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# Analysis of translation and angular motion in loaded and unloaded positions in the lumbar spine

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ABSTRACT

*Background Context:* Abnormalities in intervertebral rotation and translation are important to diagnosis and treatment planning for common spinal disorders. Tests that do not sufficiently load the spine can result in misdiagnosed motion abnormalities. Upright flexion and extension x-rays are commonly used despite known limitations. Additional evidence is needed in support of preliminary studies suggesting that the change from standing to supine may sufficiently stress the spine to diagnose motion abnormalities.

*Purpose:* Compare intervertebral translation between flexion and extension to translation between upright and supine positions in a representative clinical population.

*Study Design/Setting:* Prospective analysis of images retrospectively collected from routine clinical practices.

*Methods:* After obtaining IRB approval for analysis of previously obtained images, patients were identified via chart reviews where a neutral-lateral x-ray and an MRI or CT exam were obtained for diagnosis of a spinal disorder and where flexion-extension x-rays had been obtained to help diagnose abnormal intervertebral motion. The mid-sagittal slice from the MRI or CT exam was paired with the neutral-lateral radiograph. Intervertebral translation at the L4-L5 and L5-S1 levels between supine and standing and between flexion and extension were measured from the images using previously validated methods. The translations were classified as normal or abnormal with reference to a previously obtained database of intervertebral motion in radiographically normal and asymptomatic volunteers.

*Results:* At the L5-S1 level in particular, there tended to be greater translation between the supine and standing than between upright flexion and extension. On average, translations were below that found in asymptomatic volunteers. No abnormal translations were detected from flexion-extension radiographs whereas approximately 7% of levels had abnormal translations between supine and upright positions.

*Conclusions:* Intervertebral translations between supine and standing, measured using the mid-sagittal slice from a MRI or CT exam and a lateral x-ray with the patient standing can help to identify abnormal motion. This would be particularly valuable for patients with limited flexion and extension. This study thereby adds to the evidence in support of measuring intervertebral motion between the supine and upright positions to detect abnormal intervertebral motion.

## Introduction

The vertebral column requires mobility to allow for optimal function and stability to protect the neurological structures. This ambiguous relationship can lead to pathological changes that result in excessive spinal motion with resulting pain and disability [1–5]. Sagittal plane intervertebral translation and rotation are basic metrics that have been used to determine disease and justify surgical intervention including spinal stabilization. Proper understanding of these metrics is critical to appropriate decision making in management of spinal disorders. Thus, a reliable diagnostic test that can identify or rule-out abnormal intervertebral motion would be clearly valuable.

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Perhaps most surprising, despite liberal application of the interpretation of instability for clinical decision-making, there is currently no well-validated diagnostic test for spinal instability available to clinicians [6–9]. Greater than 4 mm of translation or 10 degrees of angulation have been accepted as markers of pathologic instability [5], but there is no high-quality evidence to support use of these criteria.

Spinal motion is commonly evaluated by standing flexion and extension x-rays. Recent literature has explored alternatives to these radiographs to better demonstrate intervertebral mobility, including lateral decubitus, motion films with concurrent axial compression-distraction, and sitting as well as supine lateral imaging. Lowe et al demonstrated a significant increase in anterior sagittal translation when weight-bearing lateral radiographs were compared to supine radiographs [10]. Although maximal static translation was most commonly seen in the upright position, other studies have demonstrated compressive follower loads during standing could stiffen the spine and potentially conceal abnormal dynamic sagittal translation [11]. In another study, Friberg et al compared axial compression-distraction and found that anterior translation was maximal when in a loaded position [12]. Later, Wood et al demonstrated a significant increase in detection of abnormal translation when using flexion/extension radiographs in the lateral decubitus position as compared to standing radiographs [13], suggesting that unloaded radiographs could be a more sensitive method in evaluation of dynamic lumbar instability. Provided these various findings, achieving consensus on the preferred method for detecting or ruling-out abnormal intervertebral motion requires additional data.

Modern imaging techniques, namely magnetic resonance imaging (MRI) and computerized tomography (CT) scans are extremely accurate in the diagnosis of many lumbar conditions and are used frequently in the assessment of low back pain. In addition, standing radiographs are routinely obtained during the diagnostic work up of low back disorders. The goal of this study was to examine whether loading of the spine has an effect on diagnosing abnormal intervertebral motion (IVM). The null hypothesis is that there is no difference between the IVM seen between a supine image (MRI or CT) and standing image (standing lateral x-ray) versus IVM seen with traditional standing flexion and extension films. In addition to looking at the effect of loading on motion, from a practical standpoint, this would have the potential of eliminating the need for additional imaging (flexion and extension films) and all the advantages that come with reducing extra testing and exposure to radiation.

