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ORIGINAL ARTICLE

ISSLS PRIZE IN BIOENGINEERING SCIENCE 2018: dynamic imaging of degenerative spondylolisthesis reveals mid-range dynamic lumbar instability not evident on static clinical radiographs

Malcolm E. Dombrowski[1] · Bryan Rynearson[1] · Clarissa LeVasseur[1] · Zach Adgate[1] · William F. Donaldson[1] · Joon Y. Lee[1] · Ameet Aiyangar[1,2] · William J. Anderst[1]

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Abstract

Purpose Degenerative spondylolisthesis (DS) in the setting of symptomatic lumbar spinal stenosis is commonly treated with spinal fusion in addition to decompression with laminectomy. However, recent studies have shown similar clinical outcomes after decompression alone, suggesting that a subset of DS patients may not require spinal fusion. Identification of dynamic instability could prove useful for predicting which patients are at higher risk of post-laminectomy destabilization necessitating fusion. The goal of this study was to determine if static clinical radiographs adequately characterize dynamic instability in patients with lumbar degenerative spondylolisthesis (DS) and to compare the rotational and translational kinematics in vivo during continuous dynamic flexion activity in DS versus asymptomatic age-matched controls.

Methods Seven patients with symptomatic single level lumbar DS (6 M, 1 F; 66 ± 5.0 years) and seven age-matched asymptomatic controls (5 M, 2 F age 63.9 ± 6.4 years) underwent biplane radiographic imaging during continuous torso flexion. A volumetric model-based tracking system was used to track each vertebra in the radiographic images using subject-specific 3D bone models from high-resolution computed tomography (CT). In vivo continuous dynamic sagittal rotation (flexion/extension) and AP translation (slip) were calculated and compared to clinical measures of intervertebral flexion/extension and AP translation obtained from standard lateral flexion/extension radiographs.

Results Static clinical radiographs underestimate the degree of AP translation seen on dynamic in vivo imaging (1.0 vs 3.1 mm; $p = 0.03$). DS patients demonstrated three primary motion patterns compared to a single kinematic pattern in asymptomatic controls when analyzing continuous dynamic in vivo imaging. 3/7 (42%) of patients with DS demonstrated aberrant mid-range motion.

Conclusion Continuous in vivo dynamic imaging in DS reveals a spectrum of aberrant motion with significantly greater kinematic heterogeneity than previously realized that is not readily seen on current clinical imaging.

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✉ William J. Anderst
anderst@pitt.edu

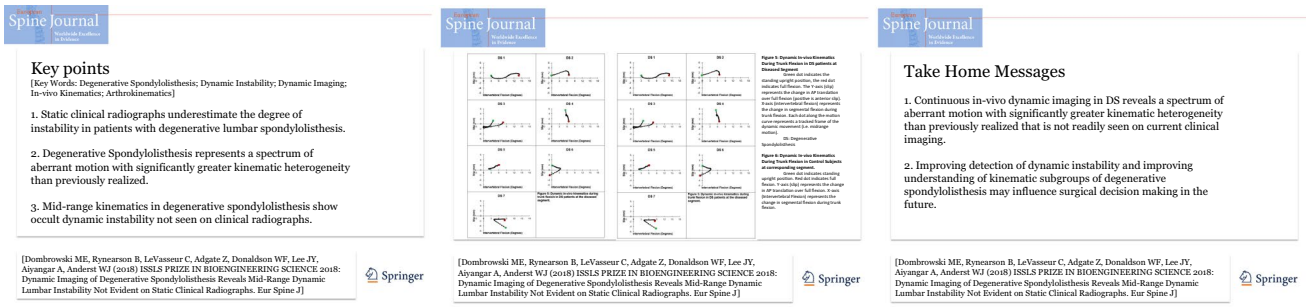
Ameet Aiyangar
ameet.aiyangar@empa.ch

[1] Department of Orthopaedic Surgery, Orthopaedic Biodynamics Laboratory, University of Pittsburgh, 3820 South Water Street, Pittsburgh, PA 15203, USA

[2] EMPA (Swiss Federal Laboratories for Materials Science and Research), Mechanical Systems Engineering (Lab 304), Ueberlandstrasse 129, 8400 Duebendorf, Switzerland

Level of evidence Level V data

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



Keywords Degenerative spondylolisthesis · Dynamic instability · Dynamic imaging · In vivo kinematics · Arthrokinematics

Introduction

Degenerative spondylolisthesis (DS) in the setting of symptomatic lumbar spinal stenosis is commonly treated with spinal fusion in addition to decompression with laminectomy and is accepted by many as the surgical standard of care [1–4]. Historically, it has been argued that decompression and laminectomy without fusion will destabilize the degenerated segment resulting in progressive listhesis with eventual restenosis [4, 5]. This perspective has become more controversial, however, as some studies have shown acceptable results with decompression alone [5–7], while others demonstrate fusion confers superior clinical outcomes [1–3, 8].

