

Predictability of severity of disc degeneration and disc protrusion using horizontal displacement of cervical dynamic radiographs

A retrospective comparison study with MRI

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Abstract

The aim of this study is to investigate the usefulness of flexion-extension (dynamic) radiographs in evaluating the severity of disc degeneration and disc protrusion in cervical magnetic resonance image (MRI). Patients complaining of neck or arm pain with no prior surgical history and who had undergone both cervical MRI and dynamic radiographs were included in this study. The following patients were excluded: those who had any history of trauma, autoimmune disease such as rheumatoid arthritis or ankylosing spondylitis, prior cervical fracture or prior cervical spine surgery. Based on these criteria, 161 patients who visited our department for neck pain or upper extremity radicular symptoms were initially included retrospectively. Among them, 69 patients were excluded due to the lack of cervical MRI or dynamic radiographs. Therefore, a total of 92 patients were included for analysis in this study. The maximal diameter of disc protrusion in sagittal or axial MRI, the severity of cervical disc degeneration, and segmental horizontal displacement in dynamic cervical radiographs are the main outcome measurements. In the results of this study, the extension radiograph of C5/6 had the highest sensitivity (93.33%) and specificity (100%) in predicting cervical disc protrusion followed by C4/5 (sensitivity; 77.28%, specificity 92.86%) among the dynamic radiographs. Segmental horizontal displacement at the C3/4, C4/5, and C5/6 level in the neutral and extension radiographs had a significant correlation with the severity of cervical disc degeneration in MRI ($P < .05$). At the C6/7 level, however, only extension radiograph had a significant correlation with the severity of cervical disc degeneration in the MRI ($P < .05$). In conclusion, if MRI is not available in a primary clinical setting, dynamic cervical radiographs may be useful in predicting the severity of degenerative disc and disc protrusion in cervical MRI. Among the dynamic cervical radiographs, the extension radiograph was the most sensitive for predicting the severity of cervical disc degeneration and disc protrusion, especially at the C3/4, C4/5, C5/6, and C6/7 levels in MRI.

Abbreviations: AP = antero-posterior, ICC = interclass correlation coefficient, MRI = magnetic resonance image, PLL = posterior longitudinal ligament, RT = repetition time, TE = echo time.

Keywords: cervical radiograph, disc degeneration, dynamic X-ray, magnetic resonance image

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1. Introduction

The intervertebral disc forms a fibro-cartilaginous joint between the vertebrae and consists of 3 distinct components, including the nucleus pulposus, the annulus fibrosus, and the cartilaginous endplates.^[1] In intervertebral discs, progressive morphologic and cellular changes occur with age and degeneration.^[2,3]

Magnetic resonance imaging (MRI) can provide a noninvasive morphologic evaluation of the cervical spine and intervertebral disc.^[4] Especially in T2-weighted MRI, progressive degenerative changes of the intervertebral disc can be observed in accordance with the reduction of signal intensity.^[5] In clinical practice, however, MRI has a problem as a routine examination due to its high cost compared to its advantages in diagnosing cervical disc diseases, such as radiculopathies. On the contrary, upright antero-posterior (AP) and neutral lateral radiographs are routinely obtained for the evaluation of the cervical spine in clinical practice.^[6] However, those radiographs are less useful compared to MRI in diagnosing cervical disc diseases. While the usefulness of flexion-extension radiographs in the evaluation of the spine trauma patient is well accepted,^[7,8] the role of dynamic radiographs in nontrauma population has not been well defined thus far.^[6] One previous study investigated the utility of flexion-extension radiographs in evaluating the degenerative cervical spine; however, the researchers investigated only the additional utility obtained from

dynamic radiographs in detecting a listhesis compared with the neutral plain radiographs (segmental horizontal displacement). This study concluded that dynamic radiographs should no longer be regarded as a useful part of the initial imaging for patients with degenerative cervical disease.^[6]

Unlike the previous study, we hypothesized that the listhesis in dynamic cervical radiographs may be useful in predicting the severity of cervical disc degeneration and disc protrusion, because listhesis is a process of continuous change resulting from segmental instability in the spine after degenerative change in the cervical intervertebral disc. So, in this study, we investigated the possibility of cervical dynamic radiographs as a diagnostic tool for predicting the severity of cervical disc degeneration and disc protrusion.

2. Materials and methods

2.1. Patients

This study received Institutional Review Board approval. Among the patients who visited our department, those with axial neck pain or upper extremity radicular symptoms were investigated retrospectively. Patients who had undergone both cervical MRI and dynamic radiographs were included. The following patients were excluded: those who had any history of trauma, autoimmune disease such as rheumatoid arthritis or ankylosing spondylitis, prior cervical fracture or prior cervical spine surgery. Based on these criteria, 161 patients who visited our department for neck pain or upper extremity radicular symptoms between September 2013 and December 2016 were initially included. Among them, 69 patients were excluded due to the lack of cervical MRI or dynamic radiographs. Therefore, a total of 92 patients were included for analysis in this study (Fig. 1).

