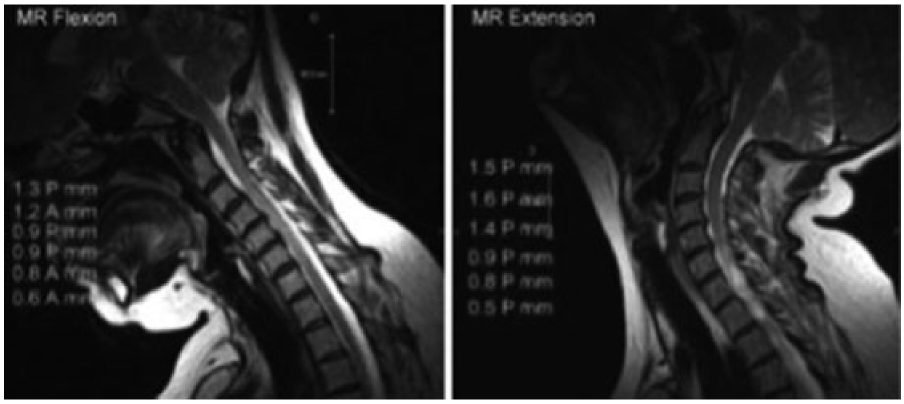

Fig. 3 Representative flexion and extension sagittal slices.[15]

Levels above the disk herniation did not experience a change in angular variation and levels below had a decrease of 5.2% per millimeter of herniation. Degree of disk degeneration was not correlated with changes in translational motion or angular variation of adjacent segments. Disk degeneration was associated with increased disk height below and decreased disk height above, but disk herniation was not correlated with a difference in disk height at adjacent levels.[9,10]

Evaluation of Cervical Spine Changes in Individualized Provocative Positions

A study by Muhle et al examined changes in the cervical spine according to individualized provocative maneuvers. A total of 21 patients, 17 with disk herniation and 4 with cervical spondylosis, were examined prospectively. Each patient had symptoms elicited by flexion, extension, axial rotation, or a combination of positions. Patients were examined at neutral and in their individualized provocative position. There were no changes in the size of disk herniation in any provocative position compared with neutral. Cervical cord rotation or displacement was seen in the provocative position for five patients (axial rotation $n = 3$, extension and axial rotation $n = 2$). When patients combined axial rotation toward the pain with extension, foraminal size decreased. There was no change or a decrease in foraminal size in extension or axial rotation toward the painful side.[11]

Jaumard et al conducted a prospective study with a similar method in which they sought to define anatomic changes between neutral and pain-provoking maneuvers in patients with: (1) radicular symptoms, evidence of root compression and positive electromyogram (EMG), (2) radicular symptoms, no evidence of root compression and positive EMG, and (3) asymptomatic controls. In lieu of a pain-provoking position, asymptomatic controls were scanned in left and right axial torsion. A total of 18 patients were scanned. There were no differences identified between symptomatic and asymptomatic patients as a whole, but several differences were identified differences in cord-to-canal distances between the three groups.[5]

Kinematics of the Upper Cervical Spine

Morishita et al retrospectively studied the kinematics of the upper cervical spine. A total of 60 patients with neck pain and cervical spondylosis without neurogenic symptoms were examined and sorted into three groups based on space available for cord (SAC) at the level of the atlantoaxial articulation. Measurements were taken of the anterior atlantodens interval (AADI) and the cervicomedullary angle in flexion neutral, and extension and differences were calculated between each position. AADI increased significantly from extension to flexion, but there were no differences in each posture between groups. The cervicomedullary angle increased from flexion to extension, but there were no differences in each posture by group. There was a greater change in AADI between neutral and extension in patients with >14 mm of SAC compared with those with <14 mm. Patients who had >15 mm of SAC also had a greater change in AADI from flexion to extension compared with patients with <14 mm of SAC. There were no other differences between AADI between groups and positions. There were no correlations between AADI and cervicomedullary angle. The authors concluded that only the kinematics of atlantoaxial movement were restricted in patients with less SAC.[12]

Kinematics of the Upper and Subaxial Cervical Spine

Hayashi et al examined the relationship between supper cervical spine motion and intervertebral disk degeneration in the subaxial spine in patients with cervical spondylosis. kMRIs were reviewed of 446 patients with neck pain with and without neurologic symptoms and classified into tertiles based on sagittal angular motion. The authors found a significant decrease in subaxial angular motion as grade of disk degeneration increased. The angular motion of Oc–C1 was greater in patients with decreased subaxial sagittal motion. The authors concluded that Oc–C1 was able to provide compensation for motion lost in the subaxial spine secondary to disk degeneration.[13]

