

Do in vivo kinematic studies provide insight into adjacent segment degeneration? A qualitative systematic literature review

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Abstract

Purpose While much evidence suggests that adjacent segment degeneration is merely a manifestation of the natural degenerative process unrelated to any spine fusion, a significant body of literature supports the notion that it is a process due in part to the altered biomechanics adjacent to fused spine segments. The purpose of this study was to review and critically analyze the published literature that investigated the in vivo kinematics of the adjacent segments and entire lumbar spine in patients receiving spinal fusion or motion-preserving devices.

Methods A systematic review of the PubMed database was conducted, initially identifying 697 studies of which 39 addressed the in vivo kinematics of the segments adjacent to spinal implants or non-instrumented fusion of the lumbar spine.

Results Twenty-nine articles studied fusion, of which three reported a decrease in range of motion of the caudal adjacent segment post-fusion. Examining the rostral adjacent segment, twelve studies observed no change, nine studies found a significant increase, and three studies reported a significant decrease in sagittal plane range of motion. Of the six studies that analyzed motion for the entire lumbar spine as a unit, five studies showed a

significant decrease and one study reported no change in global lumbar spine motion. Kinematics of the segment rostral to a total disc replacement was investigated in six studies: four found no change and the results for the other two showed dependence on treatment level. Fifteen studies of non-fusion posterior implants analyzed the motion of the adjacent segment with two studies noting an increase in motion at the rostral level.

Conclusions There appears to be no overall kinematic changes at the rostral or caudal levels adjacent to a fusion, but some patients (~20–30 %) develop excessive kinematic changes (i.e., instability) at the rostral adjacent level. The overall lumbar ROM after fusion appears to decrease after a spinal fusion.

Keywords In vivo · Kinematics · Range of motion · Lumbar spine · Fusion · Adjacent segment degeneration · Biomechanics

Introduction

Degeneration of the mobile intervertebral levels adjacent to a spinal fusion is a clinically common occurrence that does not consistently lead to symptoms or the need for further surgical treatment. While numerous clinical studies have identified a variety of risk factors associated with adjacent segment degeneration (ASD), the actual risk factors and pathogenesis remains unclear [1, 2]. While some consider ASD to be a manifestation of the normal process of spinal degeneration [3, 4], others believe it is accelerated by altered biomechanics at the levels immediately adjacent to the fusion level [2, 5, 6].

Adjacent segment degeneration may be manifested as either osteophytes and disc collapse that may diminish

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motion or as listhesis, which may increase intersegmental spinal mobility. Either of these two patterns of ASD may lead to clinical symptoms and neural element compression. The degree to which altered biomechanics at these adjacent segments contributes to the development of either of these patterns of ASD is not clearly understood.

Many *in vitro* studies have been performed in human cadaveric specimens to help identify a potential biomechanical explanation of ASD. These studies reported many changes at the adjacent levels, including increased range of motion [7, 8, 9, 10], abnormal facet joint loading [9], and increased intradiscal pressure [10, 11]. The detection of hypermobility in these *in vitro* studies is absolutely dependent on the experimental testing protocol [1]. Displacement-controlled protocols are based on the assumption that, post-operatively, patients replicate the same pre-operative total range of motion (ROM). Load-controlled protocols assume that patients will yield to post-operative activity restrictions and apply the same loads to their spine as pre-operatively [12]. Whether clinically observed scenarios represent the first or second of these experimental approaches or an intricate and dynamic blend of the two remains unknown. Moreover, while the posture of the spine and its movement are controlled by muscles attached to and between each individual vertebra, the majority of experimental studies only apply loading to the uppermost level of the spine. These and the limitations of *in vitro* experimental studies, which are reviewed thoroughly in the review article by Volkheimer et al. [12], necessitate a review of the reported *in vivo* changes after spinal surgery.

To shed light on the degree to which biomechanical mobility changes at the adjacent intervertebral level occur in patients, a series of biomechanical measurements have been made in clinical studies. The vast majority of these measurements are kinematic, i.e., relate to intervertebral motion. The purpose of this review article is to summarize and critically analyze the results from these clinical studies examining the kinematics of the adjacent segment and of the entire lumbar spine. The review includes studies of vertebral fusion and those with total disc replacement and various posterior non-fusion stabilization devices, in the lumbar spine.

Methodology

A comprehensive search of the PubMed database was conducted using the keywords “adjacent” and “lumbar” in combination with one of the following keywords: “range(s) of motion”, “kinematic”, “kinematics”, “instability”, “mobility”, “hypermobility”, or “angulation”. The search was limited to the English literature and

performed from 1970 to 2013 and generated 697 articles. Each title and abstract and, when necessary, the full text, were reviewed to select the studies that addressed the ROM of the segment adjacent to spinal implants or non-instrumented fusion in the lumbar spine of living human subjects. Thirty-five articles met the inclusion criteria. An additional four studies were found following a manual search of the references cited in these chosen articles. Subject matter experts were consulted to determine if additional articles existed. This search yielded a total of 39 articles for review. The included studies were divided into three surgical procedure groups: fusion (with or without instrumentation), total disc replacement (TDR), and posterior non-fusion implants. A summary of the articles is presented in Tables 1, 2 and 3.

Kinematic terminology

There are many kinematic parameters that may be used to describe the relative movements between vertebrae. These include range of motion (ROM), neutral zone (NZ), and instantaneous axis of rotation (IAR); precise definitions of these parameters can be found elsewhere [13]. In this review, the focus is on ROM, as that parameter has been reported most reliably in studies of *in vivo* kinematics.

ROM is defined as “the difference between the two points of physiologic extent of movement” [13] and it can be reported for either angular or translational motion. Clinical studies investigating ROM mostly refer to angular changes between vertebrae or/and antero-posterior vertebral translation which in some cases is referred to asolisthesis: anterolisthesis or retrolisthesis.

There exist many definitions of spinal instability and it is often linked to certain kinematic parameters. For this review, instability in the clinical realm means excessive ROM beyond a pre-determined threshold, which for sagittal plane motion ranges between 3 and 4.5 mm for translation [14, 15] and 8°–15° for angular change [14, 16].

Kinematic measuring methods

The position of the vertebrae and the resultant kinematics of the spine in human subjects is typically recorded using skin-mounted markers or with medical imaging. The imaging techniques include standard planar radiography, biplanar stereophotogrammetry, videofluoroscopy, and less frequently computed tomography and magnetic resonance imaging (MRI).