2.2. Image acquisition

Among the 92 patients included our study, 4 patients had undergone cervical MRI and dynamic radiography at another hospital. The remaining 88 patients' dynamic radiographs and cervical MRI were obtained by the following methods. AP and neutral lateral radiographs were taken with the patients in their natural posture. In addition, flexion-extension radiographs were taken by asking each patient to achieve his or her maximum effort at flexion and extension. The cervical MRI scans were performed with a 1.5-tesla (Avanto, Siemens, Germany) with gradients between 33 mT/m and 1 slew rate of 150T/ms. The protocol included the following: T1-

weighted SE sagittal sequences with 400 milliseconds repetition time (TR), 7.4 milliseconds echo time (TE), 90 flip angle with a thickness of 3 mm; T2-weighted FFE sagittal sequences with 3500 milliseconds TR, 120 milliseconds TE, 90 flip angle with a 3 mm thickness; axial sequences on T2-weighted FFE 3D, 50 milliseconds TR, 12 milliseconds TE, 7 flip angle, 0.5 mm thickness.

2.3. Image analysis

All radiograph analysis was performed by 2 independent physiatrists who were blinded to the results of MRI evaluation. The digital radiographs were viewed using the preview program (INFINITT, Seoul, South Korea).^[9] All measurements were made with digital measuring tools. In the dynamic radiographs, the presence of listhesis as well as the degree of listhesis was finally recorded. The listhesis was measured on these lateral radiographs as the AP distance from the posterior-inferior cortex of the upper vertebrae to the posterior-superior cortex of the inferior vertebrae.^[6] A positive value indicated anterior displacement (anterolisthesis), whereas a negative value indicated posterior displacement (retrolisthesis) (Figs. 2–4).

We used a slice in which the disc protrusion was most prominent in the sagittal or axial images and measured the maximal diameter of the protruding disc.^[4] The posterior aspect line between the rostral and caudal vertebral body was used as the standard, and we measured the maximal diameter of the disc protrusion from the standard line to the posterior top of the disc protrusion.^[4] The direction of disc protrusion was also classified as posterior protrusion and postero-lateral protrusion based on the direction of the maximally protruding disc. Posterior protrusion was defined if the angle between the direction of the maximally protruding cervical disc and the mid-line of vertebral body in the axial image was $<45^\circ$. Postero-lateral disc protrusion was, if the angle between the direction of the maximally protruding cervical disc and the mid-line of the vertebral body in the axial image, $>45^\circ$.

We also evaluated the degeneration of the intervertebral discs in the MRI. The severity of degeneration of the cervical disc was defined according to the modified Pfirrmann classification system,^[10,11] a range from 1 to 5. Measurement of the segmental displacement and the maximal diameter of the protruding disc was repeated to test the reliability of the measurements, and the interclass correlation coefficient (ICC) of each parameter for inter- and intra-rater reliability was calculated using SPSS software, version 22.0 (SPSS, Chicago, IL).

2.4. Statistical analysis

Statistical analysis was performed using the SPSS software, version 22.0 (SPSS). We determined the sensitivity, specificity, accuracy, negative predictive value, positive predictive value, and relative risk using 2/2 correlation tables by the segmental displacement in dynamic radiographs versus cervical disc protrusion in MRI. The Spearman correlation test was used to evaluate the correlation between the degree of segmental displacement in the dynamic radiographs and the severity of degenerative cervical disc and protrusion in the cervical spine MRI, and $P < .05$ was considered statistically significant.

3. Results

3.1. Reliability of the measurement

The ICC for intra-rater reliability was 0.89 ± 0.04 for segmental displacement, and 0.91 ± 0.05 for the maximal diameter of the protruding cervical disc. The ICC for inter-rater reliability was

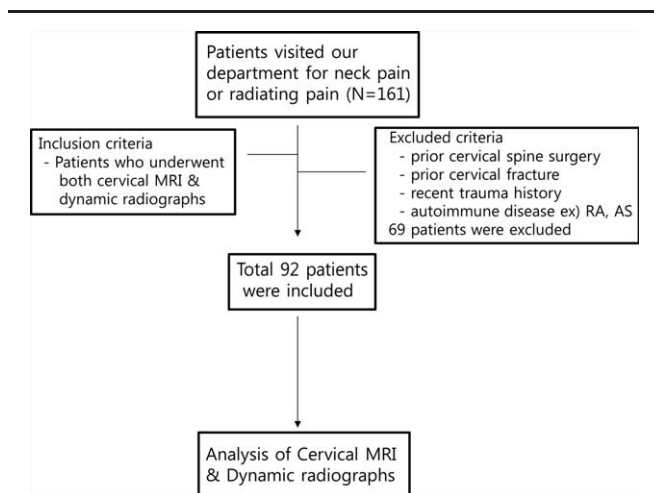


Figure 1. Flow chart of this study.