## Materials and methods

The study protocol was approved by an IRB at the Medical University of South Carolina (IRB# Pro00056829). Studies were acquired from an electronic imaging database. All patients seen by physicians within the spine center from 2010 to 2016 were identified and their charts queried for CPT codes consistent with radiographic imaging as well as MRI or CT of the lumbar spine. Each chart was reviewed, and patients were included in the study if they had flexion and extension studies as well as a supine study (either CT or MRI). As this was a retrospective collection of images, it is assumed that the flexion-extension images had been ordered for the additional diagnostic information the referring clinician intended to achieve. Patients were excluded if they had any fractures, history of cancer or infection of the lumbar spine, or history of prior surgery of the lumbar spine.

Flexion, extension and neutral lateral radiographs, and either a supine MRI or CT exam were then downloaded into a secured network and transferred to an imaging core laboratory (Medical Metrics, Inc.) for analysis. Imaging for each subject was anonymized and assigned a unique study-specific ID. IVM at the L4-L5, and L5-S1 levels was analyzed from each of the included studies for each patient. For MRI or CT studies, the mid sagittal slice was used for evaluation of alignment.

Sagittal plane intervertebral rotation and translation was measured using previously validated computer-assisted technology [14,15]. Disc angle was measured as the angle between a line through inferior endplate of the superior vertebra and a line through the superior endplate of the inferior vertebra. Intervertebral rotation was calculated as the change in disc angle, and intervertebral translation was calculated as the displacement of the posterior inferior corner of the superior vertebra in a direction defined by the superior endplate of the inferior vertebra (Fig. 1). The absolute value of translation was expressed as a percent of the superior endplate of the inferior vertebra at the level analyzed. This is necessary due to the lack of a method to correct for radiographic magnification. Normalizing to endplate width also helps to minimize the effect of variability in vertebral size between individuals and between spinal levels. The translation per degree of rotation (TPDR) was also calculated. This ratio helps to control for variation in patient effort when asked to flex and extend. TPDR was only calculated when there was at least 5 degrees of rotation.

In addition, intervertebral motion data for 384 asymptomatic subjects from two previously completed studies were used to define normal intervertebral motion [16,17]. This was used to help calculate a Z-score defined as the number of standard deviations from the mean. The Z-score provides additional information to facilitate understanding of the results. Using the data for the asymptomatic subjects, a Z-score was calculated for the intervertebral rotation, translation, and TPDR by subtracting the average for the asymptomatic subjects and then dividing by the standard deviation (SD) for the asymptomatic subjects. This was done on a level-specific basis (e.g. only data for the asymptomatic L5 levels was used to compare to the symptomatic L5 levels). A Z-score > 2 was used to classify each measurement as greater than normal. TPDR expressed as a Z-score will be referred to as the sagittal plane shear index (SPSI). When calculating a Z-score for translation between supine and flexion or supine and extension, data for translation between flexion and extension in the asymptomatic population was used for the normalization. Since neither supine-to-flexion nor supine-to-neutral data are available for an asymptomatic population, intervertebral translation between flexion and extension (from the previously described 384 asymptomatic subjects) was used when calculating Z-scores for translation between supine-to-flexion and supine-to-neutral.

## Results

The required imaging was available for 74 patients. The age of the patients was 56.9 ± 12 years and there were 44 females and 30 males. The intervertebral rotation between flexion and extension was ≥ 5 degrees in 18 of 74 L4-L5 levels analyzed and in 31 of 73 L5-S1 levels. One L5-S1 level could not be analyzed due to inability to visualize S1. Table 1 summarizes the intervertebral motion metrics, including the significance levels for differences between the L4-L5 and L5-S1 levels.

The intervertebral rotation between flexion and extension averaged 3.5 ± 2.9 deg at L4-L5 and 5.4 ± 4.3 deg at L5-S1. Expressed as a Z-score, the intervertebral rotation was -3.5 ± 0.85 at the L4-L5 levels and -1.5 ± 0.7 at the L5-S1 levels (SD from average in the asymptomatic volunteers). There were no subjects where the magnitude of intervertebral rotation was more than two standard deviations above the average for the asymptomatic population. The intervertebral translation between flexion and extension averaged 2.2 ± 1.8 at the L4-L5 levels and 1.4 ± 1.1 at the L5-S1 levels (percent endplate width). Expressed as a Z-score, intervertebral translation averaged -2.4 ± 0.69 at L4-L5 and -0.29 ± 0.41 at L5-S1 (SD from average in the asymptomatic volunteers). There were no subjects where the magnitude of intervertebral translation was more than two standard deviations above the average for the asymptomatic population.