The use of markers attached to the skin is the safest way for tracking the spine motion since ionizing radiation is not required. However, there are some well-recognized experimental limitations, including the relative movement between the markers and the skin and the absence of direct

Table 1 Summary of the clinical articles addressing kinematics of the segments adjacent to a spinal fusion

Author	Study Type	Study Design	No. of Patients	Diagnosis	Type of Surgery	Age ^a (year)	Length of FU (month)	Length of Fixation		Index Levels	Absolute values for sagittal ROM ^b			
								single-level	multi-level		Total Lumbar	Rostral AS	Caudal AS	
Frymoyer <i>et al.</i> 1979 [36]	Retro	Case control (control group: nonfusion)	132	Residual back pain, nerve root symptoms and functional impairment	96 Fusion (disc excision + posterior midline fusion)	38	164	9	87	9 L5-S1, 8 L4-S1, 6 L3-S1	Biplanar orthogonal radiographs Flexion-Extension (without pelvic restraint)	Smaller	Larger	Not applicable
Luk <i>et al.</i> 1995 [38]	Retro	Case control (control group: asymptomatic volunteers)	52	Degenerative disc disease	52 ALIF	37	> 60	32	20	32 L4-L5, 20 L4-S1	Radiographs Flexion-Extension (with patients lying on one side and wrapping their arms around their knees to assist flexion)	Smaller	Smaller (single-level)	Smaller
Seitsalo <i>et al.</i> 1997 [37]	Retro	Case control (control group: patients with conservative treatment; normal data from literature)	227	Symptomatic isthmic spondylolisthesis at L5	145 Fusion (87 posterior fusion, 55 posterolateral fusion, 3 anterior fusion)	14 (8-19)	185 (60-360)	48	97	48 L5-S1, 84 L4-S1, 13 L3-S1	Radiographs Flexion-Extension (standing)	NI	No difference	Not applicable
Leferink <i>et al.</i> 2002 [40]	Pro	Case control (control group: normal data from literature)	82	Fracture of thoracolumbar spine	Fusion (with either Dick internal fixator or Universal Spine System; both were taken out after 9 months)	39	24	82	-	18 T12, 42 L1, 17 L2, 5 L3	Radiographs Flexion-Extension (standing)	NI	Smaller	Smaller
Kamioka & Yamamoto 1990 [41]	Retro	Case series	26	Spondylolytic or degenerative spondylolisthesis	Fusion (laminectomy + fusion + trapezoid shape plate and screws)	49 (12-67)	29 (7-56)	26	-	4 L3-L4, 17 L4-L5, 5 L5-S1	Radiographs Flexion-Extension	Decreased	Increased (lumbosacral fusion)	Mixed (floating fusion)
Axelsson <i>et al.</i> 1997 [70]	Pro	Case series	6	Back pain + spondylolysis-olisthesis Grade 1-2	Posterolateral fusion without fixation	37 (28-46)	12	6	-	L5-S1	RSA Supine-Sitting	NI	No change	Not applicable
Chou <i>et al.</i> 2002 [44]	Retro	Case series	32	degenerative spondylolisthesis or spinal stenosis	Fusion (posterior decompression + posterolateral fusion + Isola rods or VSP plates)	71 (61-83)	56 (48-66)	18	14	18 L4-L5, 8 L3-L5, 6 L2-L5	Radiographs Flexion-Extension	Decreased	No change	Decreased

Table 1 continued

Author	Study Type	Study Design	No. of Patients	Diagnosis	Type of Surgery	Age ^a (year)	Length of FU (month)	Length of Fixation			Absolute values for sagittal ROM ^b		
								single-level	multi-level	Index Levels	Total Lumbar	Rostral AS	Caudal AS
Axelsson <i>et al.</i> 2007 [71]	Pro	Case series	9	painful degenerative disc disease at L4-L5 or/and L5-S1	6 Posterolateral fusion with and 3 without fixation), 3 ALIF with threaded cages	45 (35-59)	60	6	3	2 L4-L5, 4 L5-S1 3 L4-S1	NI	No change	NI
Kim <i>et al.</i> 2009 [73]	Retro	Case series	28	Degenerative disc disease or Spondylolisthesis	14 Instrumented posterolateral fusion 14 Anterior fusion without instrumentation	45 (21-57)	24	28	-	L4-L5	NI	Increased	No change
Ogawa <i>et al.</i> 2009 [79]	Pro	Case series	54	spinal canal stenosis + lumbar spine instability	27 Instrumented posterolateral fusion + conventional sublamina stabilization at cephalad end site of fusion 27 Instrumented posterolateral fusion without wiring	67 (34-80)	40 (29-55)	-	54	Not specified	NI	Decreased	NI
Kaito <i>et al.</i> 2010 [6]	Retro	Case series	85	L4 spondylolisthesis	Instrumented PLIF	64 (36-83)	39 (24-84)	85	-	L4-L5	NI	No change	NI
Aota <i>et al.</i> 1995 [16]	Retro	Cross sectional (checking for instability)	65	spinal canal stenosis, instability, disc herniation	laminectomy + lateral fusion + fixation	56 (36-78)	39 (24-65)	44	21	34 L4-L5, 10 L5-S1 8 L3-L5, 9 L4-S1 4 L3-S1	NI	NI	NI
Wimmer <i>et al.</i> 1997 [68]	Retro	Cross sectional (checking for instability)	120	painful spondylolisthesis (95 isthmic, 4 dysplastic, 21 degenerative)	combined anterior and posterior fusion + fixation (pedicle screws or laminar hooks)	40 (9-65)	36 (26-84)	46	74	11 L4-L5, 35 L5-S1 45 L4-S1, 6 L3-L5, 18 L3-S1, 2 L2-L5, 3 L2-S1	NI	NI	NI
Nakai <i>et al.</i> 1999 [14]	Retro	Cross sectional (checking for instability)	48	degenerative spondylolisthesis, lumbar intervertebral disk herniation	PLIF	49 (22-73)	103 (60-180)	45	3	3 L3-L4, 37 L4-L5, 5 L5-S1 2 L3-L5, 1 L4-S1	NI	NI	NI
Lai <i>et al.</i> 2004a [80]	Retro	Cross sectional (checking for instability)	60	degenerative or spondylolytic spondylolisthesis	Laminectomy + posterolateral fusion + instrumentation	60 (36-77)	72	60	-	5 L3-L4, 46 L4-L5, 9 L5-S1	NI	NI	NI