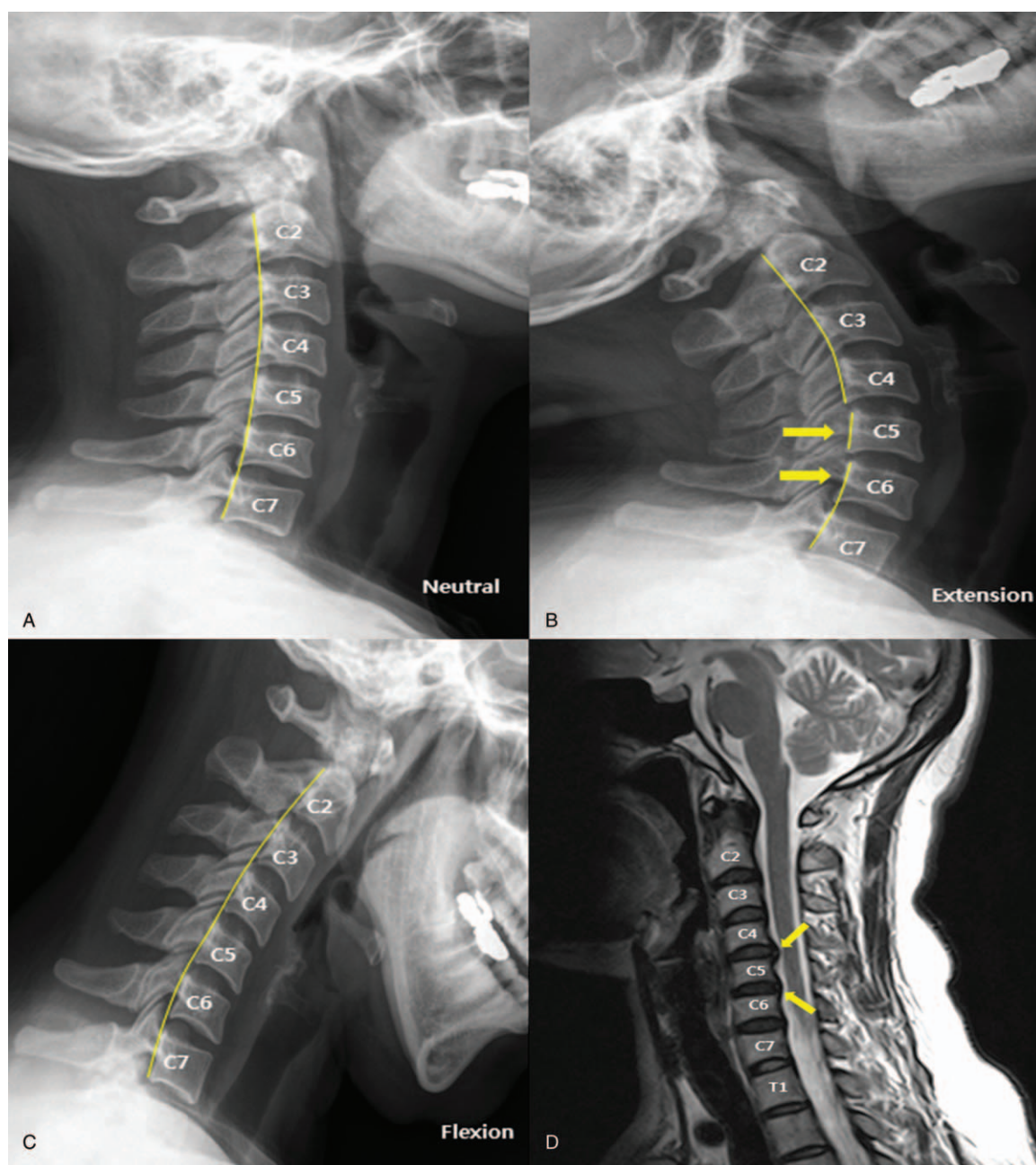


Figure 2. Cervical dynamic radiographs and magnetic resonance images (MRIs). (A) Neutral radiograph. The segmental displacement was not observed in neutral radiograph. (B) Extension radiograph. The segmental displacement between C4 and C5, and between C5 and C6 were observed. (C) Flexion radiograph. The segmental displacement was not observed in flexion radiograph. (D) T2-weighted sagittal MRI of the cervical spine. Disc protrusion between C4 and C5, and between C5 and C6 were observed. Disc protrusion in MRI was consistent with segmental displacement in extension radiograph.

0.87 ± 0.02 for segmental displacement, and 0.84 ± 0.04 for the maximal diameter of the protruding cervical disc. The following classification scheme was used for ICC: <0.40 =poor, 0.40 to 0.59 =fair, 0.60 to 0.74 =good, and >0.74 =excellent.^[12,13] Thus, the measurement method for these parameters was considered to be reliable.

3.2. Patient characteristics

We reviewed the medical records of 92 patients with an age range of 23 to 68 years (46.00 ± 11.81 years). Of these, 68 (73.9%) were males and 24 (26.1%) were females.

3.3. Dynamic radiograph analysis

In dynamic radiographs, an extension radiograph showed more listhesis (segmental horizontal displacement) compared to neutral and flexion radiographs. Among the extension radiographs, segmental displacement between C4/5 and C5/6 was more frequent than any other cervical disc levels (Table 1). The average degrees of listhesis between C5 and 6 were 1.80 ± 0.65 mm in neutral, 1.92 ± 0.85 mm in extension, and 1.29 ± 0.27 mm in flexion radiographs, respectively. The average degrees of listhesis in patients who had a listhesis between C7 and T1 vertebral body in neutral, extension, and flexion radiographs were 0 mm, -0.48 ± 1.47 mm, and -1.41 mm, respectively (Table 1). The average degree of listhesis in other levels is shown in Table 1.

