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ORIGINAL ARTICLE

Kinematic characteristics of patients with cervical imbalance: a weight-bearing dynamic MRI study

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Abstract

Study design It is a retrospective analysis of 1806 consecutive cervical magnetic resonance images taken in weight-bearing flexion, neutral, and extension positions.

Objective The aim was to identify the kinematic characteristics of patients with cervical imbalance. Additionally, factors were analysed in the neutral position that could predict the characteristics.

Summary of background data Little is known about the kinematic characteristics during cervical flexion and extension positions of the patient with cervical imbalance (cervical sagittal vertical axis (cSVA) in neutral position ≥ 40 mm).

Methods After evaluating the whole images, cervical imbalance group (cSVA ≥ 40 mm, $n = 43$) and matched control group (< 40 mm, $n = 43$) were created using propensity score adjusting for age, gender, and cervical alignment. They were compared for cervical motion, changes in disc bulge, and ligamentum flavum (LF) bulge from flexion to extension. Multinomial logistic regression analysis and receiver operating characteristic curve analysis were calculated to verify the predictive factors and cut-off value of the identified characteristics.

Results There were no significant differences in range of motion and the change in bulged discs. There was significant difference in the presence of LF bulge from flexion to extension ($p = 0.023$); the incidence of LF bulge increased sharply from neutral to extension in imbalance group, while there was linear increase in control group. The canal diameter (odds ratio = 0.61, $p = 0.002$) and disc height (odds ratio = 1.60, $p = 0.041$) showed significant relationship with the segments with LF bulge observed in extension but not in neutral position in the imbalance group; the cut-off values were 10.7 mm for canal diameter (sensitivity 82.5%, specificity 66.7%) and 7.1 mm for disc height (70.8%, 58.5%).

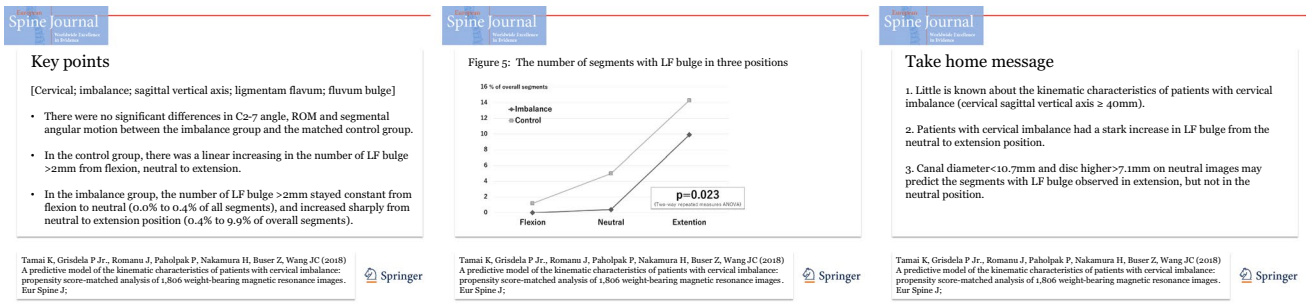
Conclusion Patients with cervical imbalance had a stark increase in LF bulge from the neutral to extension position. Canal diameter < 10.7 mm and disc height > 7.1 mm on neutral images may predict the segments with LF bulge observed in extension, but not in the neutral position.

Level of evidence II (Diagnostic: individual cross-sectional studies with consistently applied reference standard and blinding).

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00586-018-05874-2) contains supplementary material, which is available to authorized users.

Extended author information available on the last page of the article

Graphical abstract These slides can be retrieved from Electronic Supplementary Material.



Keywords Cervical · Imbalance · Sagittal vertical axis · Ligamentum flavum · Kinematic magnetic resonance images · Flavum bulge · Disc height · Canal diameter

Introduction

Multiple publications have established that the spinopelvic sagittal balance has direct effects on health-related quality of life (HRQOL); however, the importance of cervical sagittal balance was first reported in 2012 and is still under investigation [1–3]. Although there are many factors that describe cervical balance, cervical sagittal vertical axis (cSVA) is considered as one of the best indicators [4, 5]. cSVA represents the horizontal distance between the plumb line of C2 and the vertebral body of C7, with a distance of ≥ 40 mm recognized as a threshold of cervical imbalance that correlates significantly with poor surgical outcomes and health-related quality of life [3, 6]. Several reports recommended that corrective surgery for cervical spinal sagittal imbalance should be considered if the patient's cSVA is ≥ 40 mm [3, 7]. To understand the kinematic characteristic during cervical flexion and extension positions such as range of cervical motion, the change in ligamentum flavum (LF) bulge, disc bulge, or the spinal canal diameter is essential knowledge to treat the patients with cervical imbalance conservatively or surgically. However, little is known about the kinematic characteristics of patients with cervical imbalance.

One of the problems in identifying kinematic characteristics is the presence of confounders. There are many factors which have an impact on cervical balance, including age, cervical alignment, and gender [8–10]. Propensity score-matched analysis was developed to overcome such inherent limitations of observational datasets [11]. Propensity score analysis is one-to-one matching procedure based on the estimated propensity score which was calculated by logistic regression model including the data of cofounders as independent variables. The analysis can make it possible to analyse the differences between the two groups without the influence of included confounders [12].