Table 1 continued

Author	Study Type	Study Design	No. of Patients	Diagnosis	Type of Surgery	Age ^a (year)	Length of FU (month)	Length of Fixation			Absolute values for sagittal ROM ^b			
								single-level	multi-level	Index Levels	Total Lumbar	Rostral AS	Caudal AS	
Lai et al. 2004b [76]	Retro	Cross sectional (checking for instability)	101	degenerative or spondylolytic spondylolisthesis	Laminectomy + posterolateral fusion + instrumentation	61 (36-78)	(72-84)	60	41	5 L3-L4, 46 L4-L5, 9 L5-S1	NI	NI	NI	
Anderst et al. 2008 [17]	Pro	Case series	5	Not specified	4 Instrumented posterior fusion, 1 Anterior fusion with interbody cage	44	6	4	1	2 L5-S1, 2 L4-L5 1 L4-S1	NI	NI	NI	

ALIF anterior lumbar interbody fusion, AS adjacent segment, FU follow-up, NI not investigated, PLIF posterior lumbar interbody fusion, Pro prospective, RCT randomized controlled trial, Retro retrospective

^a The number in this column represents the average age of the patients. The range of patients' ages is put in parentheses for studies that reported that value

^b Absolute values for ROM are considered as either "increased", "no change", or "decreased", if the comparison is made between pre- and post-operative values. If the post-operative ROM is contrasted versus a control group, the words "larger", "no difference", or "smaller" are used. The status is "NI" (not investigated) for studies that did not calculate or compare those values

correlation between the skin motion and that of the underlying vertebral column. Therefore, the true kinematics of the vertebrae cannot be accurately defined by this method [17].

For this reason, most clinical researchers use radiography or X-ray techniques to examine ROM, as these more clearly delineate the borders and the motion of the vertebrae (Fig. 1a). The kinematics can be recorded in three dimensions using biplanar radiography in a technique called roentgen stereophotogrammetric analysis (RSA) which requires the insertion of small tantalum beads in the vertebrae but provides high kinematic accuracy [17] (Fig. 1b). Another approach is to use videofluoroscopy where continuous patterns of vertebral motion in two or three dimensions can be captured. Clearly, for all of these investigations there exists a trade-off between the duration of patients' activity (i.e., time of radiation exposure) and level of kinematic accuracy (i.e., intensity of radiation). Computed tomography has also been used to measure vertebral kinematics as a research tool [18, 19]. The excellent visualization of the vertebrae in three dimensions is its main advantage, but the limited ability for subjects to move within the scanner and the high radiation dose are major limitations (Fig. 1c).

MRI has also been used as an alternative to the radiographic methods with the main advantage of no radiation exposure. However, the imaging time is much longer [20] and bone is more difficult to distinguish in MRI, which makes it less suitable for tracking motion in dynamic activities (Fig. 1d).

The accuracy and precision of measuring kinematic parameters varies between these techniques. The highest accuracy can be obtained by RSA (~0.1 mm and ~0.2°) [17, 21], followed by biplanar radiography (~0.5 mm and ~0.5°) [22–25], MRI (~0.5 mm and ~0.5°) [26, 27], computed tomography (~1 mm and ~1°) [28], and plain radiography (~1°–5°) [29]. Similarly, the highest precision has been reported for RSA (~0.1 mm and ~0.2°) [17, 30], followed by CT (~0.1 mm and ~0.2°) [19], biplanar radiography (~0.5 mm and ~0.5°) [22], MRI (~1 mm and ~1°) [27, 31], and radiographs (~1°–5°) [32–35].

Among the 39 articles included for review, two articles studied dynamic motion of the spine through videofluoroscopy, three studies used MRI, and three studies performed static RSA. The remaining 31 studies used static radiographs.

Kinematic study designs

There are several types of study designs included in the literature where kinematics of the adjacent level and the entire lumbar spine were reported. These include the case–

Table 2 Summary of the clinical articles addressing kinematics of the segments adjacent to a TDR

Author	Study Type	Study Design	No. of Patients	Diagnosis	Type of Surgery	Age ^a (year)	Length of FU (month)	Length of Fixation		Imaging Method	Absolute values for sagittal ROM ^b		
								single-level	multi-level		TL	Rostral AS	Caudal AS
Auerbach et al. 2007 [39]	Pro	Case control (control group: asymptomatic volunteers)	13	Degenerative disc disease	8 ProDisc-L	45	5 (6-14)	3	5 L4-L5 or L5-S1, 3 L4-S1	Videofluoroscopy Flexion-Extension (standing)	NI	Mixed	NI
					5 Circumferential fusion	36	3	2	3 L4-L5 or L5-S1, 2 L4-S1		NI	Increased	NI
					4 asymptomatic Volunteers	25	-	-	-				
Delamarter et al. 2003 [42]	Pro	RCT	53	Degenerative disc disease	35 ProDisc-II	40 (19-59)	6	19	16	Radiographs Flexion-Extension	NI	No change	NI
					18 Circumferential fusion	42 (26-59)	8	10	10 L4-S1		NI	No change	NI
Cunningham et al. 2008 [59]	Pro	RCT	93	Symptomatic degenerative disc disease	61 CHARITE	40	24	61	L4-L5	Radiographs Flexion-Extension	NI	No change	No change
					31 ALIF with BAK threaded cages	40	32	-	-		NI	No change	No change
Guyer et al. 2009 [60]	Pro	RCT	133	Degenerative disc disease	90 CHARITE	40 (19-60)	60	90	26 L4-L5, 64 L5-S1	Radiographs Flexion-Extension	NI	No change	No change
					43 ALIF with BAK threaded cages	39 (25-55)	60	43	10 L4-L5, 33 L5-S1		NI	No change	No change
Auerbach et al. 2009 [43]	Pro	RCT	200	Degenerative disc disease	155 ProDisc-L	39	24	155	51 L4-L5, 104 L5-S1	Radiographs Flexion-Extension	Mixed	NI	NI
					45 Circumferential fusion	40	45	-	15 L4-L5, 30 L5-S1		No change	NI	NI
Berg et al. 2011 [58]	Pro	RCT	152	Symptomatic degenerative disc disease	80 ProDisc, CHARITE, or Maverick	40 (21-55)	24	Not specified	Not specified	Radiographs (DCRA) Flexion-Extension (lying down)	NI	Mixed	No change
					72 Fusion (44 Posterolateral fusion and 28 PLIF)						NI	Increased	No change
Zigler et al. 2012 [15]	Pro	RCT	166	Degenerative disc disease	123 ProDisc-L	38	60	123	3 L3-L4, 45 L4-5, 75 L5-S1	Radiographs Flexion-Extension	NI	No change	Increased
					43 Circumferential fusion	41	43	-	1 L3-L4, 12 L4-L5, 30 L5-S1		NI	No change	No change