There was a significant and strong linear relationship between intervertebral rotation and translation using the Z-score data from the flexion-extension studies ($P$<0.0001, $R^2$ = 0.8). SPSI averaged -0.025 ± 1.56 SD from average, with no significant difference between L4-L5 and L5-S1. SPSI was > 2 in four of the 49 levels where TPDR could be calculated from the flexion-extension radiographs (at least 5 degrees of intervertebral rotation was required before calculating TPDR).

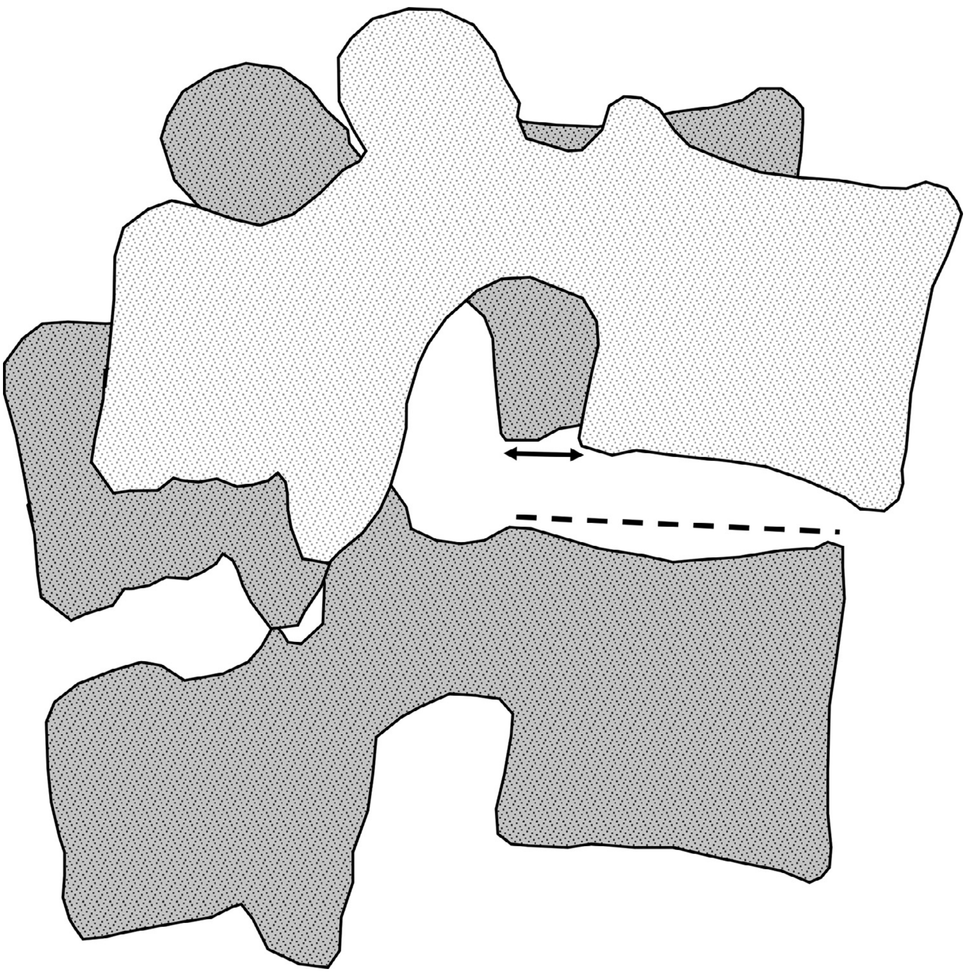

**Fig. 1.** Line drawings of an L4-L5 segment in extension (speckled outlines) and with the L4 vertebra in flexion (gray shaded outline). With the measurement technology that was used, the position of L5 in flexion is the same as it is in extension. Intervertebral translation was calculated as the translation of the posterior-inferior corner of the superior vertebra in a direction defined by the superior endplate of the inferior vertebra.