Another problem is the imaging methodology. Although dynamic X-ray films are generally used for analysing the kinematic characteristics of patients, it is impossible to analyse essential components such as the discs or ligaments by X-ray film. However, kinematic magnetic resonance imaging (kMRI), which is firstly reported in 2006 and taken in various weight-bearing positions including neutral, flexion, and extension positions, allows us to evaluate not only the angular parameters but also the quality of cervical spine constructs such as the disc or ligamentum flavum (LF) [13–16]. In addition, the image enables us to analyse missed LF or disc bulge which indicate the bulging seen on extension or flexion, but not seen in neutral posture [17].

Based on those backgrounds, the primary aim of this study was to identify the kinematic characteristics of patients with cervical imbalance by comparing them to the matched control group selected by propensity score analysis using kMRI data. Additionally, factors in the neutral position that could predict the changes in kinematic characteristics were determined.

Materials and methods

Our database was compliant with all regulations associated with the Health Insurance Portability and Accountability Act (HIPPA). The institutional review board (IRB) of our institution approved the study protocol with a full waiver of HIPAA Authorization and Informed Consent, due to the retrospective nature of our study.

Patient population

We retrospectively reviewed 1806 consecutive patients who received a cervical MRI for neck pain or radiculopathy with or without neurological deficits between November 2010

and February 2016. The MRI of the cervical spine was performed using a 0.6-T MRI machine with the characteristics mentioned as follows: type: iron-frame electromagnet; configuration: front-open and top-open design; field orientation: horizontal, transverse to the patient; and patient gap: 46 cm pole-to-pole, horizontal gap (Upright Multi-Position, Fonar Corp., New York, NY, USA). The imaging protocol included T1- and T2-weighted sagittal and axial fast spin-echo images that were obtained using a flexible surface coil with the patient seated in upright weight-bearing neutral positions.

Parameters' definitions

Observers reviewed the images using the eRAD PACS system software (version 7.2.38.0, South Carolina, USA), and measured each parameter using images of mid-sagittal slice. The definitions of parameters are as follows: cSVA: the horizontal distance between the centre of C2 and the posterosuperior corner of the C7 vertebral body [3]. Cervical alignment: categorized into one of the four groups: lordosis, kyphosis, straight, and sigmoid, using the system proposed by Chiba et al. [18]. C2–7 angle: the angle between the posterior border of C2 and C7, determined using Harrison's posterior tangent method [19]. C2–7 range of motion (ROM): C2–7 angle at extension position minus flexion position. Segmental angular motion: the difference of intervertebral angles between two vertebrae from flexion to extension [16]. Segmental translational motion: the anteroposterior motion of the superior and inferior vertebrae relative to each other between flexion and extension; > 2.0 mm was defined as a segment with instability [20]. Anteroposterior (AP) diameter of the spinal canal: the minimum sagittal diameter of cerebrospinal fluid at the cervical disc levels on T2-weighted mid-sagittal images. Disc bulge: the distances from the line connecting the posterior cranial and caudal edges of two adjacent vertebral bodies to the point of greatest disc protrusion (Fig. 1). LF bulge: a perpendicular distance > 2 mm between the posterior border of the LF and the highest point of the LF protrusion (Fig. 1) [17, 21]. Disc height: the distances between the mid-superior endplate and mid-inferior endplate of adjacent vertebral bodies. The inter- and intra-observer reliabilities were calculated using interclass correlation coefficient for continuous variables, and kappa value for categorical variables. The inter-observer reliability of all variables was good or excellent; likewise, the intra-observer reliability of all variables was excellent [22, 23] ("Appendix 1").

Study design and statistical analysis

The current study was broken down into three sub-aims (Fig. 2).

Sub-aim 1 Identify the trend of cSVA based on gender, age, cervical alignment using neutral MR images of 1806 patients. The average cSVA was compared between subgroups stratified by age (> 40, 40–49, 50–59 or 60 ≤) using the Jonckheere–Terpstra trend test, gender (male or female) using a *t* test, and cervical alignment groups (lordosis, kyphosis, straight or sigmoid) using one-way analysis of variance (ANOVA) and Tukey's test as post hoc multiple comparisons.

Sub-aim 2 Demonstrate the kinematic characteristics of patients with cervical imbalance. The matched control group (cSVA < 40 mm) was created and compared with the imbalance group (cSVA ≥ 40 mm) with respect to spinal mobility between flexion and extension, as well as the change in AP diameter, disc bulge and LF bulge from flexion through neutral to extension. The matching procedure classified patients in the two groups according to the similarity of their propensity scores. To estimate the propensity score which