A discussion of lumbar stability is critical to the understanding of DS and its contemporary management. Vertebral listhesis in this setting represents a pathologic increase in motion secondary to loss of the anatomic restraint of the intervertebral disc and facet joints. However, a simple binary classification of "stable" or "unstable" is inadequate to fully characterize DS and may be insufficient to guide clinical decision making. Specifically, DS can be further defined by the presence or absence of dynamic instability. Dynamic instability may be defined as segmental anterior–posterior (AP) translation occurring actively with flexion or extension of the lumbar spine. The presence of a dynamic phenotype has been shown to be an important risk factor for failure of decompression and laminectomy without fusion [9].

Clinically, instability is identified by measuring anterior–posterior (AP) translation on static end-range flexion and extension lateral radiographs [10, 11] with a change of greater than 3 mm considered by many to indicate dynamic instability [12–18]. However, ascertaining AP translation on static clinical radiographs is problematic, because not only is this technique prone to high measurement error and relatively poor reliability [19], but also it precludes analysis of potentially important mid-range kinematics. Mid-range kinematics could evince occult dynamic instability, i.e., motion not appreciated when only evaluating listhesis at terminal range of motion. Characterizing the translational behavior of lumbar DS in its entirety will not only deepen our understanding of this common clinical entity, but could also prove useful for predicting which patients are at higher risk of post-laminectomy destabilization necessitating fusion.

Therefore, the primary aim of this study was to determine if AP translation in lumbar DS, as measured on static clinical end-range flexion lateral radiographs, reflects the magnitude of AP translation measured during dynamic in vivo lumbar flexion. Our secondary aim was to characterize the rotational and translational kinematic in vivo patterns of DS as compared to asymptomatic controls. We hypothesized that static clinical radiographs would underestimate the true degree of dynamic listhesis occurring over the entirety of lumbar flexion and that DS patterns would exhibit increased kinematic variability when compared with asymptomatic controls.

Materials and methods

Seven patients (6 M, 1 F; 66 ± 5.0 years) with symptomatic L3/L4 or L4/L5 lumbar DS and seven age-matched asymptomatic controls (5 M, 2 F age 63.9 ± 6.4 years) provided written informed consent to participate in this IRB-approved study. DS patients were recruited from clinic and consented to undergo motion analysis pre-operatively. Both groups had a waist size of less than 36 in. and the healthy controls had no history of lower back problems or previous history of lumbar surgery.

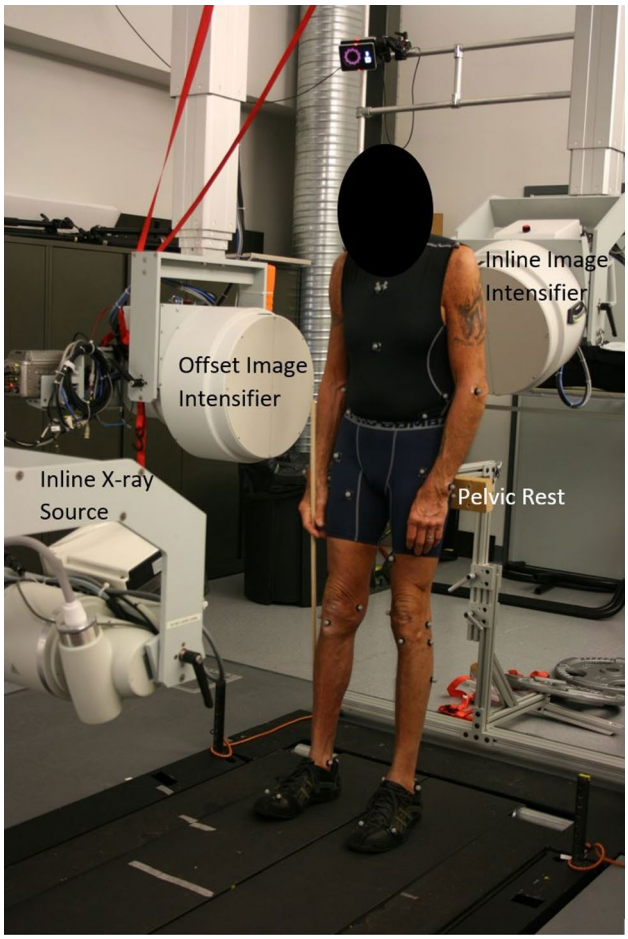


Fig. 1 Positioning of the participant within the biplane dynamic stereo X-ray (DSX) system

Participants stood in a custom-built biplane dynamic stereo X-ray (DSX) system and performed continuous flexion and extension of their trunk from an upright position to as far as comfortably possible without knee bending (Fig. 1). Pelvic motion was limited by keeping light, but constant contact of the buttocks with a semi-rigid pelvic rest. Radiographic images of the lumbar region (L1–S1) were collected for two flexion–extension trials at 20 frames per second for 4–8 s per trial (radiographic settings: 85 kV, 250–400 mA, 4 ms pulse duration). Surface markers were placed on the shoulders, C7, sternum, arms, pelvis, greater trochanters, thighs, legs and feet and recorded at 60–100 Hz using an 11 camera Vicon system (Vicon MX, Centennial CO, USA) simultaneously with the DSX system. Overall trunk motion was calculated relative to the horizontal using the surface markers.