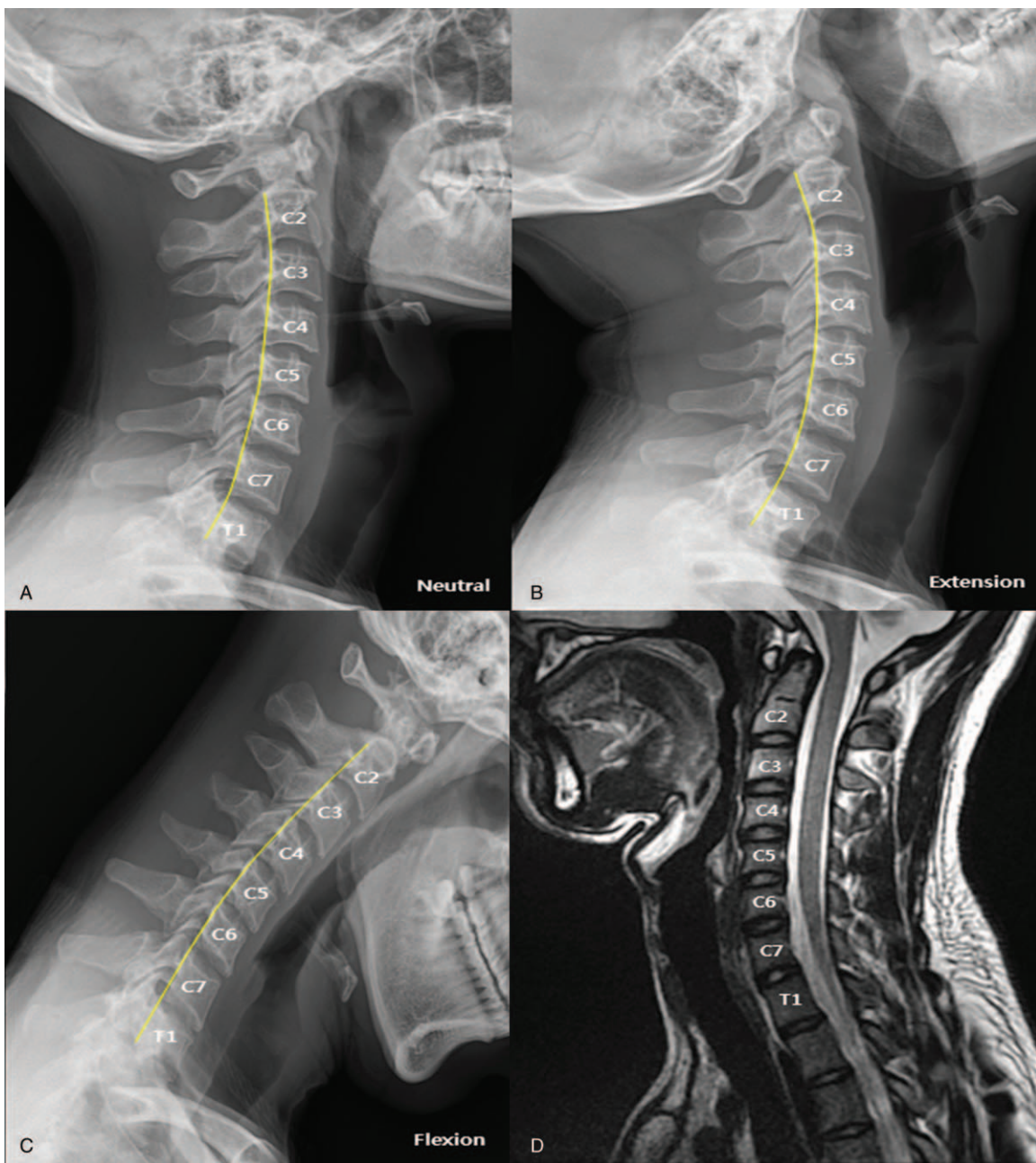


Figure 3. Cervical dynamic radiographs and magnetic resonance images (MRIs). (A) Neutral radiograph. The segmental displacement was not observed in neutral radiograph. (B) Extension radiograph. The segmental displacement was not observed. (C) Flexion radiograph. The segmental displacement was not observed in flexion radiograph. (D) T2-weighted sagittal MRI of the cervical spine. Disc protrusion was not observed in cervical MRI.

3.4. MRI analysis

A total of 88 (95.7%) patients had a protruding cervical disc at more than one disc level. There was no patient with a protruding C2/3 disc, but 9 (39.13%) patients had a protruding C3/4 disc, 52 (56.52%) patients had a protruding C4/5 disc, 45 (65.22%) patients had a protruding C5/6 or C6/7 disc, and 2 (8.70%) patients had a protruding C7/T1 disc (Table 1). Among the patients with a protruding C5/6 disc, 5 (33.33%) had a posteriorly protruding disc and 10 (66.67%) had a posterolaterally protruding disc (Table 1). The results of the other cervical levels are shown in Table 1.