ALIF anterior lumbar interbody fusion, AS adjacent segment, FU follow-up, NI not investigated, PLIF posterior lumbar interbody fusion, Pro prospective, RCT randomized controlled trial, Retro retrospective

^a The number in this column represents the average age of the patients. The range of patients' ages is put in parentheses for studies that reported that value

^b Absolute values for ROM are considered as either "increased", "no change", or "decreased", if the comparison is made between pre- and post-operative values. If the post-operative ROM is contrasted versus a control group, the words "larger", "no difference", or "smaller" are used. The status is "NI" (not investigated), for studies that did not calculate or compare those values

Table 3 Summary of the clinical articles addressing kinematics of the segments adjacent to a posterior non-fusion implant

Author	Study Type	Study Design	No. of Patients	Diagnosis	Type of Surgery	Age ^a (year)	Length of FU (month)	Length of Fixation			Absolute values for sagittal ROM ^b		
								single-level	multi-level	Index Levels	TL	Rostral AS	Caudal AS
Beastall <i>et al.</i> , 2007 [20]	Pro	Case series	24	Dominant low back pain	Dynesys (with/without nerve root decompression)	44 (25-59)	9	8	16	Mixed	Decreased	No change	No change
Lee <i>et al.</i> , 2008 [64]	Pro	Case series	19	Spinal stenosis with degenerative spondylolisthesis, ASD after fusion, disc herniation	Dynesys (decompression)	61 (46-70)	27 (16-35)	9	10	Mixed	No change	No change	No change
Hu <i>et al.</i> , 2011 [46]	Retro	Case series	32	Lumbar intervertebral disc protrusion, degenerative stenosis, degenerative isthmus spondylolisthesis	Dynesys (posterior laminectomy)	58 (43-78)	16 (6-23)	23	9	1 L2-L3, 2 L3-L4, 12 L4-L5, 8 L5-S1 2 L2-L4, 3 L3-L5, 4 L4-S1	NI	No change	No change
Kim <i>et al.</i> , 2011 [61]	Retro	Case series	21	Degenerative spinal stenosis + spondylolisthesis grade I and/or dynamic instability	Dynesys (decompression)	61 (4-50)	29	7	14	Mixed	No change	Increased	No change
Cakir <i>et al.</i> , 2009 [45]	Retro	Case series	26	Back pain+claudication due to degenerative instability+spinal stenosis	11 Dynesys (decompression) 15 Fusion (decompression + fusion + fixation)	57 (24-56) 58 (30-72)	37 45	11 15	-	L4-L5	No change	No change	No change
Yu <i>et al.</i> , 2012 [67]	Pro	RCT	53	Spinal stenosis + severe instability	27 Dynesys 26 Instrumented PUF	52 56	36	27	-	L4-L5	NI	NI	NI
Champain <i>et al.</i> , 2007 [81]	Retro	Case control (Control group: asymptomatic volunteers)	49	Back pain+ disc herniation	Twinflex (discotomy + posterolateral lumbosacral fusion + Twinflex)	47 (29-73)	60 (24-120)	11	38	12 L3-S1, 26 L4-S1, 11 L5-S1	NI	Mixed	Mixed
Park <i>et al.</i> , 2009 [63]	Retro	Case series	27	Chronic degenerative herniated lumbar disc+stenosis, flexion instability, degenerative/spondylolytic spondylolisthesis	Bioflex (decompressive laminectomy with/without discotomy + bioflex without fusion)	59 (47-80)	12	3	24	Not specified	Decreased	No change	No change