Lumbar spine computed tomography (CT) scans were collected (LightSpeed Pro 16, Ge Medical Systems, Waukesha, WI) with a slice thickness of 1.25 mm and a resolution of 0.5 mm × 0.5 mm. Each vertebra was segmented from the CT images to create 3D bone models (Mimics 14.0, Materialise Inc., Ann Arbor, MI). The estimated total effective radiation dosage from DSX was 4.7 mSv, while the effective CT radiation dose was 9.3 ± 2.2 mSv.

A volumetric model-based tracking process was used to determine the position and orientation of each vertebra in the radiographic images for one of the two trials performed by each individual, selected based on radiographic image quality (Fig. 2).

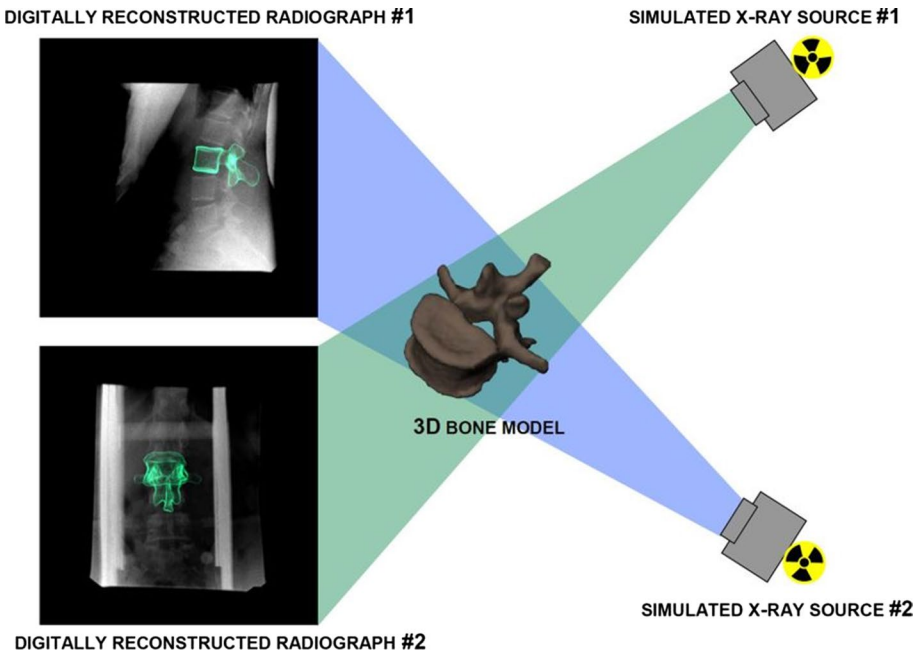


Fig. 2 Two radiographic source and detector pairs. The volumetric model-based tracking technique. Each subject-specific 3D bone model created from CT is placed in a computer-generated reproduction of the biplane system (middle). Simulated X-rays are passed through the 3D bone model to generate digitally reconstructed radiographs (DRRs). Bone position and orientation are determined by an optimization process that matches the DRRs to the edge-enhanced radiographs. This process is completed for each vertebra

Model-based tracking validation

The model-based tracking technique was validated by comparing bone motion as measured by implanted beads (the 'gold standard') to motion as measured by the model-based tracking technique. Two subjects not included in the DS or control cohorts had three to four 2.0 mm diameter tantalum beads implanted into the fused and adjacent vertebrae during laminectomy plus fusion surgery. Six months after surgery, biplane radiographs were collected at 30 frames per second during flexion/extension movements as described above. Movement of the vertebrae with implanted beads was analyzed for a total of five trials for the validation.

Dynamic in vivo kinematic analysis

Kinematic analysis was performed exclusively on the diseased motion segment which was diagnosed by a fellowship trained spine surgeon. Vertebral anatomical coordinate systems (ACS) were defined by three mutually orthogonal axes—AP (antero-posterior), ML (medial–lateral), and SI (superior–inferior) defined by placing virtual markers on the 3D bone models of each participant, with the origin at the vertebral body center. Rotation and translation of the superior vertebra relative to the inferior vertebra were determined pre-surgery by relating frame-by-frame position of the superior vertebral ACS relative to the inferior vertebral ACS. AP translation was measured as the AP distance from the manually identified point of the most inferior-posterior aspect of the superior vertebral body and the most superior-posterior aspect of the inferior vertebral body (Fig. 3). Segmental kinematics were normalized to the static upright position. Only frames in which a participant's trunk was flexing as determined by the surface marker data were included in the present analysis.

Static clinical radiographic analysis

Clinical measures of intervertebral flexion and extension and AP translation were measured on pre-surgical upright and full flexion static radiographs by two observers via the standard measuring approach described in the literature [13, 20] (Fig. 4). Paired *t* tests were used to identify differences between static clinical imaging and dynamic imaging in terms of static listhesis in the neutral upright position, maximum AP translation (i.e., slip) and sagittal range of motion, with significance set at $p < 0.05$.