3.5. Relation between dynamic radiographs and findings in cervical MRI

In the Spearman correlation test, the extension radiograph tended to have more significant correlations with the maximal diameter of the protruding disc in the cervical MRI compared to neutral and flexion radiographs (Table 2). In the neutral radiograph, only segmental displacement between C5 and C6 had a significant correlation with the maximal diameter of the C5/6 protruding disc in MRI ($P < .05$). In the flexion radiograph, there was no segmental displacement which had a significant correlation with any cervical disc level in MRI. However, segmental displacement between C3/C4, C4/C5,

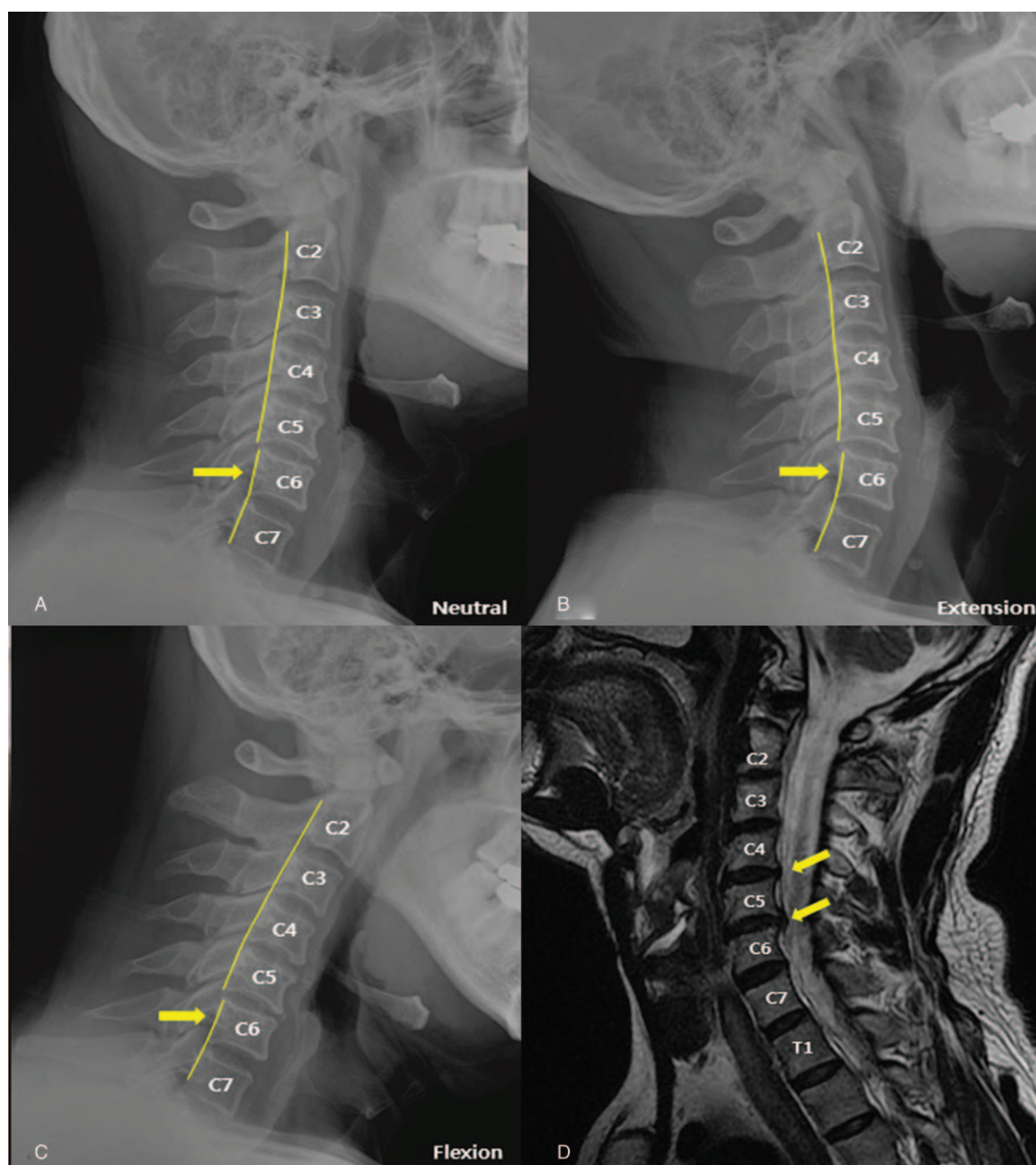


Figure 4. Cervical dynamic radiographs and magnetic resonance images (MRIs). (A) Neutral radiograph. The segmental displacement between C5 and C6 was observed in neutral radiograph. (B) Extension radiograph. The segmental displacement between C5 and C6 was observed. (C) Flexion radiograph. The segmental displacement between C5 and C6 was observed. (D) T2-weighted sagittal MRI of the cervical spine. Disc protrusion between C4 and C5, and between C5 and C6 were observed. Disc protrusion between C5 and C6 in MRI was predicted by dynamic cervical dynamic radiographs, but not disc protrusion between C4 and C5.

and C6/C7 in the extension radiograph had significant correlations with the maximal diameter of the protruding disc in cervical MRI ($P < .05$) (Table 2). In addition, the segmental displacement of C3/4, C4/5, and C5/6 in the neutral and extension radiographs had a significant correlation with the severity of the degenerative disc in cervical MRI ($P < .05$) (Table 2). In C6/7, however, only extension radiographs had a significant correlation with the severity of the degenerative disc in cervical MRI ($P < .05$) (Table 2).