Table 3 continued

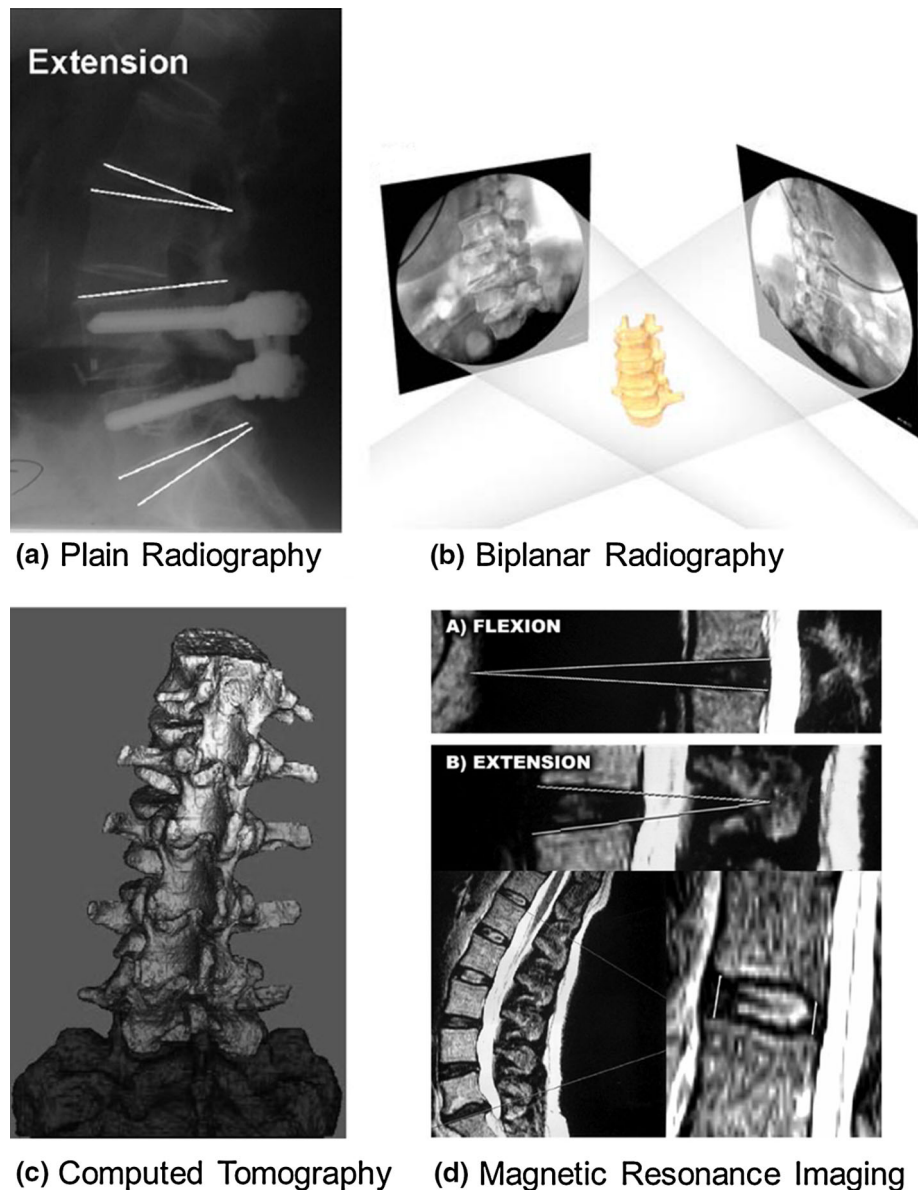
Author	Study Type	Study Design	No. of Patients	Diagnosis	Type of Surgery	Age ^a (year)	Length of FU (month)	Length of Fixation			Absolute values for sagittal ROM ^b		
								Type of Surgery	single-level	multi-level	Index Levels	Imaging Method	TL
Siddiqui <i>et al.</i> , 2006 [65]	Pro	Case series	26	Lumbar Spinal Stenosis + neurogenic intermittent claudication	X-Stop	71 (57-93)	6	15	11	MRI	No change	No change	No change
Nandakumar <i>et al.</i> , 2010 [62]	Pro	Case series	38	Symptomatic spinal Stenosis	X-Stop	>50	24	22	16 (double-level)	MRI Flexion-Extension (sitting)	No change	single-level: Increased double-level: No change	No change
Jia & Sun 2012 [66]	Retro	Case series	19	Lumbar degenerative disease	Wallis (decompression)	61 (46-70)	27 (16-35)	Not specified	Not specified	Radiographs Flexion-Extension	No change	No change	No change
Ha <i>et al.</i> , 2013 [72]	Pro	Case series	31	Degenerative lumbar stenosis + neurogenic claudication + pain	DIAM (decompressive laminotomy)	63 (46-72)	31 (24-56)	31	-	Radiographs Flexion-Extension (standing)	NI	No change	No change
Kong <i>et al.</i> , 2007 [47]	Retro	Case series	42	Degenerative Spinal Stenosis with segmental instability	18 Coflex (decompression with laminotomy)	62 (40-71)	12	18	-	Radiographs Flexion-Extension	NI	No change	No change
Liu <i>et al.</i> , 2012 [82]	Retro	Case series	67	Lumbar intervertebral disc herniation or spinal stenosis	25 PLIF + Wallis or Coflex (discectomy + interbody fusion + fixation + Wallis or Coflex)	45 (21-64)	24 (12-40)	25	-	Radiographs Flexion-Extension	NI	Mixed	Not applicable
Korovessis <i>et al.</i> , 2009 [5]	Pro	RCT	45	Symptomatic spinal stenosis or spondylolisthesis	24 Fusion + Wallis (decompression + posterior rigid fixation + fusion + Wallis) 21 Fusion (decompression + posterior rigid fixation + fusion)	65 (32-72)	54 (32-72)	-	45	Radiographs Flexion-Extension (sitting)	NI	No change	NI

ALIF anterior lumbar interbody fusion, *AS* adjacent segment, *FU* follow-up, *NI* not investigated, *PLIF* posterior lumbar interbody fusion, *Pro* prospective, *RCT* randomized controlled trial, *Retro* retrospective

^a The number in this column represents the average age of the patients. The range of patients' ages is put in parentheses for studies that reported that value

^b Absolute values for ROM are considered as either "increased", "no change", or "decreased", if the comparison is made between pre- and post-operative values. If the post-operative ROM is contrasted versus a control group, the words "larger", "no difference", or "smaller" are used. The status is "NI" (not investigated), for studies that did not calculate or compare those values

Fig. 1 Four common techniques used for in vivo measurement of kinematics of the lumbar spine. Using plain radiography, only 2D kinematics of the spine can be measured (a), while by using two x-ray sources in the biplanar radiography technique, 3D kinematics can be captured (b). Computed tomography (c) can also provide 3D images of the spine and be used for 3D kinematic measurement. For no radiation, MRI can be used for kinematic measurement (d). The images are adapted from [19], [20], [45], and [78] with permission from Lippincott Williams & Wilkins and Springer



control design, in which the post-operative kinematics is compared to a non-operative control group. Several different control groups have been used in the literature, including non-fusion back pain patients [36], patients with conservative treatment for back pain [37], asymptomatic volunteers [38, 39], and normal values from the literature [37, 40]. Another study design is a longitudinal case series where the post-operative kinematics was compared to the same patients before the fusion procedure. Randomized controlled trials (RCT) provide the highest level of evidence and are more commonly used to evaluate the effect of a treatment by randomly selecting the eligible participants for either the treatment group or the control group and comparing the outcomes. These different study

designs, where appropriate, are recorded in the summary Tables presented.

A fourth study design for reporting kinematic differences post-surgery is a cross-sectional radiographic analysis whereby the authors defined a magnitude of motion that they deemed to reflect an unstable vertebral level. They then compared the number of patients with adjacent segment motion above this certain magnitude, thereby providing an indication of substantial kinematic changes post-surgery.

The vast majority of the reviewed studies reported two-dimensional motion and most of that was in the sagittal plane (i.e., flexion–extension). In our analysis, we included any studies that reported absolute kinematic data in any

direction. Some studies on this subject reported relative kinematic changes and we believe this approach does not adequately reflect the actual changes that occur at a particular vertebral level and thus we did not include these data in this review. This topic is included in the “Discussion” section.

Within these studies, there exists a wide range of potentially important parameters such as age of the patients, initial diagnosis, type of surgery, and length of fixation that could influence the kinematic findings at the adjacent segment. However, there do not exist sufficient numbers of subjects to tease out the effects of these parameters. They are included in the tabulated results, however.

Results

Fusion

Twenty-nine articles were identified in the fusion group; with seventeen studying only fusion while twelve included comparisons with either total disc replacement (TDR) or a posterior non-fusion implant (see Tables 1, 2, and 3).

For the segment immediately rostral to the fusion, twelve studies observed no changes in the average flexion–extension ROM, nine studies found an increase (or larger value), and three studies noted a significant decrease (see Table 4). None of the studies that examined the second, third or fourth rostral segments reported any significant increase in flexion–extension ROM [40–42].

For the first segment immediately caudal to the fusion, seven studies reported no change in flexion–extension ROM and three studies observed a decrease (see Tables 1, 4).