Segmental Motion and Its Relationship to Disk Degeneration, Sagittal Alignment, and Cord Compression

Miyazaki et al investigated the relationship between changes in in sagittal alignment, kinematics, and disk degeneration. A total of 201 patients with mild neck pain with and without neurologic symptoms were evaluated retrospectively by kMRI. Patients were divided into five groups based on C1–7 Cobb angle of sagittal alignment in neutral: kyphosis, straight, hypolordosis, normal, and hyperlordosis. Angular variation and translational motion tended to decrease as alignment changed from normal to less lordotic. Patients with hypolordosis had a greater contribution of C1–2, C2–3, and C3–4 and less contribution of C4–5, C5–6, and C6–7 to total angular mobility compared with patients with normal alignment. As lordosis decreased, there was an association with higher grade of disk degeneration at C2–3 and C3–4. The authors concluded that changes in the sagittal alignment of the cervical spine affect kinematics and the relative contribution of each motion segment to mobility.[14]

In a separate retrospective study of 168 symptomatic patients, Miyazaki et al found that translational motion was greater in disks with intermediate degeneration compared with those with mild degeneration. Translational motion and angular variation was significantly less for disks with severe degeneration compared with those with less degeneration. Levels C4–5 and C5–6 provided the majority of total angular mobility for disks with normal to mild degeneration. In disks with severe degeneration, the mobility of levels C4–5 and C5–6 were significantly decreased. Thus as disk degeneration progressed, there were changes in translational motion and angular variation.[15]

Morishita et al retrospectively reviewed kMRIs in flexion, neutral, and extension of 289 patients with neck pain with or without neurologic symptoms in the setting of cervical spondylosis. Each segment was assessed for disk degeneration, cord compression, and segmental mobility. Segmental mobility was defined as the sagittal angular motion of each segment as a proportion of the total sagittal motion of the cervical spine between flexion and extension. There was less segmental mobility in patients with severe cord compression and moderate disk degeneration compared with those with both severe cord compression and severe disk degeneration. In segments with moderate disk degeneration, severe cord compression was associated with less segmental mobility compared with no cord compression. In segments with severe disk degeneration, the degree of cord compression was not correlated with changes in mobility.[16]

Prevalence and Kinematics of Spondylolisthesis

Suzuki et al retrospectively studied the prevalence of degenerative cervical spondylolisthesis in 468 patients with neck pain with or without neurologic symptoms. They described the associated between grade of spondylolisthesis, disk degeneration, angular motion, translational motion, and SAC. Spondylolisthesis at one or more levels was observed in 20% of patients; 3.4% of all patients had listhesis greater than 3 mm. Levels with spondylolisthesis had more severe disk degeneration compared with levels without. Translational motion was greater in levels with 2 to 3 mm of listhesis compared with segments without. Translational instability was observed more frequently (16.7%) in levels with >3 mm of listhesis compared with those with 2 to 3 mm of listhesis (4.3%) or no listhesis (3.4%). There was greater cord compression and less SAC in levels with spondylolisthesis. Here kMRI was able to demonstrate the spondylolisthesis was associated with decreased segmental SAC and increased translational motion.[17]

Cervical Spine Canal Diameter and Degenerative Changes

Morishita et al examined the relationship between spinal canal narrowing and pathologic changes of the cervical spine, including disk degeneration, cervical cord compression, and cervical mobility. They retrospectively examined kMRIs of 295 patients with neck pain with or without neurologic symptoms and divided patients into groups based on canal diameter < 13 mm, 13 to 15 mm, and > 15 mm. Patients with canals < 13 mm had a higher grade of disk degeneration at C3–4, C5–6, and C6–7 compared with patients with wider canals. Patients with canals < 13 mm also had more pronounced disk degeneration at C4–5 compared with patients with canals > 15 mm. There was greater cord compression in patients with canals < 13 mm compared with patients with wider canals at C3–4 and C5–6. Comparing patients with canals < 13 mm to those with canals > 15 mm, patients with smaller canals had more cord compression at every level except C2–3. Between the three groups, there were no differences in angular mobility observed, although percent segmental mobility was significantly greater at C4–5, C5–6, and C6–7 in patients with canals <13 mm compared with patients whose canals were 13–15 mm.[18] This study demonstrated that the congenitally narrow canal is associated with unique kinematic and pathologic traits.