Intervertebral translation was calculated for all 74 subjects between the upright neutral and supine positions and averaged 2.2 ± 1.8 at L4-L5 and 3.6 ± 2.7 at L5-S1 (percentage endplate width). Calculated as a Z-score, intervertebral translation between standing neutral and supine averaged -2.4 ± 0.69 at L4-L5 and 0.5 ± 0.98 at L5-S1 (SD from average). This translation was > 2 SD above normal in six subjects. Intervertebral translation was also calculated between the upright flexed and supine positions and averaged 3.4 ± 3.1 at L4-L5 and 3.8 ± 3.0 at L5-S1 (percentage endplate width). Calculated as a Z-score, intervertebral translation between flexion and supine averaged -1.9 ± 1.2 at L4-L5 and 0.58 ± 1.1 at L5-S1 (SD from average). This data is summarized in Figs. 2 and 3. This translation was > 2 SD above normal in 11 subjects.

Intervertebral translation was greatest between flexion and extension at 30% of levels, greatest between supine and flexion at 28% of levels, and greatest between supine and neutral at 42% of levels. This may be due to the lack of sufficient flexion in some patients. Based on paired t-tests, the absolute value of translation (in percent endplate width) was significantly greater between supine and upright standing compared to between flexion and extension at the L5-S1 level ($P$<0.0001) but not at the L4-L5 level ($P$=0.55). Based on paired t-tests, the absolute value of translation was significantly greater between supine and upright flexion compared to between flexion and extension both at the L4-L5 ($P$=0.0002) and L5-S1 ($P$<0.0001) levels.

Videos are available through the links below that help to visualize relative motion between L5-S1 in one subject. The videos show motion between flexion and extension radiographs (2.7 % endplate width translation, video link 1), between a supine MRI and upright standing radiograph (9.2 % endplate width translation, video link 2), and between supine MRI and flexion radiograph (11.0 % endplate width translation, video link 3).

## Discussion

The primary purpose of this study was to determine if better information regarding lumbar spinal intervertebral translation can be obtained with unloaded supine and loaded upright imaging versus purely loaded flexion and extension films. This was a pragmatic study using imaging that is obtained in routine clinical practice. We assumed that the spine position and loading is the same in a supine MRI as in a supine CT exam, but without supporting evidence. The load on the spine is expected to be substantially greater in the upright flexed and neutral positions compared to when the supine MRI or CT exam was obtained. The intervertebral motion between flexion and extension was considered “load-bearing”, while the intervertebral motion between flexion versus supine and neutral versus supine was considered to represent “unloading” of the spine. It is appreciated that the spine is supporting some load even in the supine position, but the magnitude of the load acting perpendicular to the vertebral endplates can be expected to be substantially less than when in an upright position [18]. Intervertebral translations would thereby be less constrained.

The data from this study suggest that in some patients the most effective method for detecting abnormal spine motion (motion greater than defined by the 95% confidence interval in radiographically normal asymptomatic volunteers) may be in the assessment of intervertebral translation between the supine and upright flexed positions. Intervertebral motion greater than two standard deviations from the average in asymptomatic volunteers can also be detected between supine and up-