Among the studies that looked at ROM of the entire lumbar spine, one study saw no change [43], and five reported a decrease after fusion [36, 38, 41, 44, 45].

For lateral bending, three studies investigated the adjacent segment ROM [17, 20, 46], but only one of them found a significant change, which was a reduction in ROM [20]. Axial rotation ROM was reported in one study [17], but no comparison to the pre-operative ROM was made.

Three studies defined subgroups of subjects for further analysis. Kaito et al. [6] identified three groups: no ASD, radiographic but asymptomatic ASD and symptomatic ASD. They observed that while pre-operatively there was no difference between the groups regarding adjacent segment kinematics, post-operatively, both the group with symptomatic ASD and the group with radiographic ASD manifested a significantly larger ROM in comparison to the group with no ASD. Kong et al. [47] observed that 33 % of the patients experienced an increase of more than 5° of rotation between pre-operative and post-operative ROM at

Table 4 How do the absolute values for sagittal ROM change after a spinal fusion?

	Total lumbar spine			Rostral AS			Caudal AS		
	Increase	No change	Decrease	Increase	No change	Decrease	Increase	No change	Decrease
RCT	Auerbach et al. [43]			Korovessis et al. [5] Berg et al. [58]	Delamarter et al. [42] Cunningham et al. [59] Guyer et al. [60] Zigler et al. [15]		Cunningham et al. [59] Guyer et al. [60] Berg et al. [58] Zigler et al. [15]		
CS	Kamioka and Yamamoto [41] Chou et al. [44] Cakir et al. [45]	Kamioka and Yamamoto [41] Yamamoto [41] Kong et al. [47] Ogawa et al. [79] Kim et al. [73] Liu et al. [82]			Axelsson et al. [70] Chou et al. [44] Axelsson et al. [71] Kim et al. [73] Cakir et al. [45] Kaito et al. [6]	Ogawa et al. [79]		Kong et al. [47] Kim et al. [73] Cakir et al. [45]	Chou et al. [44]
CC	Frymoyer et al. [36] Luk et al. [38]			Frymoyer et al. [36] Auerbach et al. [39]	Luk et al. [38] Seitsalo et al. [37]	Luk et al. [38] Leferink et al. [40]			Luk et al. [38] Leferink et al. [40]

RCT randomized controlled trial, CS case series, CC case control, AS adjacent segment

Table 5 Incidence of instability after a spinal fusion

	Rostral		Caudal	
	Study	Instability incidence	Study	Instability incidence
Translational	Nakai et al. [14]	1/48 = 2 %	Nakai et al. [14]	0/48 = 0 %
	Zigler et al. [15]	2/43 = 5 %	Zigler et al. [15]	0/43 = 0 %
	Wimmer et al. [68]	13/120 = 11 %		
	Ogawa et al. [79]	4/27 = 15 %		
	Chou et al. [44]	6/32 = 19 %		
	Seitsalo et al. [37]	32/145 = 22 %		
	Auerbach et al. [39]	4/5 = 80 %		
Angular	Nakai et al. [14]	0/48 = 0 %	Nakai et al. [14]	0/48 = 0 %
Mixed	Lai et al. [76]	10/60 = 17 %	Aota et al. [16]	1/61 = 2 %
	Lai et al. [80]	19/101 = 19 %	Lai et al. [80]	3/101 = 3 %
	Aota et al. [16]	14/61 = 23 %	Yu et al. [67]	1/26 = 4 %
	Yu et al. [67]	6/26 = 23 %	Lai et al. [76]	3/60 = 5 %

$$\text{Instability incidence} = \frac{\text{Number of the patients with instability}}{\text{Total number of the patients}}$$

the rostral adjacent segment, 46 % showed an increase of less than 5° and 21 % had a decreased ROM. With comparable analyses, similar trends were observed in studies by Kamioka and Yamamoto [41].

Eleven studies investigated the “instability” of the adjacent segment, where “instability” was defined as per our Methodology description above (see Table 5). Six of the studies only analyzed translational instability; of the remaining five studies, one study separated the incidence of translational instability from angular instability, but the other four studies analyzed them together. While observed instability at the caudal adjacent segment was rare (between 0 and 5 %), the majority of studies observed that rostral adjacent segment instability occurred more commonly, among 10–30 % of the patients.

Total disc replacement (TDR)

For TDR, many studies investigated the kinematics of the operated levels [35, 48–57], but only six studies addressed absolute values for the adjacent segment ROM (see Table 2). Four of the articles found no change in ROM for the immediately rostral adjacent segment. The other two articles indicated differences that appeared dependent on the anatomical level of the TDR surgery. Berg et al. [58] saw no change when the TDR was L5–S1, but did find an increase when the surgical level was L4–L5. Auerbach et al. [39] observed an increase in extension ROM when the index level was L5–S1 and no change when the surgical level was L4–L5 (see Table 6).

For the caudal adjacent segment, three studies found no change [58–60] and only one study noted an increase in motion [15].

One study reported that if the surgical level was L4–L5, there was an observed increase in range of motion of the entire lumbar spine, however, when L5–S1 was the surgical level, there was no such observed change [43].

Neither rostral nor caudal adjacent segment instability was observed in the two studies that investigated this parameter [15, 39].

Posterior non-fusion implants

Fifteen studies reported on kinematic changes following surgery with posterior non-fusion implants and these can be divided into two subgroups: eight studies that used pedicle screw-based systems such as Dynesys, Twinflex, BioFlex, etc., and seven studies that used Interspinous Distraction Devices (ISDD) such as the X-Stop spacer, Coflex, DIAM and Wallis implants. Only two of the 15 studies demonstrated a significant increase in the flexion–extension ROM at either the rostral or the caudal adjacent segments. Kim et al. [61] reported an increase in ROM at the rostral adjacent segment and Nandakumar et al. [62] reported an increase in motion at the caudal segment (see Table 7).

Total lumbar ROM decreased in two studies [45, 63], and did not change in any of the other studies that investigated this parameter [45, 61, 62, 64–66].

Rostral adjacent segment instability was examined in two studies, and found to affect 29 % of patients in one

Table 6 How do the absolute values for sagittal ROM change after a TDR?

Total lumbar spine			Rostral AS			Caudal AS		
Increase	No change	Decrease	Increase	No change	Decrease	Increase	No change	Decrease
Auerbach et al. [43]	Auerbach et al. [43]		Auerbach et al. [39] Berg et al. [58]	Delamarter et al. [42] Auerbach et al. [39] Cunningham et al. [59] Guyer et al. [60] Berg et al. [58] Zigler et al. [15]		Zigler et al. [15]	Cunningham et al. [59] Guyer et al. [60] Berg et al. [58]	

Table 7 How do the absolute values for sagittal ROM change after a posterior non-fusion implant?