3.6. Diagnostic utility

Among the dynamic radiographs, the segmental displacement of C5/6 in the extension radiograph had the highest sensitivity

(93.33%) and specificity (100%) in predicting cervical disc protrusion followed by C4/5 (sensitivity; 77.28%, specificity 92.86%) (Table 3). The other results of sensitivity, specificity, negative predictive value, positive predictive value, and relative risk are shown in Table 3.

4. Discussion

It is generally accepted that the AP and neutral lateral radiographs of the cervical spine can be helpful in assessing the overall cervical morphology for patients presenting to the clinicians with cervical-related complaints.^[6] The purpose of this

Table 1**Characteristics of patients.**

	C2/3	C3/4	C4/5	C5/6	C6/7	C7/T1
Disc protrusion on MRI, n	0	36	52	60	60	8
Prevalence, %	0	39.13	56.52	65.22	65.22	8.70
Maximal diameter of protruded disc, mm	0	3.21 ± 0.79	2.76 ± 0.85	2.99 ± 0.88	3.21 ± 1.14	2.87 ± 0.64
Direction of disc protrusion, n (%)						
Posterior	0	6 (66.67)	9 (69.23)	5 (33.33)	7 (46.67)	0 (0.00)
Postero-lateral	0	3 (33.33)	4 (30.77)	10 (66.67)	8 (53.33)	2 (100)
Listhesis, n						
Neutral	0	12	12	28	16	0
Extension	8	36	48	52	24	12
Flexion	0	8	0	8	8	4
Degree of listhesis, mm						
Neutral	0	1.91 ± 0.46	2.10 ± 0.17	1.80 ± 0.65	1.80 ± 0.27	0
Extension	1.41 ± 0.17	1.98 ± 0.54	1.63 ± 0.37	1.92 ± 0.85	1.73 ± 0.37	-0.48 ± 1.47
Flexion	0	1.38 ± 0.10	0	1.29 ± 0.27	1.47 ± 0.59	-1.41

MRI = magnetic resonance image.

study was to determine the potential incremental utility of dynamic cervical radiographs in predicting the severity of cervical disc degeneration and disc protrusion after excluding patients with recent history of trauma, prior surgery, rheumatoid arthritis, etc, for which the dynamic cervical radiographs had already been accepted as useful. To the best of our knowledge, the usefulness of flexion-extension radiographs in predicting the severity of degenerative cervical disc and protrusion in MRI has never been investigated.

In this study, extension cervical radiographs tended to have higher sensitivity and specificity to cervical disc protrusion in MRI compared to neutral and flexion radiographs, especially at the C5/6, C3/4, C4/5, and C6/7 disc levels. Especially at the C5/6 disc level, the segmental displacement of extension radiographs had the highest sensitivity (93.33%) and specificity (100%). Moreover, the degree of segmental displacement in extension lateral radiographs had significant correlations with the maximal diameter of the protruding disc at the same level. These findings mean that the segmental displacement in extension radiographs may be useful for predicting a protruding cervical disc in C3/4, C4/5, C5/6, and C6/7 without MRI. However, the utility of other levels such as C2/3 and C7/T1 was less compared to other cervical disc levels. These findings may be because the region from C3 through C7, in contrast to C2 and T1, is bordered by a highly mobile upper cervical region which accommodates approximately half of all cervical motion.^[14] Additionally, we found that the segmental displacement in dynamic radiographs also had significant correlations with the severity of disc degeneration

in cervical MRI. Among the dynamic radiographs, extension radiographs had significant correlations with the severity of disc degeneration, especially in C3/4, C4/5, C5/6, and C6/7. These findings may suggest that disc degeneration also affects the incidence of segmental displacement in dynamic radiographs.

Cervical degeneration is a continual process consisting of 4 phases: dysfunction, disc degeneration, spondylosis, and stabilization.^[14] In the presence of disc degeneration, the constant loading and unloading of the spine associated with normal motion can lead to progressive disc degeneration with consecutive loss of segment height.^[14] These changes lead to increased mobility within the degenerated segments in the cervical spine and these segmental instabilities are aggravated in dynamic cervical motions. In addition, the soft tissues around the cervical spine, such as the posterior longitudinal ligament (PLL), also contribute to these segmental instabilities. The PLL lies behind the vertebral bodies, beginning from the occipital bone to the sacrum.^[15] The PLL, which is composed of 2 layers, links up with the intervertebral disc at multiple levels.^[16,17] The normal biomechanical function of the PLL is believed to maintain the stability of the spine and prevent disc protrusion into the spinal canal.^[18] In cases of degeneration, however, these functions of PLL can obviously be weakened because of the breakdown of the PLL's elasticity and tensile strength.^[19] These biomechanical changes of the PLL are thought to cause a segmental displacement in dynamic radiographs along with a degenerative change of cervical disc. Moreover, tension on PLL can be increased by flexing the neck, which stretches PLL, in contrast to extending