Results

Model-based tracking validation

Implanted beads (i.e., the "gold standard") were tracked with a precision of 0.11 mm. The precision of bone tracking using the model-based matching technique was 0.3, 0.2 and 0.3 mm in translation for the ML, AP and SI directions, respectively, and 0.5°, 0.4° and 0.5° in rotation for flexion/extension, rotation and lateral bending directions, respectively, when compared with the gold standard.

Kinematic comparisons: in vivo versus clinical radiographs in DS patients

Maximal AP translation during dynamic flexion was greater than what was measured in the static clinical flexion–extension radiographs (3.1 vs 1.0 mm; $p = 0.03$) (Table 1).

No significant differences between static and dynamic measurements were identified in intervertebral flexion ROM (3.3° vs 4.9°, respectively, $p = 0.12$) (Table 1). There was no significant difference in the degree of spondylolisthesis in the neutral position on static vs. dynamic imaging (6.8 vs 6.9 mm, respectively, $p = 0.75$) (Table 1).

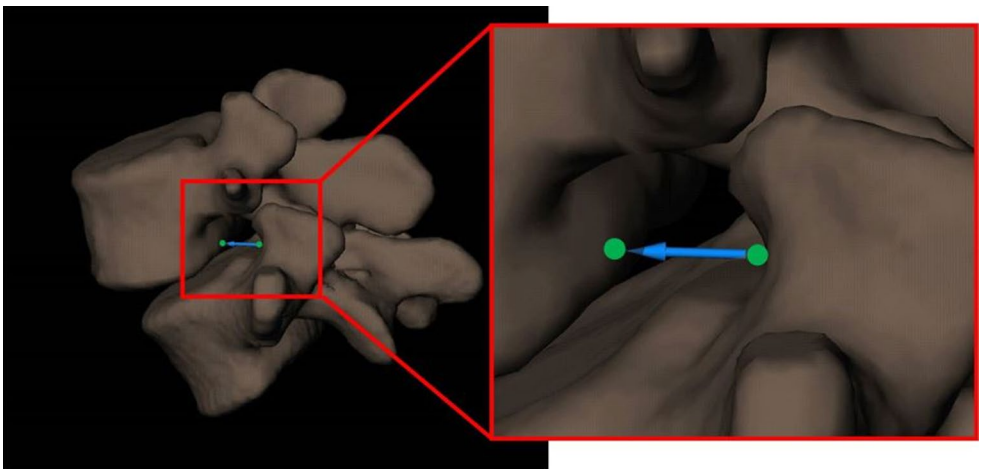


Fig. 3 Kinematic analysis of in-vivo kinematics. AP translation (slip) measured from in vivo kinematics. Landmarks placed on the inferior-posterior endplate of the superior vertebra and the superior-posterior endplate of the inferior vertebra were used to calculate dynamic slip during flexion