	Total lumbar spine			Rostral AS			Caudal AS		
	Increase	No change	Decrease	Increase	No change	Decrease	Increase	No change	Decrease
PSDS	Lee et al. [64] Kim et al. [61] Cakir et al. [45]		Beastall et al. [20] Park et al. [63]	Kim et al. [61]	Beastall et al. [20] Lee et al. [64] Cakir et al. [45] Park et al. [63] Hu et al. [46]			Beastall et al. [20] Lee et al. [64] Cakir et al. [45] Park et al. [63] Hu et al. [46] Kim et al. [61]	
ISDD	Siddiqui et al. [65] Nandakumar et al. [62] Jia and Sun 2012 [66]		Nandakumar et al. [62]	Siddiqui et al. [65] Kong et al. [47] Korovessis et al. [5] Nandakumar et al. [62] Jia and Sun 2012 [66] Liu et al. [82] Ha et al. [72]	Liu et al. [82]		Siddiqui et al. [65] Kong et al. [47] Nandakumar et al. [62] Jia and Sun 2012 [66] Ha et al. [72]		

ISDD interspinous distraction devices, PSDS pedicle screw-based dynamic stabilizers

study [61], but only 4 % in the other [67]. Neither of these two studies noted any instability at the caudal adjacent segment.

Discussion

The etiology of adjacent segment degeneration (ASD) after spinal surgery is clearly complex and likely multifactorial. It is a challenging topic with some questioning the existence of ASD, alternatively suggesting that any observed degenerative changes adjacent to a spinal fusion are merely the natural history of that intervertebral segment independent of any surgical intervention [1, 3, 4]. The absence of consensus on this point makes studying its etiology very challenging. However, given the preponderance of literature on the topic and the frequent presentation of symptomatic adjacent segment disease, it seems likely that ASD does exist to some degree.

With respect to its etiology, the predominant hypothesis is that ASD is due, at least in part, to biomechanical

changes within the instrumented segments and at the adjacent vertebral levels. It certainly seems reasonable that a spinal fusion would alter the loading patterns and/or the manner in which the spine moves and that some form of degenerative changes might result. However, interestingly, this has never been proven conclusively. There is a vast body of in vitro literature that describes adjacent segment changes at the remaining unfused lumbar spinal motion segments. As the review by Volkheimer et al. [12] demonstrates, however, these studies are based upon assumptions that are either false or unproven.

Spinal degeneration affects most or all segments of the lumbar spine. It is unknown how the biomechanical alterations associated with an adjacent fusion may influence this degenerative process within the unfused segments; either by accelerating disc collapse, osteophyte formation and stability of motion segments, or by inducing hypermobility orolisthesis at these adjacent levels.

The primary objective of this study was to review all of the in vivo kinematic data on this topic, to determine the evidence, if any, for kinematic changes adjacent to a spinal

fusion, TDR, or a posterior non-fusion implant in the lumbar spine. A secondary objective was to examine the nature, magnitude and interrelationship of these kinematic changes.

While the studies included were somewhat heterogeneous and the data available inconsistent, some summary observations can be made. Adjacent to a spinal fusion, the majority of studies do not demonstrate any predictable change in vertebral kinematics. While some studies have reported an increase in the ROM of the immediately rostral segment, no studies report an increase in kinematics caudal to a spinal fusion.

Despite the failure of these studies to observe any predictable change in adjacent segment kinematics, clinical experience is that some patients do experience both asymptomatic and symptomatic increases in intervertebral kinematics adjacent to a spinal fusion, with reported rates ranging from 10 to 30 % [6, 16, 47, 68].

Our review of the literature found fewer reported kinematic changes adjacent to a TDR or a flexible posterior device (see Table 4). However, more studies and longer follow-up periods are required before any firm conclusions can be made.

The overall motion of the entire lumbar spine appears to decrease after a spinal fusion, based on five of the six studies that measured this parameter. This is actually contrary to a fundamental assumption of many *in vitro* studies using displacement control that presumed that overall spine motion after spinal fusion would be the same as pre-operatively. This includes the popular hybrid method for assessing the adjacent segment as proposed by Panjabi [69]. Obviously, this is an important point for future investigations on this topic.

Challenges and limitations of studies

There are clearly many challenges in conducting *in vivo* studies of ASD. We outline some of the challenges here and also describe some of the limitations in the existing literature. These include topics such as study design, patient selection, and analysis of kinematic data.

To study the kinematics of ASD, one needs a reasonably accurate method of measuring spinal motion. Three-dimensional dynamic measurement would be ideal but this capability, which has been used previously for various joints [21, 24], has been used more recently for the spine [17]. The study by Anderst et al. [17] demonstrates the possibility of such measurement in the spine using dynamic RSA, with the main limitation of this technique being the invasiveness of the insertion of tantalum beads before the surgery. Nevertheless, it is an exciting methodology that promises to enhance our future understanding of this problem. Three-dimensional static motion of the spine after

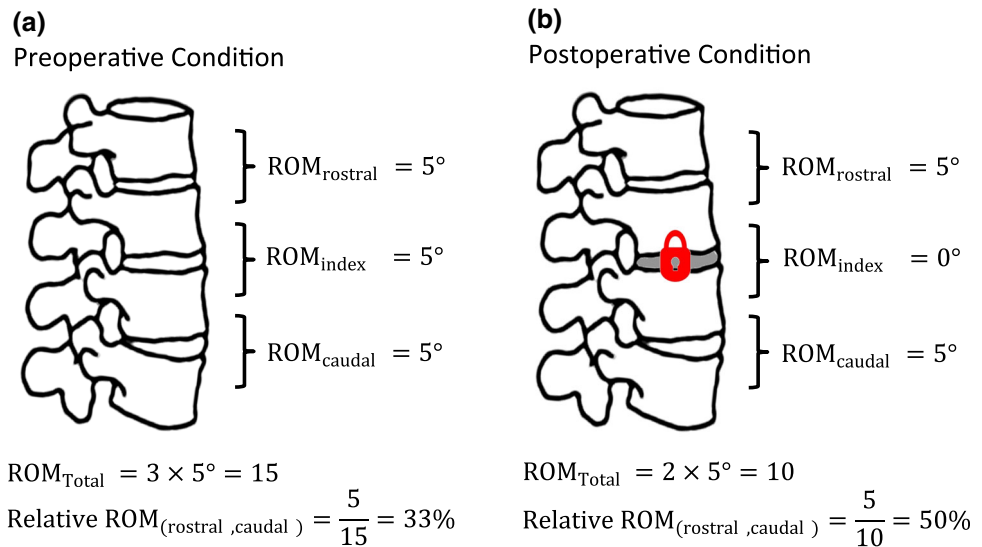
fusion has been used to study ASD using the RSA technique and these studies are extremely insightful, since they represent highly accurate motion measurements [70, 71]. The majority of studies summarized in this review used simple X-ray techniques to report two-dimensional, static kinematics of the spine after fusion. These studies are the lowest accuracy and simply report the relative positions of the vertebrae at their endpoints of motion, but they are a good start to help us understand the problem.