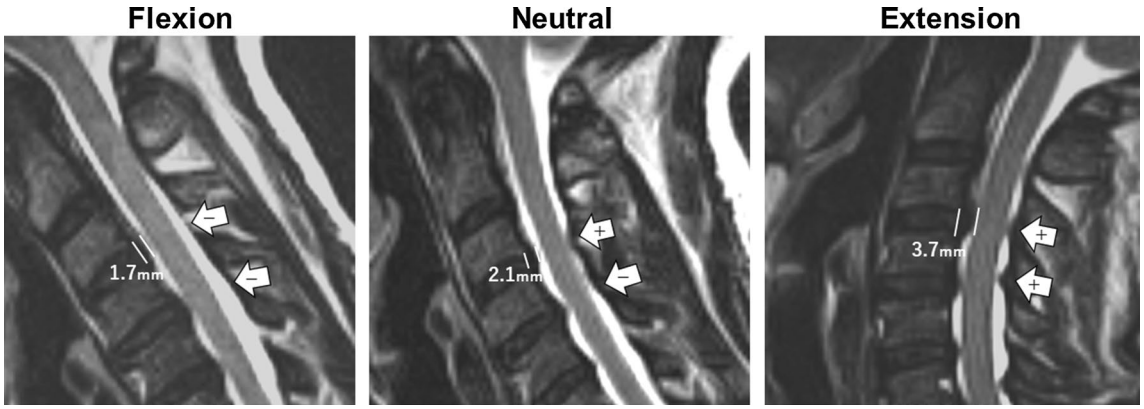


Fig. 1 Representative case of dynamic canal stenosis 56 years old male. The distances of disc bulge at C3–4 increased from flexion (1.7 mm), neutral (2.1 mm) to extension (3.7 mm). There are no ligamentus fluvum (LF) bulge in flexion, however, one LF buige emerged in neutral at C3–4 (white arrow 1). Finally, in extension position, 3 levels including C3–4, C4–5 as well as C6–7 showed the LF bulge more than 2 mm (white arrow 1, 2, 3)

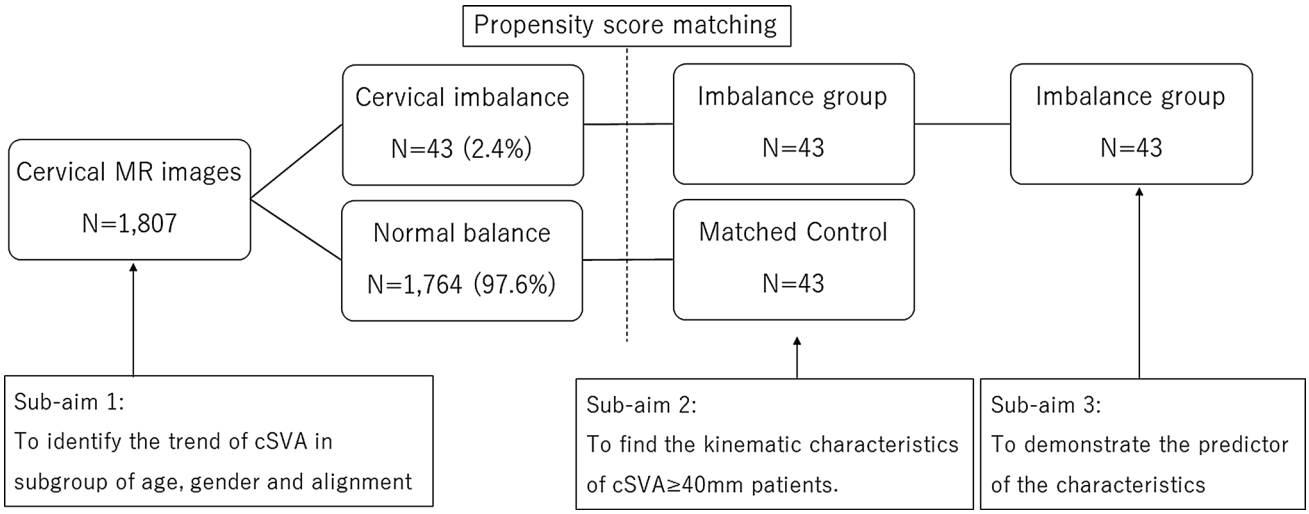


Fig. 2 Flowchart of current study

represents the estimated probability of the patients with cervical imbalance, we fitted a logistic regression model with patient's age, sex, and cervical alignment as independent variables. Subsequently, one-to-one matching was performed to adjust for patients' baseline of age, sex, and cervical alignment of the matched control group with cervical imbalance group, using a nearest-neighbour matching procedure that matched propensities had to be within 0.01 units of each other. Segmental mobility parameters included C2–7 angle in three positions, ROM and segmental angular motion from C2–3 to C6–7 assessed using Mann–Whitney U test, as well as the number of vertebrae with segmental translation > 2 mm from C2–3 to C6–7 assessed with Fisher's exact probability test. Two-way repeated measures ANOVA was performed to compare the trend from flexion though neutral to extension; the trends of the mean value of spinal canal AP diameter at C2–3 to C6–7; the mean distance of disc bulge at C2–3 to C6–7; and the total number of LF bulges > 2 mm at C2–3 to C6–7 were compared between the imbalance group and the matched control group.

Sub-aim 3 Identify predictors of the kinematic characteristics demonstrated in sub-aim 2 using multinomial logistic regression analysis. The data of cervical imbalance group were analysed in this step. In the regression analysis, independent variables included patients' attributes such as age and cSVA, and segmental factors in neutral position which seemed to relate to the kinematic characteristics such as canal diameter and disc height. If the identified predictive factors in logistic regression analysis were continuous variables, each variable was separately applied in the receiver operating characteristic (ROC) curves to investigate the cut-off values. The area under the ROC curve (AUC) and 95% confident intervals (CI) were calculated. The cut-off value was defined as the point corresponding to the maximum sum of the sensitivity and specificity. All analyses were performed using SPSS computer software (version 23; SPSS, Chicago, IL, USA). $p < 0.05$ was considered as statistically significant.