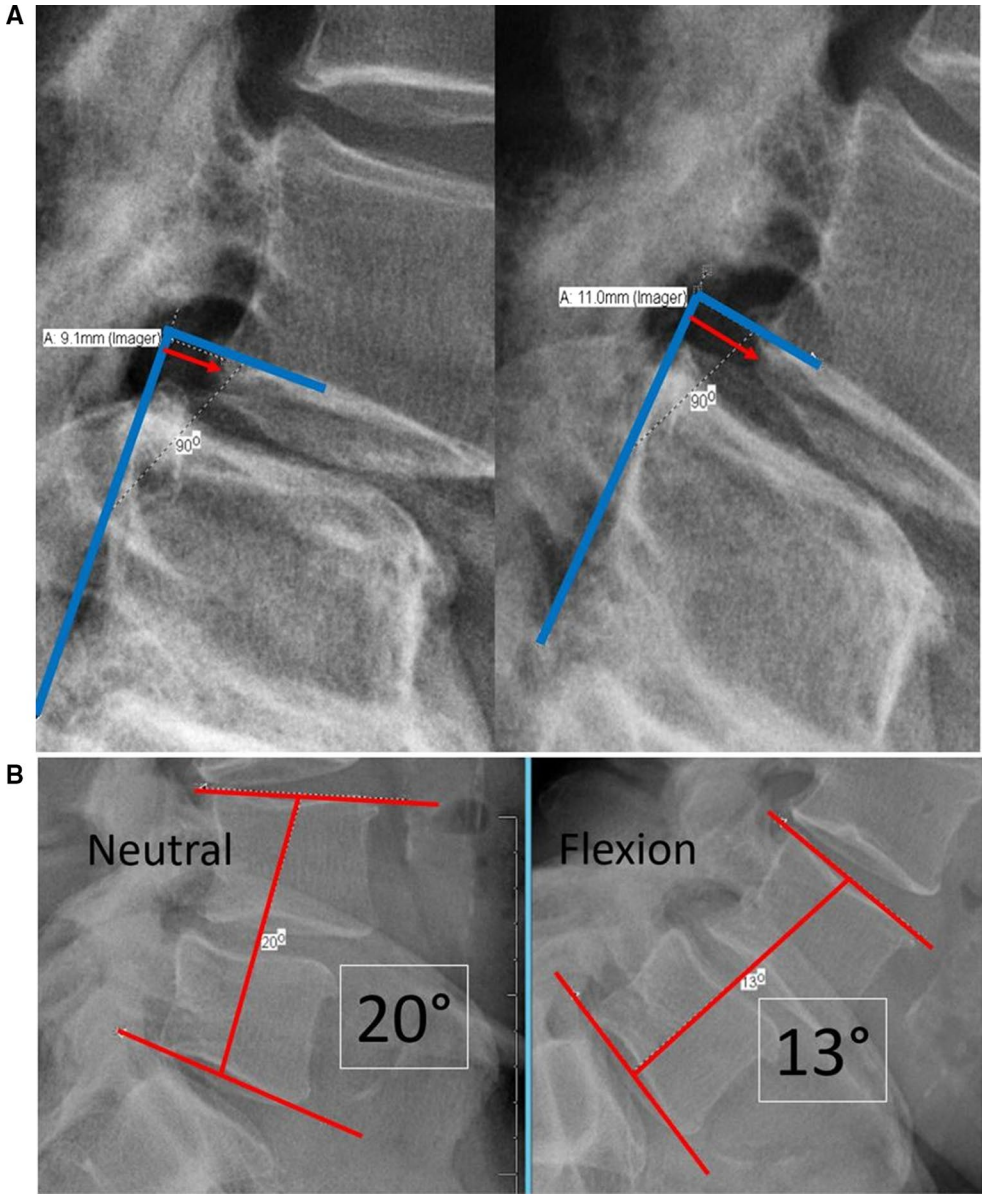


Fig. 4 Clinical measurement of AP translation and intervertebral flexion on static radiographs. **a** AP Translation. **b** Intervertebral flexion

Qualitative in vivo kinematic assessment

Dynamic in vivo AP translation in DS patients

The diseased motion segment in DS patients demonstrated three primary motion patterns (Fig. 5: *y*-axis). Subjects 4 and 6 (2/7; 29%) both exhibited a continuous reduction in the magnitude of anterolisthesis, i.e., the direction of intervertebral segmental sagittal translation was in the opposite direction of torso flexion. Subjects 1, 2 and 3 (3/7; 42%) all finished in the same sagittal translation at the end range of trunk flexion and demonstrated a reversal of translation through the mid-range. Subjects 5 and 7 (2/7; 29%) both showed increased anterior translation throughout the entire mid-range of flexion, ending in a more anterior position at terminal trunk flexion compared to neutral standing position.

Dynamic in vivo intervertebral sagittal rotation in DS patients

In subjects 1, 2 and 5 (3/7; 42%), segmental flexion steadily increased throughout mid-range trunk flexion ending in a more flexed position at the end range of motion (Fig. 5: *x*-axis). Subject 4's (1/7; 14%) flexion angle stayed relatively constant throughout trunk flexion. Subjects 3, 6 and 7 (3/7;

Table 1 Static clinical radiographic measurements compared to in vivo dynamic measurements of intervertebral flexion, maximum slip and upright neutral initial slip in patients with DS

Subject	Flexion ROM (°)		Maximum slip (mm)		Initial slip (mm)	
	Clinical	In vivo	Clinical	In vivo	Clinical	In vivo
1	8.0	11.0	1.8	2.1	5.6	3.7
2	7.0	6.9	2.0	2.0	5.6	4.7
3	1.0	7.7	0.2	3.0	6.0	6.1
4	2.0	1.3	0.4	4.6	2.1	3.5
5	2.0	4.2	1.9	1.8	9.4	10.0
6	3.0	4.2	1.3	3.7	9.2	7.2
7	5.0	4.9	0.4	3.4	8.7	10.0
Average	3.3	4.9	1.0	3.1	6.8	6.9
P value	0.12		**0.03**		0.75	

Bold value indicates P value < 0.5

Flexion ROM change in intervertebral flexion seen on clinical flexion–extension radiographs and from in vivo neutral position to full flexion. *Maximum slip* maximum AP translation seen on clinical flexion–extension radiographs and in vivo neutral position to full extension. *Initial slip* initial amount of anterolisthesis seen on neutral clinical radiographs and in vivo dynamic neutral position imaging

43%) had a reversal of flexion angle during mid-range trunk flexion.

Dynamic AP translation in controls

In general, all asymptomatic controls (100%) showed a steady increase in segmental anterior translation during trunk flexion with only control subject 7 showing an initial posterior translation, but a quick reversal and steady increase thereafter (Fig. 6: *y*-axis).

Dynamic sagittal rotation in controls (Fig. 6: *x*-axis)

In general, all asymptomatic controls (100%) showed a steady increase in segmental flexion over the entire range of trunk flexion with only subjects 3 and 5 showing initial extension then quick reversal with steady increase in flexion thereafter (Fig. 6: *x*-axis).