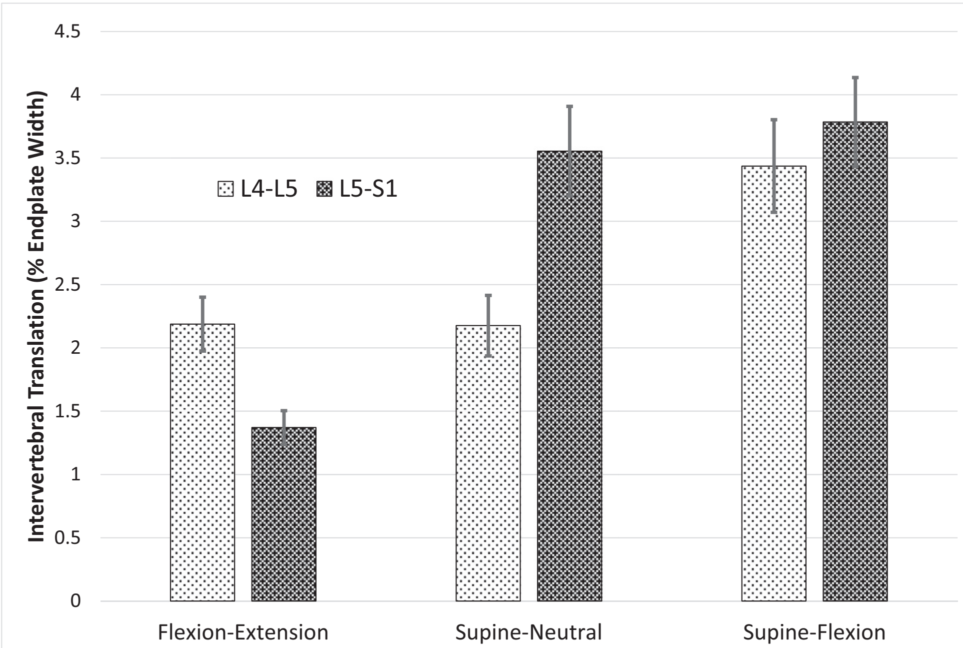


**Fig. 2.** Comparison of intervertebral translation between upright flexion and extension, between neutral upright and supine, and between upright flexion and supine.

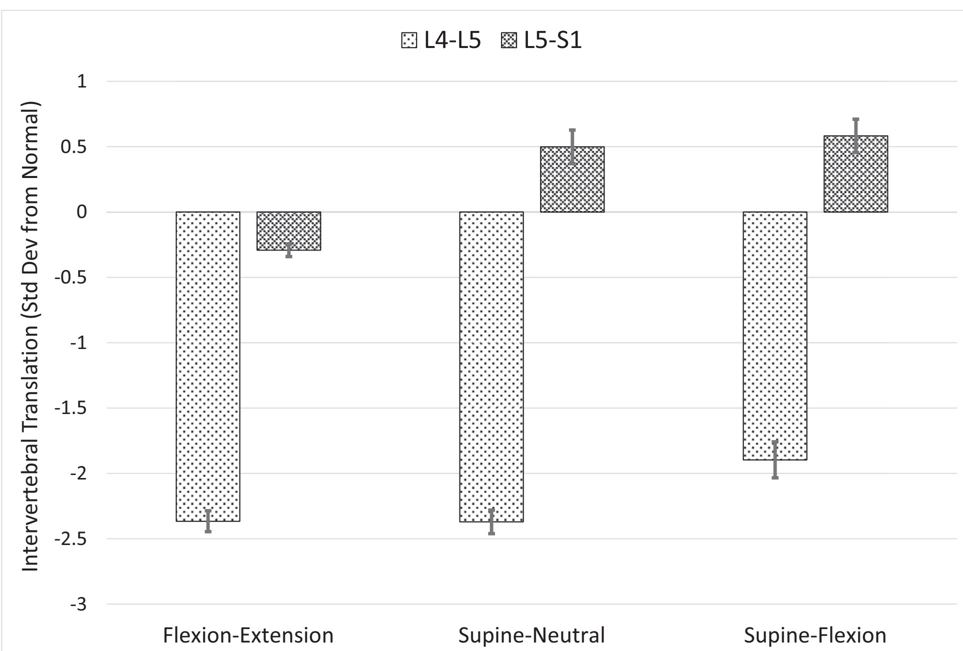


**Fig. 3.** Comparison of intervertebral translation between each patient position expressed as standard deviations from the average found at radiographically normal levels in asymptomatic volunteers.

right neutral positions, but fewer abnormal motions were detected using this combination. Furthermore, when comparing intervertebral motion in patients relative to normative values, the average amount of angular motion was noticeably smaller than translational motion. This is consistent with the observation of more translation Z scores > 2 than rotation Z scores > 2. This suggests that abnormal biomechanics in the degenerative spine, at least in the sagittal plane, may be more likely observed for translation than rotation.

A strong linear correlation was observed between intervertebral rotation and translation measured from the flexion-extension studies ($R^2$=0.8). Based on that observation, it can be hypothesized that additional patients would have been found to have abnormal translation between flexion and extension if there had been greater intervertebral rotation (induced by greater patient effort and thereby greater rotation).

One clear advantage of measuring motion between upright and supine positions is the relative lack of dependence on patient effort. In this study, at least 5-degree of intervertebral rotation was required for analysis of rotation, since without enough intervertebral motion, it is not possible to determine whether abnormal motion can occur during flexion to extension. Motion < 5 degrees was assumed to be within the neutral zone of intervertebral motion [19–21], where the spine is not sufficiently stressed to allow for detection of incompetent intervertebral motion restraints.