Possibly, the most challenging element in measuring spinal kinematics with respect to ASD is obtaining reliable measurements in patients with low back pain by standardizing the techniques used to obtain radiographs. Various protocols were utilized for taking flexion–extension radiographs. In most of the studies reporting on flexion–extension ROM, patients were asked to naturally flex and extend as much as they could while sitting [5, 20, 65, 62] or standing [14, 37, 39, 72, 73]. In some cases patients were assisted by leaning against a table [37], wrapping their arms around their knees [38] or using support bars [20]. Four studies took the images with patients lying supine or prone [58, 65, 70, 71], and in two studies flexion–extension radiographs were taken with patients in the lateral decubitus position [16, 38]. However, there were many studies that did not clearly describe or even mention the protocol adopted by patients when measuring kinematics. Since spine posture and type of activity performed during imaging as well as the patient's level of comfort can all affect the range and the pattern of motion, investigators must standardize the techniques for these evaluations particularly when attempts are made to compare between studies. These technical issues may increase the variability in the data and thereby mask real differences if sufficient care is not taken.

Due to high inter-individual variability in spinal segmental alignment and consequently in kinematics, the comparison of post-operative with pre-operative kinematic data is ideal since the statistical comparisons are then done with each subject as their own control. Presence and absence of symptoms during evaluation will confound these measurements. Several studies compared post-operative results against asymptomatic controls or literature norms. However, this is fraught with challenges due to the wide variation between subjects. Both approaches remain feasible, but the former is certainly preferred.

For the analysis of kinematic data, most studies reported the absolute magnitude of segmental ROM. In contrast, some studies reported the relative contribution of that level to overall lumbar spine ROM [43, 44, 59, 74, 75]. In the context of understanding ASD, the former method of comparing absolute motions is clearly optimal since the tissues at that intervertebral joint will be under the same stresses and strains only when the absolute kinematics are

Fig. 2 Schematic demonstration of the difference between absolute ROM and relative ROM. Assuming a pre-operative ROM of five degrees for each segment (a) and considering the ROM to decrease to zero post-operatively only at the operated (index) level (b), then, although the relative ROM (i.e. $\frac{\text{Absolute ROM}}{\text{Total ROM}}$) for each adjacent segment increases from 33 to 50 %, absolute ROM at the adjacent segments remains unchanged (5°). Therefore a change in relative ROM does not necessarily represent a change in absolute ROM



the same. The latter method of comparing relative motions is potentially misleading. For example, by comparing the percent contribution of each segment to the total lumbar spine ROM between a fusion and an asymptomatic group, Lin et al. [75] reported that a compensatory increased mobility occurred at the adjacent segments above the fusion; whereas, an increase in percent segmental ROM does not mean an increase in absolute values for ROM and thus it does not reflect increased stresses or strains in those tissues. In a study by Cunningham et al. [59], the fusion group experienced a significant increase in percentage of segmental ROM at both rostral and caudal levels but the corresponding absolute values did not change, which is due to the decrease in total lumbar ROM. Thus, it is hard to see how such a change in relative ROM could be suggested as a cause of ASD. We prepared a simple example to reflect this situation in Fig. 2.

The majority of studies combine patients with different lengths and levels of fixation for analysis (see Tables 1, 2, and 3), while there were studies that showed different length of fixation results in different kinematic behavior of the adjacent segment. Luk et al. [38] observed that in comparison with asymptomatic volunteers, patients with single-level fusion had smaller ROM at the rostral level while patients with multi-level fusion showed no difference. In the study by Kim et al. [61], excessive translational ROM (more than 4 mm) was observed at the rostral adjacent segment only in the group with multiple levels of fixation. By investigating patients with different length and levels of fusion, Wimmer et al. [68] showed that instability correlated with the number of fused segments and that the instability occurred only in those who had lumbosacral fusion.

Similarly, the surgical approach may influence the adjacent segment kinematics. Kim et al. [73] described two

groups; one undergoing interbody fusion from anterior method alone (ALIF), and the other one undergoing instrumented posterolateral fusion. Two years post-surgery, only the group with instrumented posterolateral fusion experienced an increase at the rostral adjacent segment, which may be due to iatrogenic injury of posterior musculature in the posterolateral fusion group. Lai et al. [76] noted a significantly lower incidence of adjacent segment instability (6 %) in patients whose supra- and interspinous ligaments were preserved by partial laminectomy in comparison with those who underwent total laminectomy (24 %). These observations suggest that distinction between patients undergoing different surgery methods may affect the outcomes of the studies that analyzed the patients altogether irrespective of the surgical methods they received [37, 68].

Future considerations

To study the ASD phenomenon from a biomechanical perspective, more accurate measurement of spine motion and adjacent segment kinematics is needed. Accurate kinematic data can serve as inputs to computational models that would enable the calculation of intervertebral loading changes such as disc pressures or facet contact forces at different levels of the spine. Given the high stiffness of the spine, even small errors in kinematic inputs result in large errors in the predicted loads. Moreover, since the motion of the spine is coupled (e.g., between lateral bending and axial rotation [77, 78]), capturing the kinematics in 2D may not be sufficient for a precise analysis of spinal biomechanics. Therefore, a movement toward more accurate 3D dynamic tracking of spine motion seems reasonable [17, 39].

There are several possible hypotheses regarding why the issue of adjacent segment degeneration is so prevalent. Most prominent is the theory that biomechanical forces are increased at these levels. This paper demonstrates that even if there are increased forces on adjacent segments, very few of them demonstrate kinematic instability. Thus, other theories of etiology become more relevant such as the issues of sagittal alignment predisposing to ASD and the issue of the biological health of the adjacent motion segment.

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