Discussion

The present study shows that static clinical flexion–extension radiographs appear to underestimate the true degree of AP translation that occurs during trunk flexion when compared with dynamic in vivo continuous kinematic analysis in patients with DS. Additionally, DS appears to exhibit distinct kinematic heterogeneity when compared with asymptomatic age-matched controls. This has previously not been described in the literature, particularly during mid-range of motion. Recent studies questioning the reflexive use of fusion procedures in patients with DS has prompted the spine community to revisit the concept of lumbar instability and how its presence or absence should dictate surgical decision making. This study confirms that there may be more to the story that is not readily obtainable on current functional clinical imaging.

The definition of instability continues to be a major topic of discussion in the surgical spine community, and at this point, there is insufficient evidence to make recommendations on the most appropriate diagnostic or physical examination test consistent with fixed or dynamic deformities in DS patients. There are several studies that use change ≥ 3 mm in AP translation on lateral flexion–extension radiographs [21], but that has been commonly refuted [13, 19, 22]. Despite the diagnostic ambiguity of dynamic instability, its theoretical presence currently dictates surgical decision making [23].

Traditionally, in patients with spondylolisthesis, it has been commonly thought that lumbar spine flexion produces an increase in anterior translation of the superior vertebral body relative to the inferior body [24]. However, the inverse has also been reported as early as 1944 by Knuttson et al., who found four cases of retrolisthesis of the superior vertebral body on forward bending at the L5/S1 segment [25]. This phenomenon has more recently been described in patients with spondylolytic spondylolisthesis [26]. One study showed that nearly half of the patients analyzed with spondylolytic spondylolisthesis displayed this so-called "paradoxical motion" via measurement of instantaneous center of rotation, with displacements ranging from 0.5 to 4.5 mm [27]. Interestingly, the current study of DS patients also showed this kinematic entity and is the first to our knowledge describing this phenomenon in DS and above the L5/S1 segment.

Mid-range kinematics has long been thought to be the missing link for accurate descriptions of dynamic lumbar instability [28, 29], necessitating the creation of new