The translation per degree of rotation (TPDR) has been shown to be greater in symptomatic versus asymptomatic subjects [3,22] and has been shown to be significantly higher in the presence of the facet fluid sign [23]. This metric has the advantage of helping to minimize variability in patients, and between timepoints in each patient, that is due

**Table 1**
Summary statistics for intervertebral motion metrics. P-values are for the comparison between L4-L5 and L5-S1.

| Metric | Position 1 | Position 2 | Mean[SD] L4-L5 % Endplate Width | Mean[SD] L5-S1 % Endplate Width | P-value | Mean[SD] L4-L5 Z-score | Mean[SD] L5-S1 Z-score | P-value |
|---|---|---|---|---|---|---|---|---|
| Rotation | Upright-Flexion | Upright-Extension | 3.5[2.9] | 5.4[4.3] | 0.0015 | -3.5[0.85] | -1.5[0.7] | <0.0001 |
| Translation | Upright-Flexion | Upright-Extension | 2.2[1.8] | 1.4[1.1] | 0.0015 | -2.4[0.69] | -0.29[0.41] | <0.0001 |
| TPDR / SPSI | Upright-Flexion | Upright-Extension | 0.51[0.18] | 0.21[0.16] | <0.0001 | -0.29[1.5] | 0.28[1.3] | 0.16 |
| Translation | Supine | Upright-Neutral | 2.2[1.8] | 3.6[2.7] | 0.0016 | -2.4[0.69] | 0.5[0.98] | <0.0001 |
| Translation | Supine | Upright-Flexion | 3.4[3.1] | 3.8[3.0] | 0.49 | -1.9[1.2] | 0.58[1.1] | <0.001 |

to differences in patient effort when asked to flex and extend. Intervertebral rotation can be highly dependent on patient effort [24] and is thus limited as a metric for instability. Intervertebral translation, being linearly related to rotation, is thereby also limited as a stand-alone metric for instability. Clinical interpretation of TPDR, since it is level dependent [16], would require using a look-up table to determine if a measurement is normal or abnormal. Expressing TPDR using a Z-score makes it easy for clinicians to interpret, since a value greater than two informs the clinician that a level has a TPDR that would be rarely found in an asymptomatic subject. Z-scores are very commonly used in clinical medicine and in research to facilitate interpretation and analysis of data (https://www.uth.tmc.edu/uth_orgs/educ_dev/oser/L1_6.HTM). In this study, when TPDR was presented as a Z-score, it was referred to as the Sagittal Plane Shear Index (SPSI).

There are several limitations to the current study. One disadvantage of analyzing motion between supine and standing is that significant consistent rotation is not expected. Therefore, TDPR and SPSI were only valid for loaded flexion and extension studies. Additionally, as noted, SPSI was not calculated unless there was at least 5 degrees of intervertebral rotation. This threshold was used based on a review of data on defining the neutral zone (NZ) [19–21]. Between flexion and extension, SPSI greater than 2 is above the 95% confidence interval for the asymptomatic population and is considered evidence of abnormal motion. It may be possible to overcome this weakness with unloaded extension (such as supine over a bolster) and standing flexion films. This was not evaluated in this study.

There were no specific protocols to control effort for flexion and extension in this study. Intervertebral rotation between flexion and extension was very low. There is no way to know if this was a true limitation of the patient's spine, or it was effort related due to pain or other circumstances. Previous research has demonstrated that it is possible to achieve very good intervertebral motion in symptomatic lumbar stenosis patients although that may not specifically apply to this population [25]. Further study in a prospective fashion could help insure the fidelity of the data. However, from a pragmatic standpoint, for symptomatic patients with inability to move due to pain, having a test that can be done without dependence on effort or pain tolerance is advantageous. The efficacy of flexion and extension imaging in the lumbar spine, which is a heavily utilized diagnostic study, should be questioned in absence of a protocol to assure sufficient patient effort. Further study specifically looking at appropriate testing given preliminary information regarding loaded and unloaded alignment could be valuable as well and result in cost savings as well as reduced radiation exposure. It is also important to appreciate that not all patients who have abnormal translation will be symptomatic and thus abnormal translation is only important if correlated with symptoms.

In summary, this study demonstrated that data regarding intervertebral translation can be acquired by evaluation of supine and upright imaging without the need for flexion and extension imaging, and in many cases, can detect more abnormalities than flexion and extension studies. This would be particularly true when good patient effort is lacking for active flexion and extension. This study thereby adds to the evidence in support of measuring intervertebral motion between the supine and upright positions [10,26–32]. This information can be used to help clinicians decide what imaging to order.

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## Declarations of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.xnsj.2020.100038.

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