Paraspinal Muscle Fatty Degeneration and Segmental Motion

A study by Inoue et al retrospectively reviewed kMRIs of 188 patients with symptoms of neck pain or radiculopathy. Fatty degeneration of the bilateral cervical multifidus muscles was assessed. Cervical spine motion was assessed in terms of angular variation and translational motion of each segment. These measurements were made on midsagittal images in flexion, neutral, and extension. Disk degeneration was assessed in neutral position on a graded scale. There was more fatty infiltration at C3 and C7 compared with middle levels. At C4, the grade of disk degeneration was higher in patients with <25% fatty infiltration. Angular variation was greater in patients with <25% fatty infiltration compared with those with >25% infiltration. Otherwise, the amount of fatty infiltration was not correlated with a difference in angular variation, translational motion, Cobb angle, or disk degeneration at any level.[19] This study demonstrated that fatty degeneration had a negligible effect of segmental movement of the cervical spine.

Dynamic Changes of the Ligamentum Flavum

Sayit et al retrospectively reviewed kMRIs to quantify changes of ligamentum flavum as the cervical spine moved through flexion, neutral, and extension. A total of 257 patients with symptoms of neck pain with and without radiculopathy were examined. Ligamentum flavum thickness was significantly greater in extension compared with flexion at levels C3–4, C4–5, C5–6, and C6–7; there was no difference at levels C2–3 or C7–T1. Ligamentum flavum thickness was significantly greater at C7–T1 than all other levels throughout all positions.[20]

Discussion

In this systematic review, we sought to summarize the recent data produced by kMRI of the cervical spine. A total of 16 studies were identified that examined characteristics of the cervical spine using MRI of subjects in two or more positions (►**Table 1**).

Kuwazawa et al conducted two studies that looked at flexion, extension, and neutral in both supine and upright positions. They found changes in the cord length and cross-sectional area between flexion, extension, and neutral regardless of whether the patient was supine or upright.[4,6] Muhle et al defined changes in foraminal size with axial rotation in addition to flexion, extension, and neutral positions.[8]

Table 1 Summary of literature and findings

Lead author	Type of study	Number of subjects	Subject type	Year	Findings
Muhle[8]	Prospective	30	Healthy	2001	Neuroforaminal size changed with axial rotation, flexion, extension, and neutral positioning
Kuwazawa[6]	Prospective	20	Healthy	2006	Cord length in the cervical spine changed according to position
Kuwazawa[4]	Prospective	20	Healthy	2006	Cross-sectional area of the cord changed according to position
Daffner[9]	Retrospective	407	Healthy	2009	Changes in motion at levels adjacent to disk herniation and degeneration defined
Fei[10]	Retrospective	407	Healthy	2011	Changes in motion at levels adjacent to disk herniation and degeneration defined
Muhle[11]	Prospective	21	Symptomatic	1998	Changes according to individualized provocative positions examined
Jaumard[5]	Prospective	18	Mixed	2013	Anatomic changes in provocative positions examined
Morishita[12]	Retrospective	60	Symptomatic	2009	Kinematic relationships of the occipitoatlantoaxial complex defined
Hayashi[13]	Retrospective	446	Symptomatic	2013	Occiput–C1 motion increased in patients with decreased subaxial motion in the setting of disk degeneration
Miyazaki[14]	Retrospective	201	Symptomatic	2008	Sagittal alignment affected kinematics and contributions to motion of each segment
Miyazaki[15]	Retrospective	168	Symptomatic	2008	Changes in mobility occurred as disk degeneration progressed
Morishita[16]	Retrospective	289	Symptomatic	2008	Kinematics differed according to cord compression
Suzuki[17]	Retrospective	468	Symptomatic	2013	Spondylolisthesis was associated with greater translational motion and decreased canal diameter
Morishita[18]	Retrospective	295	Symptomatic	2009	Congenitally narrow canals were associated with certain kinematic and pathologic traits
Inoue[19]	Retrospective	188	Symptomatic	2012	Fatty degeneration of paraspinal muscles did not affect segmental movement
Sayit[20]	Retrospective	257	Symptomatic	2013	Defined changes in ligamentum flavum thickness noted with movement