Results

Sub-aim 1: the trend of cSVA

Forty-three (2.4%) patients had cSVA values of ≥ 40 mm. The mean cSVA showed a significant increase with age (> 40 21.4 mm, 40–49 22.4 mm, 50–59 23.4 mm, 60 ≤ 24.2 mm, p for trend < 0.001). Furthermore, patients with kyphosis showed a significantly higher mean cSVA than the patients with lordosis (lordosis 21.8 mm, kyphosis 24.2 mm, $p < 0.001$). There were no significant differences between the subgroups in regard to gender ($p = 0.516$, Table 1).

Sub-aim 2: kinematic characteristics of imbalance group

The patient demographics of the imbalance group and the matched control group are shown in Table 2. There were no significant differences in C2–7 angle, ROM and segmental angular motion between the imbalance group and the matched control group. However, the number of segments with translation > 2 mm at C2–3, C3–4 and overall levels were significantly higher in the control group (overall $p = 0.001$, C2–3 $p = 0.036$, and C3–4 $p = 0.014$, Table 3).

The trend of the mean diameter of spinal canal at disc level showed significant differences between the imbalance group and the matched control group ($p = 0.027$, Fig. 3). While the diameters were almost the same between the

Table 1 The comparison of cSVA in each of the subgroups ($n = 1806$)

Subgroup	Patients number	cSVA mean	cSVA SD	*P* value (comparison of cSVA mean)
Age				For trend < 0.001[†]
< 40	570	21.4	8.7	
40–49	530	22.4	8.9	
50–59	532	23.4	8.9	
60≤	175	24.2	9.2	
Gender				0.516[#]
Female	939	22.7	9.6	
Male	868	22.4	8.3	
Cervical alignment				< 0.001[‡]
Lordosis	1051	21.8	8.6	< 0.001 (L vs. K)[§]
Kyphosis	382	24.2	9.5	> 0.05 (other combinations)[§]
Straight	330	23.0	8.8	
Sigmoid	44	23.8	8.6	

cSVA cervical vertical sagittal balance, *SD* standard deviation, *ANOVA* analysis of variance, *L* lordosis, *K* kyphosis

[†]Jonckheere–Terpstra trend test, [#]*t* test, [‡]one-way analysis of variance, [§]Tukey's test

Table 2 Patient's demographics of matched group

	cSVA ≥ 40 mm	Matched control	*p*-value
Total number	43	43	
Age	46.5 ± 13.5	46.8 ± 11.2	0.832[#]
Gender (female/male)	34/9	34/9	1.000[##]
Cervical alignment			0.930[##]
Lordosis	15	16	
Kyphosis	17	16	
Straight	9	10	
Sigmoid	2	1	
cSVA (C2–C7)	44.3 ± 3.6	20.2 ± 8.4	< 0.001[#]

cSVA cervical vertical sagittal balance

[#] *t* test, [##] Fisher's exact probability test

Table 3 Comparison of spinal mobility

	cSVA ≥ 40 mm	Matched control	*p*-value
C2–7 angle (degree)			
Flexion	− 9.2 ± 16.0	− 6.6 ± 17.8	0.485[¶]
Neutral	6.0 ± 14.5	11.1 ± 15.8	0.122[¶]
Extension	23.2 ± 17.6	30.2 ± 16.8	0.063[¶]
ROM (degree)	34.3 ± 17.4	36.8 ± 15.8	0.508[¶]
Segmental angular motion (degree)			
Overall	4.5 ± 3.8	4.7 ± 3.6	0.573[¶]
C2–3	6.3 ± 4.8	7.4 ± 4.2	0.264[¶]
C3–4	3.4 ± 2.7	4.9 ± 3.5	0.330[¶]
C4–5	3.8 ± 3.0	4.4 ± 3.0	0.397[¶]
C5–6	4.3 ± 3.5	3.6 ± 2.8	0.296[¶]
C6–7	4.6 ± 4.4	3.2 ± 3.1	0.109[¶]
Segmental translation > 2 mm (segments (%))			
Overall	11 (4.4%)	34 (13.2%)	> 0.001[##]
C2–3	5 (11.9%)	14 (32.6%)	0.036[##]
C3–4	2 (4.8%)	11 (25.6%)	0.014[##]
C4–5	2 (4.8%)	5 (11.6%)	0.433[##]
C5–6	2 (4.8%)	3 (7.0%)	1.000[##]
C6–7	0 (0.0%)	1 (2.3%)	1.000[##]
C7–T1	0 (0.0%)	0 (0.0%)	1.000[##]

cSVA cervical vertical sagittal balance, *ROM* range of motion

[¶]Mann–Whitney *U* test, [##]Fisher's exact probability test

two groups in flexion, the control group showed a narrower spinal canal diameter than the imbalance group in the neutral and extension position. There was no significantly different trends in disc bulge magnitude between the two groups ($p = 0.778$, Fig. 4). However, the change in the number of LF bulges > 2 mm showed a significant difference ($p = 0.023$). In the control group, there was a linear increase in the number of LF bulge over 2 mm from flexion, neutral to extension. Meanwhile, in the cervical imbalance group, the numbers of LF bulge > 2 mm stayed constant from flexion to neutral (0.0 to 0.4% of all segments), and increased sharply from the neutral to extension position (0.4 to 9.9% of overall segments, Fig. 5).