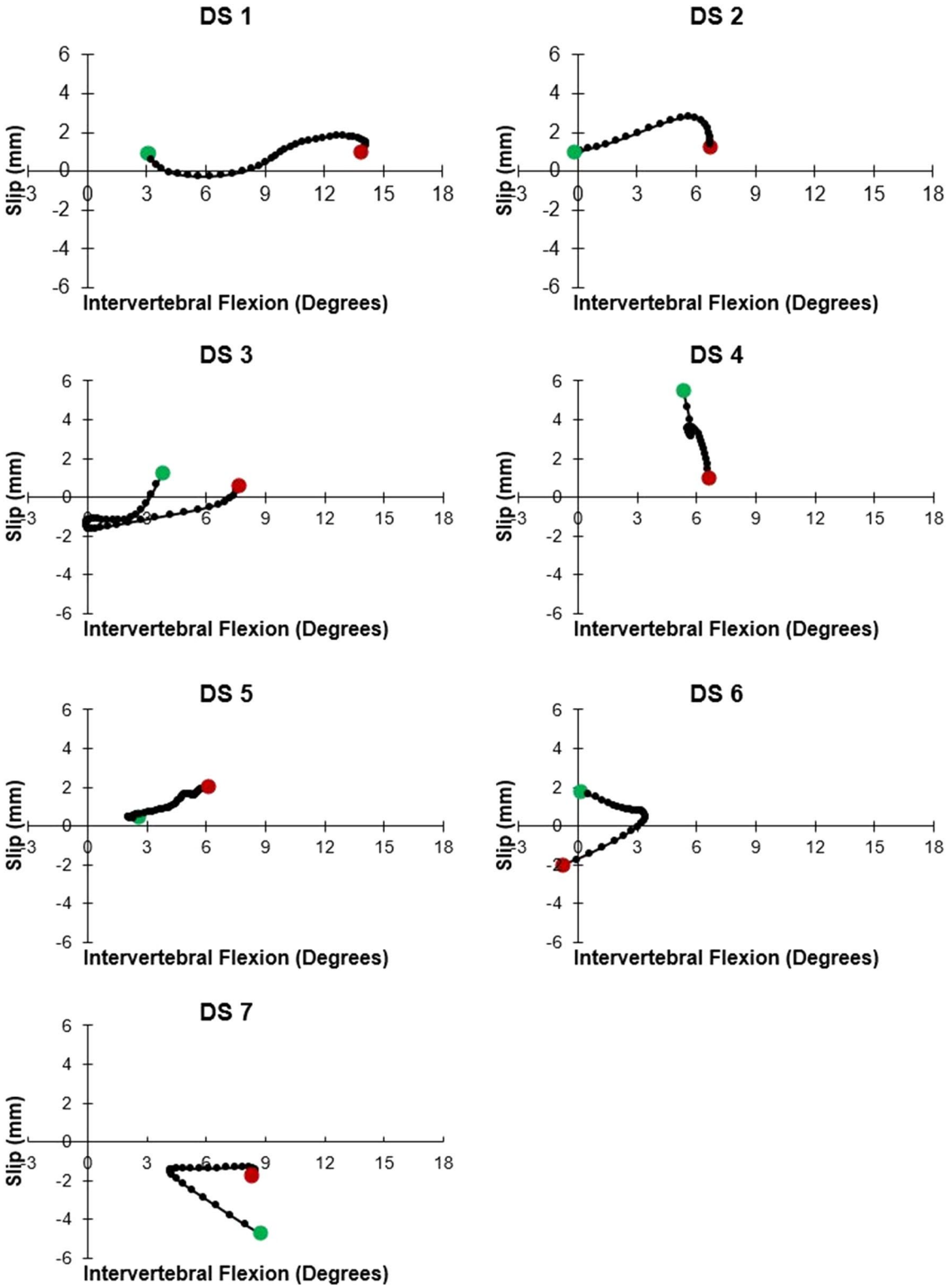


Fig. 5 Dynamic in vivo kinematics during trunk flexion in DS patients at the diseased segment. Green dot indicates the standing upright position, and red dot indicates full flexion. The *Y*-axis (slip) represents the change in AP translation over full flexion (positive is anterior slip). *X*-axis (intervertebral flexion) represents the change in segmental flexion during trunk flexion. Each dot along the motion curve represents a tracked frame of the dynamic movement (i.e., mid-range motion). *DS* degenerative spondylolisthesis