Table 2**Correlation coefficients between MRI findings of cervical disc and the degree of segmental displacement in dynamic radiographs.**

Protrusion diameter	C2/3	C3/4	C4/5	C5/6	C6/7	C7/T1
Neutral radiograph	NC	0.513 (0.012)*	0.213 (0.329)	0.592 (0.003)*	0.086 (0.698)	NC
Extension radiograph	NC	0.722 (<0.001)*	0.451 (0.031)*	0.782 (<0.001)*	0.475 (0.025)*	0.42 (0.854)
Flexion radiograph	NC	0.296 (0.170)	NC	0.317 (0.141)	0.07 (0.750)	0.66 (0.766)
Severity of DD	C2/3	C3/4	C4/5	C5/6	C6/7	C7/T1
Neutral radiograph	NC	0.437 (<0.025)*	0.465 (0.018)*	0.424 (0.022)*	0.257 (0.177)	NC
Extension radiograph	0.395 (0.057)	0.649 (<0.001)*	0.415 (0.021)*	0.592 (0.001)*	0.475 (0.013)*	-0.218 (0.276)
Flexion radiograph	NC	0.106 (0.592)	NC	0.189 (0.332)	0.166 (0.392)	NC

DD = degenerative disc, MRI = magnetic resonance image, NC = not calculable.

* $P < .05$, correlation coefficients.

Table 3**Validity values for cervical dynamic radiographs in predicting the presence of cervical disc protrusion.**

	C2/3	C3/4	C4/5	C5/6	C6/7	C7/T1
Sensitivity, %						
Neutral	NC	22.22	7.69	40.00	33.33	0.00
Extension	NC	77.78	76.92	93.33	60.00	0
Flexion	NC	11.11	0	13.33	13.33	0
Specificity, %						
Neutral	NC	100.00	100.00	100.00	100.00	95.24
Extension	91.30	92.86	90.00	100.00	100.00	90.48
Flexion	NC	100.00	100.00	100.00	100.00	90.48
Accuracy, %						
Neutral	NC	69.57	47.83	60.87	56.22	86.95
Extension	NC	86.96	82.61	95.62	73.91	82.61
Flexion	NC	65.22	43.48	43.48	43.78	82.61
PPV, %						
Neutral	NC	100	100	100	100	0.00
Extension	0.00	87.50	91	100	100	0.00
Flexion	NC	100	NC	100	100	0.00
NPV, %						
Neutral	NC	66.67	45.46	50	44.44	90.91
Extension	100	86.67	75	90	57.14	90.48
Flexion	NC	63.64	43	41	38.10	90.48
Relative risk						
Neutral	NC	3	1.83	2.00	1.80	0.00
Extension	NC	6.56	3.64	10.00	2.33	0.00
Flexion	NC	2.75	NC	1.63	1.62	0.00

NC=not calculable, NPV=negative predictive value, PPV=positive predictive value.

the neck. As the results of our study suggest, the extension radiograph is thought to be more sensitive in predicting protruding cervical disc and degenerative cervical disc in MRI compared with neutral or flexion radiographs.

Previous research that investigated the additional usefulness of cervical dynamic radiographs compared to neutral radiographs could not demonstrate such usefulness in nontraumatic cervical disorders.^[6] These results may be due to the definition of listhesis used in that study. In that study, listhesis was defined as a vertebral slip of >2 mm. So, segmental displacements <2 mm were not investigated. Since the definition of listhesis of the cervical spine is not consistent in previous studies,^[12,20] and listhesis is a process of continuous change resulting from segmental instability in the spine after degenerative change in cervical disc, slightly more precise measurement of displacement may be helpful in predicting accurately the severity of cervical disc and protrusion in MRI.

There were some limitations to the present study. First, we enrolled 92 patients with cervical disorders, which is too small a number to offer meaningful statistical significance. Additionally, we enrolled different individuals of various ages because this study was cross-sectional rather than longitudinal. However, the prevalence of cervical disc disorders was consistent with previous studies.^[21–26] In other words, this study is of relevance as it suggests that the findings of the patients studied here should be able to be applied appropriately to other analogous populations with cervical disc disorders. Further studies that incorporate a higher number of participants and longitudinal periods will be needed to clarify this shortcomings.

5. Conclusion

If MRI is not available in a primary clinical setting, dynamic cervical radiographs may be useful in predicting the severity of degenerative disc and disc protrusion in cervical MRI. Among the

dynamic cervical radiographs, extension radiographs are more sensitive for predicting the severity of degenerative disc and disc protrusion, especially at the C3/4, C4/5, C5/6, and C6/7 levels in cervical MRI. However, further evaluations are needed to facilitate additional treatment, although dynamic cervical radiography can be used to predict the severity of degenerative disc and disc protrusion.

Author contributions

Conceptualization: Chul-Hyun Kim, Jong Moon Hwang, Jin-Sung Park, Seungwoo Han, Donghwi Park.