Sub-aim 3: factors relate to LF bulge

We calculated which variables in patients with cervical imbalance could predict segmental LF bulge in extension, but not in the neutral position. The results showed that the canal diameter of the corresponding level (adjusted OR 0.61, 95% CI 0.44–0.84, $p = 0.002$), as well as the disc height of the corresponding level (adjusted OR 1.60, 95% CI 1.02–2.51, $p = 0.041$) were significant predictive factors (Table 4). ROC analysis demonstrated the AUC of canal

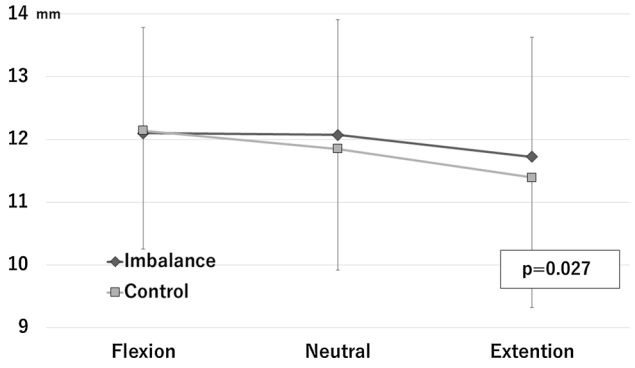


Fig. 3 The AP diameter of spinal canal at disc level in three positions

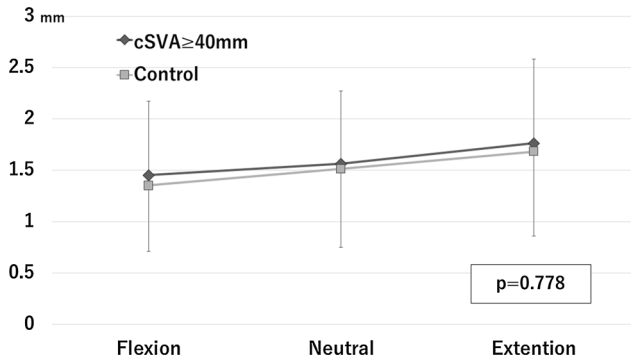


Fig. 4 The distances of disc bulge in three positions

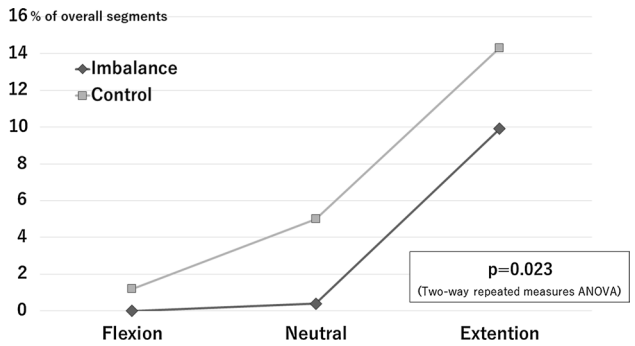


Fig. 5 The number of segments with LF bulge in three positions

diameter was 0.776 (95% CI 0.680 to 0.879, $p < 0.001$), while the AUC of disc height was 0.639 (95% CI 0.539 to 0.739, $p = 0.025$, Fig. 6). The optimal cut-off value was 10.7 mm for the canal diameter (sensitivity 82.5%, specificity 66.7%) and 7.1 mm for the disc height (sensitivity 70.8%, specificity 58.5%).

Table 4 Multinomial logistic regression analysis to predict the missed LF of cSVA ≥ 40 mm group

Variables	Adjusted OR	95% CI	*p*-value
Age	1.03	0.99–1.08	0.184
cSVA	1.10	0.95–1.27	0.222
Canal diameter of corresponding level	0.61	0.44–0.84	0.002
Disc height of corresponding level	1.60	1.02–2.51	0.041
Disc bulge of corresponding level	1.67	0.71–3.04	0.302

OR odds ratio, *CI* confidential interval, *cSVA* cervical vertical sagittal balance

Discussion

Understanding kinematic characteristics of the cervical spine is essential to correctly identify cervical disease and neurological symptoms, and to plan surgical treatment. Previous evidence demonstrated that 90% of patients with myelopathy showed increased number of compression levels in the extension MRI compared to the neutral MRI, while only 30% of patients without myelopathy showed the increased number of compression levels [24]. In addition, we previously reported the diversity of sagittal motion of T1 between flexion and extension [25]. However, the kinematic characteristics of the patient with cervical imbalance have not been investigated.

Current study demonstrated that the patients with cervical imbalance had a lower number of unstable cervical segments, wider spinal canal diameter in the extension position, as well as a stark increase in the number of LF bulges from neutral to extension position. Furthermore, we found in the imbalance group that the significant variables for predicting the number of segments with LF bulge observed in extension but not in neutral position were a canal diameter less than 10.7 mm and a disc height more than 7.1 mm on neutral images.