Multiple studies examined patients in an upright, weight-bearing position with flexion patients at 40 degrees of flexion, neutral, and −20 degrees of extension.[9,10,12–20] These studies were able to demonstrate several important findings. Daffner et al and Fei et al demonstrated the relationships between disk degeneration, disk herniation, disk height, translational motion, and angular variation. The authors concluded that, because disk herniation does not significantly increase motion in adjacent segments, the development of adjacent segment disease may be more the result of fusion as opposed to intrinsic properties of the disk.[9,10] Morishita et al defined the kinematic relationships of the occipitoatlantoaxial complex and found that only the kinematics of atlantoaxial movement are affected by narrowing of the SAC.[12] Hayashi et al elucidated the compensatory role of Oc–C1 motion when subaxial motion is lost in the setting of disk degeneration.[13] Miyazaki et al examined segmental motion in relation to sagittal alignment and disk degeneration. They concluded that changes in the sagittal alignment of the cervical spine affect kinematics and the relative contribution of each motion segment to mobility, thereby the progress of degeneration in the cervical spine.[14] They also concluded that changes in mobility occur with disk degeneration that progresses from normal motion to unstable to ankylosed.[15] Morishita et al found that cord compression may cause kinematic changes in the spine and hypothesized that that restricting segmental motion may be a mechanism to protect the spinal cord from compression.[16] Suzuki et al demonstrated that spondylolisthesis was associated with greater translational motion and decreased canal diameter.[17] Morishita et al demonstrated the unique kinematic traits of congenitally narrow canals and found that patients with narrow canals may be at increased risk of pathologic changes.[18] Inoue et al found that fatty degeneration had a negligible effect of segmental movement of the cervical spine.[19] Sayit et al defined changes in ligamentum flavum thickness.[20]

The provocative positioning studies by Jaumard et al and Muhle et al are interesting in that they sought to identify changes in positions that provoked symptoms, which often have a rotational component, as opposed to purely flexion and extension.[5,11] Unfortunately, these studies were limited in their samples sizes. Although performing kMRI in this manner would be clinically useful, especially in patients with negative findings on conventional MRI and EMG, performing these studies may be challenging for patients to remain in a provocative position long enough for imaging to be performed. In the study by Jaumard et al, 2 of the 10 symptomatic patients were unable to remain stationary long enough for images to be obtained.[5,11]

A limitation of this review is that there is a combination of retrospective and prospective studies. Furthermore, although all studies have patients in greater than one position, no standard exists for kMRI positioning; therefore, there is some variability in positioning between studies.

Although kMRI is a topic of interest in research, little is known about its use in the clinical setting. Provocative or flexion and extension positions during kMRI may be especially useful in the setting of negative findings on static MRI and EMG. kMRI in flexion and extension positions may be used to investigate translational instability and cord compression in the setting of spondylolisthesis. In addition, it may be worthwhile to obtain kMRIs on patients prior to surgical planning. This could help identify positional compression or stenosis in addition to positional instability. An area of further research using kMRI should be prospectively examining kMRIs of patients who do not have findings on conventional MRI to explore pathology that may have been missed. Another area that has yet to be studied is the progression of kinematic changes in adjacent segments following fusion.

Conclusions

KMRI is able to demonstrate findings that are not apparent on conventional MRI. It may be useful in a clinical setting when conventional imaging and diagnostic techniques fail to identify the source of a patient's cervical pathology.

Disclosures
Shinji Takahashi received funding from an AO spine fellowship. Elizabeth L. Lord, Raed Alobaidan, Jeremiah R. Cohen, Christopher J. Wang, and Benjamin J. Wang received no funding for this study. Jeffrey C. Wang is a Board member of AO Foundation, NASS, CSRS, CSRF; receives royalties from Biomet, Stryker, Alphatech, Synthes, Amedica, Osprey, Aesculap, Seaspine; has stock/stock options in FzioMed, Promethean Spine, Paradigm Spine, Benevenue, NexGen, Pioneer, Amedica, Vertiflex, Electrocore, Surgitech, Axiomed, VG Innovations, Corespine, Expanding Orthopaedics, Syndicom, Osprey, Bone Biologics, Curative Biosciences, PearlDiver, and Pioneer.