Data curation: Donghwi Park.

Formal analysis: Donghwi Park.

Investigation: Donghwi Park.

Writing – original draft: Donghwi Park.

References

- [1] Cheung KM, Karppinen J, Chan D, et al. Prevalence and pattern of lumbar magnetic resonance imaging changes in a population study of one thousand forty-three individuals. *Spine* 2009;34:934–40.
- [2] Adams MA, Roughley PJ. What is intervertebral disc degeneration, and what causes it? *Spine* 2006;31:2151–61.
- [3] Roughley PJ. Biology of intervertebral disc aging and degeneration: involvement of the extracellular matrix. *Spine* 2004;29:2691–9.
- [4] Nakashima H, Yukawa Y, Suda K, et al. Cervical disc protrusion correlates with the severity of cervical disc degeneration: a cross-sectional study of 1211 relatively healthy volunteers. *Spine* 2015;40:E774–9.
- [5] Terri M, Paajanen H, Laato M, et al. Disc degeneration in magnetic resonance imaging. A comparative biochemical, histologic, and radiologic study in cadaver spines. *Spine* 1991;16:629–34.
- [6] White AP, Biswas D, Smart LR, et al. Utility of flexion-extension radiographs in evaluating the degenerative cervical spine. *Spine* 2007;32:975–9.
- [7] Wang JC, Hatch JD, Sandhu HS, et al. Cervical flexion and extension radiographs in acutely injured patients. *Clin Orthop Relat Res* 1999; 365:111–6.

- [8] Insko EK, Gracias VH, Gupta R, et al. Utility of flexion and extension radiographs of the cervical spine in the acute evaluation of blunt trauma. *J Trauma* 2002;53:426–9.
- [9] Park D. Ultrasonography of the transverse movement and deformation of the median nerve and its relationships with electrophysiological severity in the early stages of carpal tunnel syndrome. *PM R* 2017;9:1085–94.
- [10] Wierzbicki V, Pesce A, Marrocco L, et al. How old is your cervical spine? Cervical spine biological age: a new evaluation scale. *Eur Spine J* 2015;24:2763–70.
- [11] Pfirrmann CW, Metzdorf A, Zanetti M, et al. Magnetic resonance classification of lumbar intervertebral disc degeneration. *Spine* 2001;26:1873–8.
- [12] Suzuki A, Daubs MD, Inoue H, et al. Prevalence and motion characteristics of degenerative cervical spondylolisthesis in the symptomatic adult. *Spine* 2013;38:E1115–20.
- [13] Park D. Distribution patterns of the vulnerable vessels around cervical nerve roots: a computed tomography-based study. *Am J Phys Med Rehabil* 2018;97:242–7.
- [14] 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* 2009;34:2389–94.
- [15] Chin KR, Ghiselli G, Cumming V, et al. Postoperative magnetic resonance imaging assessment for potential compressive effects of retained posterior longitudinal ligament after anterior cervical fusions: a cross-sectional study. *Spine* 2013;38:253–6.
- [16] Loughenbury PR, Wadhvani S, Soames RW. The posterior longitudinal ligament and peridural (epidural) membrane. *Clin Anat* 2006;19:487–92.
- [17] Avila MJ, Skoch J, Sattarov K, et al. Posterior longitudinal ligament resection or preservation in anterior cervical decompression surgery. *J Clin Neurosci* 2015;22:1088–90.
- [18] Yu CC, Hao DJ, Ma YL, et al. The role of posterior longitudinal ligament in cervical disc replacement: an ovine cadaveric biomechanical analysis. *Med Sci Monit* 2016;22:1843–9.
- [19] Bai CR, Wang BQ, Li KH, et al. Benefit of degenerative posterior longitudinal ligament removal during anterior decompression in cervical spondylotic myelopathy. *Orthopedics* 2015;38:e54–61.
- [20] Dean CL, Gabriel JP, Cassinelli EH, et al. Degenerative spondylolisthesis of the cervical spine: analysis of 58 patients treated with anterior cervical decompression and fusion. *Spine J* 2009;9:439–46.
- [21] Clarke E, Robinson PK. Cervical myelopathy: a complication of cervical spondylosis. *Brain* 1956;79:483–510.
- [22] Williams JL, Allen MB Jr, Harkness JW. Late results of cervical discectomy and interbody fusion: some factors influencing the results. *J Bone Joint Surg Am* 1968;50:277–86.
- [23] Henderson CM, Hennessy RG, Shuey HM Jr, et al. Posterior-lateral foraminotomy as an exclusive operative technique for cervical radiculopathy: a review of 846 consecutively operated cases. *Neurosurgery* 1983;13:504–12.
- [24] Gore DR, Sepic SB. Anterior cervical fusion for degenerated or protruded discs. A review of one hundred forty-six patients. *Spine* 1984;9:667–71.
- [25] Park D. Precise target site of ultrasound-guided C5 cervical root block. *Am J Phys Med Rehabil* 2017;96:e198–9.
- [26] Park D, Seong MY, Kim HY, et al. Spinal cord injury during ultrasound-guided C7 cervical medial branch block. *Am J Phys Med Rehabil* 2017;96:e111–4.