Although having a cSVA ≥ 40 mm is a rare condition (2.4% in this dataset), it is recognized as a key factor in poor surgical outcomes or HRQOL. In 2012, Tang et al. first reported that a cSVA ≥ 40 mm was significantly correlated with a poor neck disability index (NDI) score after cervical deformity surgery [5]. Likewise, Iyer et al. demonstrated that preoperatively, larger cSVA significantly correlated with poor preoperative NDI scores in patients with cervical deformities [5]. Based on these reports, Ames et al. created a new classification system in which having a cSVA < 40 mm was associated with better outcomes of cervical deformity surgeries [7]. Therefore, understanding the kinematic differences between the patients with

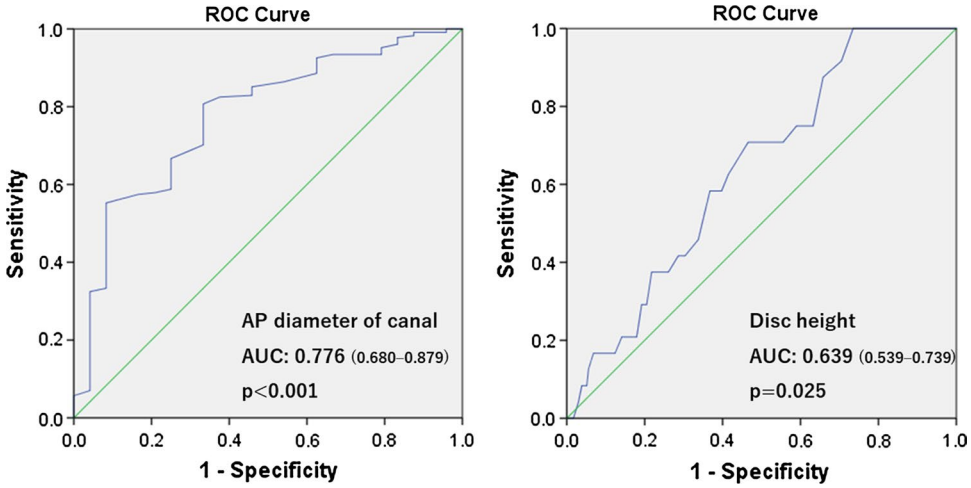


Fig. 6 ROC analysis to predict the missed LF in the patients with cervical imbalance

cSVA < 40 mm and ≥ 40 mm is critical to treat patients with cervical imbalance.

In terms of the motion of cervical spine, Xiong et al. [26] demonstrated that the C2–3 and C3–4 were the segments with largest translational motion, supporting our findings that the vertebrae with segmental translation > 2 mm were observed more frequently in upper cervical level. In addition, our current results revealed that the imbalance group had a significantly lower number of segments with instability than the matched control group.

While the change in disc bulge in three positions showed no significant differences, the trends of canal diameter at disc level showed significant differences between the two matched groups. Canal diameter at each disc level was affected by the disc bulge and LF bulge [17]. Therefore, the differences of canal diameter between two groups could be due to the differences of trends of LF bulge. Indeed, the control group showed a higher number of LF bulges in the neutral and extension position in our study.

Several studies have reported the presence of a missed LF bulge that could not be observed in the neutral position but could be seen in the extension position. Risk factors were a larger disc bulge, severe disc degeneration, greater angular motion, greater translation, and segmental kyphosis [17, 21]. In the current study, there was approximately the same number of segments with a missed LF bulge between the patients with cervical imbalance and with normal balance. However, among the cervical imbalance patients, the number of segments with LF bulge at the neutral position was extremely low (0.4% of all segments) compared to the patients with normal cervical balance, but the number increased sharply in the extension position. This could be due to the kinematic characteristics of the patients with cervical imbalance. Disc height and canal diameter at disc level were significant predictive factors for the number of segments with a missed LF bulge among patients with cervical imbalance. Interestingly, the segments with higher disc height tended to have the segments with missed LF bulge. This contradicts the previous research wherein normally balanced patients' segments with more severe disc degeneration tend to have missed LF bulge[21]. While the exact mechanism of the differences between patients with cervical imbalance and healthy patients is still unclear, it is possible that the differences are due to the unique kinematic characteristics of the patients with cervical imbalance.

The cut-off value to predict a missed LF bulge in the imbalance group can be important knowledge for a spine surgeon, especially when planning corrective surgery for cervical deformity. To correct the cervical deformity or cervical sagittal imbalance, Ames summarized several techniques defined as seven grades from grade 1: partial facet joint resection, to grade 7: complete vertebral column resection [27]. Among those techniques, partial facet joint resection without decompression, the technique of grade 1, seems to be the most common and most frequently used technique to correct cervical deformity. However, our results suggest that surgeons should consider additional posterior decompression when the canal diameter < 10.7 mm or disc height > 7.1 mm at the corresponding segment they plan to introduce a corrective lordotic change, to prevent neurological deterioration due to LF bulge. Additionally, those two findings can be observed not only in weight-bearing MR images but also in weight-bearing X-ray film or standard MR images, allowing for surgical planning to be done with the existing set-up.

This study has several limitations. Our study included symptomatic patients with neck pain or radiculopathy, with or without neurological deficits. Additionally, the lack of patients' medical records made it difficult to verify the differences in clinical scores between patients with cervical imbalance and normal balance. Third, although we reported the high inter- and intra-observer reliability, the field strength used for imaging was 0.6T which can potentially introduce the overlook of small changes in cervical

spine. Finally, cSVA of current study was measured using the weight-bearing MRI which takes in sitting position, not in standing position. Given these limitations, a large-scale longitudinal study with high-resolution standing MR images of asymptomatic patients and clinical information is needed to validate current findings.