References

1 Muhle C, Metzner J, Weinert D, et al. Kinematic MR imaging in surgical management of cervical disc disease, spondylosis and spondylotic myelopathy. Acta Radiol 1999;40(2):146–153
2 Schlamann M, Reischke L, Klassen D, et al. Dynamic magnetic resonance imaging of the cervical spine using the NeuroSwing System. Spine (Phila Pa 1976) 2007;32(21):2398–2401
3 Gerigk L, Bostel T, Hegewald A, et al. Dynamic magnetic resonance imaging of the cervical spine with high-resolution 3-dimensional T2-imaging. Clin Neuroradiol 2012;22(1):93–99
4 Kuwazawa Y, Bashir W, Pope MH, Takahashi K, Smith FW. Biomechanical aspects of the cervical cord: effects of postural changes in healthy volunteers using positional magnetic resonance imaging. J Spinal Disord Tech 2006;19(5):348–352
5 Jaumard NV, Udupa JK, Siegler S, et al. Three-dimensional kinematic stress magnetic resonance image analysis shows promise for detecting altered anatomical relationships of tissues in the cervical spine associated with painful radiculopathy. Med Hypotheses 2013;81(4):738–744
6 Kuwazawa Y, Pope MH, Bashir W, Takahashi K, Smith FW. The length of the cervical cord: effects of postural changes in healthy volunteers using positional magnetic resonance imaging. Spine (Phila Pa 1976) 2006;31(17):E579–E583
7 Liberati A, Altman DG, Tetzlaff J, et al. The PRISMA statement for reporting systematic reviews and meta-analyses of studies that evaluate health care interventions: explanation and elaboration. PLoS Med 2009;6(7):e1000100

8 Muhle C, Resnick D, Ahn JM, Südmeyer M, Heller M. In vivo changes in the neuroforaminal size at flexion-extension and axial rotation of the cervical spine in healthy persons examined using kinematic magnetic resonance imaging. Spine (Phila Pa 1976) 2001;26(13):E287–E293
9 Daffner SD, Xin J, Taghavi CE, et al. Cervical segmental motion at levels adjacent to disc herniation as determined with kinetic magnetic resonance imaging. Spine (Phila Pa 1976) 2009;34(22):2389–2394
10 Fei Z, Fan C, Ngo S, Xu J, Wang J. Dynamic evaluation of cervical disc herniation using kinetic MRI. J Clin Neurosci 2011;18(2):232–236
11 Muhle C, Bischoff L, Weinert D, et al. Exacerbated pain in cervical radiculopathy at axial rotation, flexion, extension, and coupled motions of the cervical spine: evaluation by kinematic magnetic resonance imaging. Invest Radiol 1998;33(5):279–288
12 Morishita Y, Falakassa J, Naito M, Hymanson HJ, Taghavi C, Wang JC. The kinematic relationships of the upper cervical spine. Spine (Phila Pa 1976) 2009;34(24):2642–2645
13 Hayashi T, Daubs MD, Suzuki A, et al. The compensatory relationship of upper and subaxial cervical motion in the presence of cervical spondylosis. J Spinal Disord Tech 2013; September 27 (Epub ahead of print)
14 Miyazaki M, Hymanson HJ, Morishita Y, et al. Kinematic analysis of the relationship between sagittal alignment and disc degeneration in the cervical spine. Spine (Phila Pa 1976) 2008;33(23):E870–E876
15 Miyazaki M, Hong SW, Yoon SH, et al. Kinematic analysis of the relationship between the grade of disc degeneration and motion unit of the cervical spine. Spine (Phila Pa 1976) 2008;33(2):187–193
16 Morishita Y, Hida S, Miyazaki M, et al. The effects of the degenerative changes in the functional spinal unit on the kinematics of the cervical spine. Spine (Phila Pa 1976) 2008;33(6):E178–E182
17 Suzuki A, Daubs MD, Inoue H, et al. Prevalence and motion characteristics of degenerative cervical spondylolisthesis in the symptomatic adult. Spine (Phila Pa 1976) 2013;38(17):E1115–E1120
18 Morishita Y, Naito M, Hymanson H, Miyazaki M, Wu G, Wang JC. The relationship between the cervical spinal canal diameter and the pathological changes in the cervical spine. Eur Spine J 2009;18(6):877–883
19 Inoue H, Montgomery S, Aghdasi B, et al. Analysis of relationship between paraspinal muscle fatty degeneration and cervical spine motion using kinetic magnetic resonance imaging. Global Spine J 2012;2(1):33–38
20 Sayit E, Daubs MD, Aghdasi B, et al. Dynamic changes of the ligamentum flavum in the cervical spine assessed with kinetic magnetic resonance imaging. Global Spine J 2013;3(2):69–74