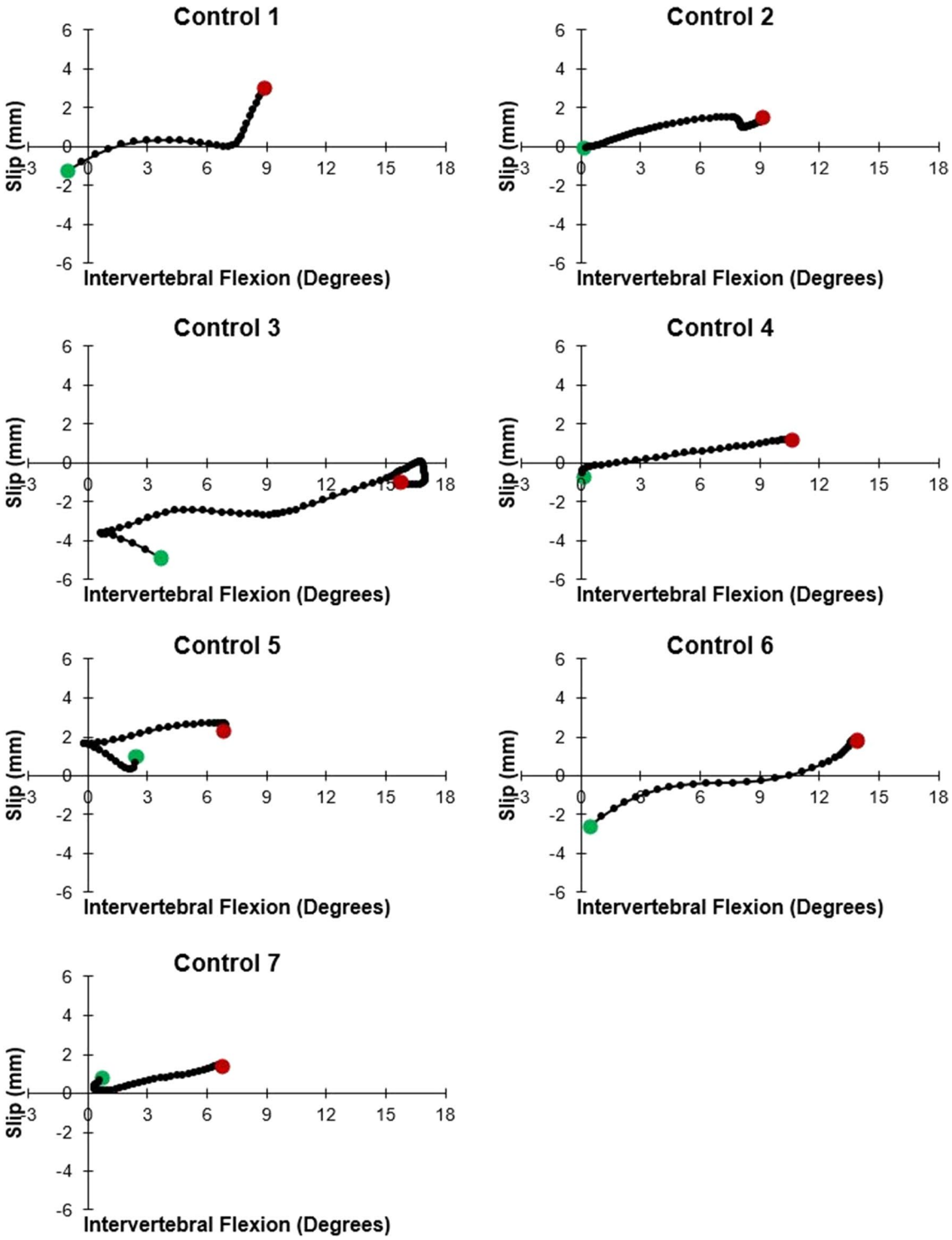


Fig. 6 Dynamic in vivo kinematics during trunk flexion in control subjects at the corresponding segment. Green dot indicates standing upright position. Red dot indicates full flexion. *Y*-axis (slip) represents the change in AP translation over full flexion. *X*-axis (Intervertebral Flexion) represents the change in segmental flexion during trunk flexion

technology with the ability to assess spine movement during the entirety of functional activity. Dynamic imaging of the lumbar spine has been attempted via digital fluoroscopic video or cineradiography with promising results, suggesting aberrant kinematics in the diseased segments [10, 28, 30]. This study expands on these by accurately assessing

continuous in vivo kinematics throughout the mid-range of functional trunk bending movements.

When analyzing the kinematic data presented, one can broadly categorize patients into three subgroups of DS: (1) "Typical" Motion, referring to the increase in anterior subluxation of the superior vertebral body on the inferior body as one's body flexes forward, (2) "Paradoxical" Motion, referring to the decrease in anterior subluxation of the superior vertebral body as one's body flexes forward and (3) "Occult" Motion, referring to either anterior or posterior translation of the superior vertebral body on the inferior vertebral body during mid-range flexion that reduces by the end range of motion. In our study, 42% of the DS patients fell within the "occult" motion subgroup and appeared to be reduced at end range of motion.

When comparing the maximal change in AP translation on static clinical lateral flexion–extension radiographs to the maximal change in AP translation on dynamic in vivo kinematic testing, it is apparent that static clinical radiographs appear to underestimate the amount of dynamic slip that occurs during body flexion in patients with DS. If one were to consider the static clinical radiographs in isolation, no patients in the cohort would have been considered to have dynamic instability using the previously published threshold of 3 mm or greater of anterior translation [17]. In comparison, 43% (3/7) of patients with DS would have been qualified as dynamically unstable when assessing mid-range kinematics. Furthermore, when looking at in vivo kinematics of DS, 100% of patients had a maximal change in AP translation of at least 1.8 mm. When comparing this to clinical flexion–extension radiographs, 3/7 DS patients had a slip of 0.4 mm or less with end range of flexion. This difference in AP translation seen is of clinical importance as even greater than 1.25 mm of AP translation is associated with the need for reoperation due to segmental instability in patients treated with laminectomy and decompression alone [9].

It has been established that decompression and simultaneous fusion can offer superior clinical results to decompression alone, but there are a percentage of patients that will be successfully treated with isolated decompression [21]. However, the addition of fusion surgery is not without risk, including increased surgical costs, complications, rate of infection, operating time and blood loss [31–33]. Thus, it is a priority to determine what patient-specific characteristics will lead to successful outcomes with decompression alone. In a systematic review by Joaquim et al., the authors found 14% of patients with decompression alone for DS required a second surgery due to iatrogenic instability [34]. Blumenthal saw an even increased number with 37.5% of patients requiring revision surgery in their prospective analysis with decompression alone [9]. The data presented in the present study offers insight as to a potential patient-specific factor that may predispose patients to unsuccessful outcomes with decompression only surgery. The present data suggest a subset of patients with "occult" dynamic instability and may be a source of failure of decompression alone surgery. Our study suggests that the concept of clinical dynamic instability needs to be revised to include mid-range motions and further studied for appropriate surgical considerations to be made.

There are important limitations to this study that deserve mention. As is common with other similar kinematic studies, there was a small sample size with only seven patients in each cohort. However, a small sample size would be expected to limit the ability to discern any potential distinct kinematic patterns; yet, we were able to identify several. Another potential limitation is the lack of standardization of body flexion between patients, which could have impacted the observed kinematic patterns. The reasons for variability in flexion ROM are likely multifactorial including patient effort related to pain or anxiety and inherent stiffness secondary to degenerative changes in the spine. In an attempt to standardize the protocol, the subjects were asked to flex to a degree that was their maximum amount without experiencing significant pain, similar to the clinical setting. Despite these inherent limitations, there was no difference between average trunk ROM between DS patients and controls (DS 58.25° vs Control 61.09°, $p = 0.7579$).

This data support that DS in fact represents a spectrum of aberrant motion with significantly greater kinematic heterogeneity than previously realized. Furthermore, our data suggest some patients exhibit so-called occult dynamic instability, i.e., AP translation not apparent using standard static clinical imaging which may have important clinical implications for surgical management. Improving the detection of dynamic instability as well as furthering our understanding of different kinematic subgroups in DS could make possible more patient-specific rather than disease-specific surgical interventions.

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Compliance with ethical standards

Conflict of interest None of the authors has any potential conflict.

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