Conclusion

This study demonstrated that patients with cervical imbalance had lower number of unstable segments, wider canal diameter in extension position as well as a sharp increase in the number of segments with LF bulge from neutral to extension, compared to the matched control group for age, gender, and cervical alignment. The significant predictors for the segments with missed LF bulge among patients with cervical imbalance were canal diameter at disc level < 10.7 mm and disc height > 7.1 mm on images of neutral position.

Compliance with ethical standards

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

Disclosures 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, North American Spine Foundation, AO Foundation, Cervical Spine Research Society; Fellowship Funding (paid to institution): AO Foundation. ZB—consultancy: Xenco Medical, AO Spine (past); research support: SeaSpine (paid directly to institution).

Appendix 1

	Between observers	Within observers
Alignment	0.854 (0.695–0.937)	0.920 (0.848–0.958)
cSVA	0.943 (0.892–0.970)	0.975 (0.938–0.990)
C2–C7 angle	0.962 (0.922–0.984)	0.955 (0.917–0.976)
Spondylolisthesis	0.730 (0.635–0.804)	0.803 (0.745–0.849)
Segmental angular motion	0.783 (0.776–0.789)	0.729 (0.701–0.745)
Segmental translational motion	0.910 (0.886–0.946)	0.931 (0.897–0.951)
AP diameter of spinal canal	0.880 (0.838–0.913)	0.891 (0.859–0.915)
LF bulge	0.815 (0.636–0.925)	0.906 (0.846–0.942)
Disc bulge	0.836 (0.681–0.916)	0.844 (0.696–0.920)
Disc height	0.771 (0.459–0.932)	0.849 (0.611–0.942)

References

1. Lafage V, Schwab F, Skalli W, Hawkinson N, Gagey PM, Ondra S, Farcy JP (2008) Standing balance and sagittal plane spinal deformity: analysis of spinopelvic and gravity line parameters. Spine (Phila Pa 1976) 33:1572–1578. https://doi.org/10.1097/brs.0b013e31817886a2
2. Terran J, Schwab F, Shaffrey CI, Smith JS, Devos P, Ames CP, Fu KM, Burton D, Hostin R, Klineberg E, Gupta M, Deviren V, Mundis G, Hart R, Bess S, Lafage V, International Spine Study G (2013) The SRS-Schwab adult spinal deformity classification: assessment and clinical correlations based on a prospective operative and nonoperative cohort. Neurosurgery 73:559–568. https://doi.org/10.1227/NEU.0000000000000012
3. Tang JA, Scheer JK, Smith JS, Deviren V, Bess S, Hart RA, Lafage V, Shaffrey CI, Schwab F, Ames CP, Issg (2012) The impact of standing regional cervical sagittal alignment on outcomes in posterior cervical fusion surgery. Neurosurgery 71:662–669. https://doi.org/10.1227/neu.0b013e31826100c9 **discussion 669**
4. Ames CP, Blondel B, Scheer JK, Schwab FJ, Le Huec JC, Massicotte EM, Patel AA, Traynelis VC, Kim HJ, Shaffrey CI, Smith JS, Lafage V (2013) Cervical radiographical alignment: comprehensive assessment techniques and potential importance in cervical myelopathy. Spine 38:S149–160. https://doi.org/10.1097/brs.0b013e3182a7f449
5. Iyer S, Nemani VM, Nguyen J, Elysee J, Burapachaisri A, Ames CP, Kim HJ (2016) Impact of cervical sagittal alignment parameters on neck disability. Spine (Phila Pa 1976) 41:371–377. https://doi.org/10.1097/brs.0000000000001221
6. Roguski M, Benzel EC, Curran JN, Magge SN, Bisson EF, Krishnaney AA, Steinmetz MP, Butler WE, Heary RF, Ghogawala Z (2014) Postoperative cervical sagittal imbalance negatively affects outcomes after surgery for cervical spondylotic myelopathy. Spine (Phila Pa 1976) 39:2070–2077. https://doi.org/10.1097/brs.0000000000000641
7. Ames CP, Smith JS, Eastlack R, Blaskiewicz DJ, Shaffrey CI, Schwab F, Bess S, Kim HJ, Mundis GM, Jr., Klineberg E, Gupta M, O'Brien M, Hostin R, Scheer JK, Protopsaltis TS, Fu KM, Hart R, Albert TJ, Riew KD, Fehlings MG, Deviren V, Lafage V, International Spine Study G (2015) Reliability assessment of a novel cervical spine deformity classification system. J Neurosurg Spine 23:673–683. https://doi.org/10.3171/2014.12.SPINE14780
8. Oe S, Togawa D, Nakai K, Yamada T, Arima H, Banno T, Yasuda T, Kobayasi S, Yamato Y, Hasegawa T, Yoshida G, Matsuyama Y (2015) The influence of age and sex on cervical spinal alignment among volunteers aged over 50. Spine (Phila Pa 1976) 40:1487–1494. https://doi.org/10.1097/brs.0000000000001071
9. Yoshida G, Yasuda T, Togawa D, Hasegawa T, Yamato Y, Kobayashi S, Arima H, Hoshino H, Matsuyama Y (2014) Craniopelvic alignment in elderly asymptomatic individuals: analysis of 671 cranial centers of gravity. Spine (Phila Pa 1976) 39:1121–1127. https://doi.org/10.1097/brs.0000000000000360
10. Tamai K, Romanu J, Grisdela P Jr, Paholpak P, Zheng P, Nakamura H, Buser Z, Wang JC (2018) Small C7-T1 lordotic angle and muscle degeneration at C7 level were independent radiological characteristics of patients with cervical imbalance: a propensity score-matched analysis. Spine J. https://doi.org/10.1016/j.spine.2018.01.012
11. Rubin DB (2010) Propensity score methods. Am J Ophthalmol 149:7–9. https://doi.org/10.1016/j.ajo.2009.08.024
12. Rubin DB (2007) The design versus the analysis of observational studies for causal effects: parallels with the design of randomized trials. Stat Med 26:20–36. https://doi.org/10.1002/sim.2739
13. Kuwazawa Y, Bashir W, Pope MH, Takahashi K, Smith FW (2006) Biomechanical aspects of the cervical cord: effects of

postural changes in healthy volunteers using positional magnetic resonance imaging. J Spinal Disord Tech 19:348–352. https://doi.org/10.1097/01.bsd.0000203273.90004.eb
14. Kuwazawa Y, Pope MH, Bashir W, Takahashi K, Smith FW (2006) The length of the cervical cord: effects of postural changes in healthy volunteers using positional magnetic resonance imaging. Spine (Phila Pa 1976) 31:E579–583. https://doi.org/10.1097/01.brs.0000229228.62627.75
15. Hayashi T, Daubs MD, Suzuki A, Scott TP, Phan KH, Ruangchainikom M, Takahashi S, Shiba K, Wang JC (2015) Motion characteristics and related factors of Modic changes in the lumbar spine. J Neurosurg Spine 22:511–517. https://doi.org/10.3171/2014.10.SPINE14496
16. Suzuki A, Daubs MD, Inoue H, Hayashi T, Aghdasi B, Montgomery SR, Ruangchainikom M, Hu X, Lee CJ, Wang CJ, Wang BJ, Nakamura H (2013) Prevalence and motion characteristics of degenerative cervical spondylolisthesis in the symptomatic adult. Spine (Phila Pa 1976) 38:E1115–1120. https://doi.org/10.1097/brs.0b013e31829b1487
17. Hayashi T, Wang JC, Suzuki A, Takahashi S, Scott TP, Phan K, Lord EL, Ruangchainikom M, Shiba K, Daubs MD (2014) Risk factors for missed dynamic canal stenosis in the cervical spine. Spine (Phila Pa 1976) 39:812–819. https://doi.org/10.1097/brs.0000000000000289
18. Chiba K, Ogawa Y, Ishii K, Takaishi H, Nakamura M, Maruiwa H, Matsumoto M, Toyama Y (2006) Long-term results of expansive open-door laminoplasty for cervical myelopathy–average 14-year follow-up study. Spine (Phila Pa 1976) 31:2998–3005. https://doi.org/10.1097/01.brs.0000250307.78987.6b
19. Donk RD, Fehlings MG, Verhagen WI, Arnts H, Groenewoud H, Verbeek AL, Bartels RH (2017) An assessment of the most reliable method to estimate the sagittal alignment of the cervical spine: analysis of a prospective cohort of 138 cases. J Neurosurg Spine. https://doi.org/10.3171/2016.10.spine16632
20. NASS (2015) NASS COVERAGE POLICY RECOMMENDATION: cervical fusion
21. Zhong G, Buser Z, Lao L, Yin R, Wang JC (2015) Kinematic relationship between missed ligamentum flavum bulge and degenerative factors in the cervical spine. Spine J 15:2216–2221. https://doi.org/10.1016/j.spinee.2015.06.048
22. Bartko JJ (1966) The intraclass correlation coefficient as a measure of reliability. Psychol Rep 19:3–11. https://doi.org/10.2466/pr0.1966.19.1.3
23. Landis JR, Koch GG (1977) The measurement of observer agreement for categorical data. Biometrics 33:159–174
24. Kim CH, Chung CK, Kim KJ, Park SB, Lee SJ, Yoon SH, Park BJ (2014) Cervical extension magnetic resonance imaging in evaluating cervical spondylotic myelopathy. Acta Neurochir (Wien) 156:259–266. https://doi.org/10.1007/s00701-013-1951-2
25. Tamai K, Buser Z, Paholpak P, Sessumpun K, Hsieh PC, Nakamura H, Wang JC (2018) MRI kinematic analysis of T1 sagittal motion between cervical flexion and extension positions in 145 patients. Eur Spine J 27:1034–1041. https://doi.org/10.1007/s00586-017-5385-z
26. Xiong C, Suzuki A, Daubs MD, Scott T, Phan K, Wang J (2015) The evaluation of cervical spine mobility without significant spondylosis by kMRI. Eur Spine J 24:2799–2806. https://doi.org/10.1007/s00586-015-4101-0
27. Ames CP, Smith JS, Scheer JK, Shaffrey CI, Lafage V, Deviren V, Moal B, Protopsaltis T, Mummaneni PV, Mundis GM, Jr., Hostin R, Klineberg E, Burton DC, Hart R, Bess S, Schwab FJ, International Spine Study G (2013) A standardized nomenclature for cervical spine soft-tissue release and osteotomy for deformity correction: clinical article. J Neurosurg Spine 19:269–278. https://doi.org/10.3171/2013.5.SPINE121067

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