BIOMECHANICS OF SPINAL MOTION SEGMENT INSTABILITY IN THE LUMBAR SPINE: A SYSTEMATIC REVIEW

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Objective. To determine the most valid biomechanical indicators of the stability of spinal motion segments in the lumbar spine, their normal values, and reproducibility for use in clinical practice of surgical treatment of degenerative diseases.

Material and Methods. To identify the most significant and sensitive criteria for assessing the biomechanics of the spinal motion segments in the lumbar spine, 4784 publications were selected using the PubMed and eLibrary search systems, of which 16 articles were selected after evaluation according to the established inclusion and exclusion criteria and served as the basis for further analysis.

Result. All segmental stability indices are divided into 3 groups: clinical, radiological and experimental. The rather subjective nature of clinical criteria is noted, including mainly either pain assessment during palpation or assessment of motor activity. At the same time, pain did not show a reliable connection with the presence of instability and can also be associated with radicular syndrome. Radiological instability criteria (static and functional radiography, CT) are in error against the background of severe pain syndrome due to reflex muscle spasm or due to limitations of the studies themselves. Based on preoperative examination data, it is quite difficult to predict the possible magnitude of instability after decompression during surgery. Biomechanical indices that are established under experimental conditions include the volume of angular motion, elasticity of the spinal motion segment, the size of the neutral zone and intradiscal pressure.

Conclusion. An obvious limitation is the current lack of technical capability for intraoperative measurement of experimental load indices *in vivo*. Development of technologies in this direction with accumulation of data and analysis of specificity and reproducibility of criteria will improve diagnostic protocols, and planning the volume and options of surgical treatment.

Key Words: biomechanics of the spine; segmental instability; degenerative diseases of the lumbar spine; biomechanical criteria.

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When studying the mechanisms of spinal motion, we deal with two large groups of biomechanical parameters: global sagittal balance and segmental stability. In our opinion, values related to the spinal motion segment (SMS) are the most interesting and the least investigated from the clinical point of view.

One of the main factors determining the use of a particular stabilization system during surgery is identification of segmental instability. When selecting a stabilization system, a surgeon tries to restore spinal supporting function in such a way that SMS mobility parameters are as close to normal as possible. Excessive rigidity of the system leads to overload of adjacent segments and structural elements, especially when it comes to multilevel degenerative lesion. Underestimated instability, as well as unreasonable use of a dynamic system, can lead to continuation or aggravation of the disease because of vertebral displacement. Despite the radiological signs of displacement (gross instability), the use of a stabilization system may not be totally reasonable in several cases, when a bone block (fusion) has been already formed in the segment by the moment of surgery, even if there is no patient's complaints.

Currently, there is a wide variety of available implants for spinal stabilization, which allows performing personalized approach to the treatment of instability. As part of the first step, the need was defined to assess the biomechanical criteria of lumbar segmental instability that help to accurately determine the indications to select the treatment technique for a particular patient.

Material and Methods

In a systematic review, A.Yu. Mushkin et al. [1] identified 5 types of literature sources dealing with biomechanics:

1) analysis of the strength of anatomical structures that form the anterior and posterior spinal columns;

2) analysis of the kinematic properties of isolated SMS and spinal regions;

3) analysis of the biomechanics of spinal deformities;

4) analysis of bone graft remodeling processes under deformation conditions;

5) analysis of implant and spine biomechanics in conditions of instrumental fixation.

Articles belonging to the first and second groups were selected to achieve the research objective. The review methodology was actualized in accordance with the PRISMA protocol [2]. The analysis was performed using search queries in the Pubmed and eLibrary systems and a full analysis of the results obtained. The keywords for the search in the Russian-language database included spinal biomechanics, biomechanics of lumbar spine, degenerative disease biomechanics, segmental instability of lumbar spine; as well as biomechanics of lumbar spine, degenerative disease biomechanics, degenerative stenosis biomechanics, biomechanics after spine fusion, anterior spine fusion biomechanics, and neutral zone of spinal motion in the English-language database.

At the first stage, 4,784 publications were selected: 4,250 publications in English on the pubmed.com site and 534 publications in Russian on the eLibrary.ru database (Fig. 1); the search depth was 50 years (1975 to 2025).

Inclusion criteria for research publications:

1) articles and literature reviews that deal with the biomechanics of the lumbar spine;

2) the publication refers to the normal anatomy and physiology of the spine, or its degenerative abnormality;

3) the publication considers biomechanical parameters having units of measurement.

Exclusion criteria:

1) the publication considers stability parameters in patients who underwent surgery (with and without implants);

2) the publication refers to global sagittal balance parameters;

3) the criteria under consideration are not characterized by high reproducibility; the citedness of the publication is less than 10;

4) patients under 18 years;

5) studies involving the use of the finite element method;

6) duplicated publications and articles with embedded citations, with the conclusions repeating the conclusions of prior publications.

Publications were included in/excluded from the research by 3 experts in the field of neurosurgery (with more than 10 years of experience in spinal surgery and surgery for degenerative diseases of the spine). In case of a debatable issue of applying the inclusion or exclusion criteria to a particular publication, the decision was made by a simple majority of experts.

Results

Analysis of sources (Table 1) allows concluding that most of the pivotal studies of spinal biomechanics were performed in the 1980s–1990s. Because of the active start of implant use in practical surgery, the interest of researchers is shifting towards spinal biomechanics under conditions of fixation. A small number of studies describe clinical and radiological criteria as a basis for determining segmental stability; most biomechanical studies are focused on experimental parameters that are used in clinical practice with limitations because of the lack of in vivo measurement technologies. Most of the articles included in this review have the mean level of evidence (level 3 according to Melnyk and Fineout-Overholt).

Spinal motion segment stability. The definition of "SMS stability" is important for understanding what can be considered normal supporting function of the spine and where it alters to abnormal. However, currently there are no clear criteria for stability, and this fact often complicates the decision on fixation and its type. Thus, the more clearly these criteria are defined, the more accurate will be the selection of surgical strategy and of an adequate implant for a particular patient.

In the classic study, White et al. [3] described stability as the ability of the spine to limit vertebral displacement under physiological load in order to prevent damage or irritation of nerve roots, as well as disabling deformations and pain caused by structural changes in spinal elements. On this basis, the same authors [4] later defined spinal instability as the loss of the ability to maintain motion patterns with no increase in neurological deficit, significant deformation, or disabling pain (pain that significantly worsens the quality of life). The American Academy of Orthopedic Surgeons gave a more simple definition of spinal stability: it is the capacity of the vertebrae to remain cohesive and maintain normal displacement during all physiological body movements [5]. One should mention that none of the above definitions includes any particular features: no measurable parameters are provided; the concepts are relatively blurry and may be understood differently by different specialists (for example, physiological load and physiological movements). Assessment of segment instability is, at the best case, limited to assessing the presence/absence of osteophytes and the stage of disc degeneration based on CT data; at worst, a SMS is fixed with implants in all cases, trying to avoid instability even with a strong bone block. Functional radiography allows more accurate criteria, however, this technique also has significant limitations: impossibility of use during periods of acute pain; measurement error because of muscle tone abnormalities; undetermined examination methodology (in a standing or lying position, what should be the flexion force, etc.). Moreover, in clinical practice, it is almost impossible to clearly estimate the expected change in spinal stability after decompression based on preoperative radiological examination.

Clinical criteria of instability are little considered in the academic literature. They include pain in the lumbar spine that changes with motion and neurological deficit. Panjabi [6] proposed a scoring system for assessing instability based on clinical and radiological criteria that considers the following: destruction of elements of the anterior (1 point) and posterior (1 point) columns; vertebral displacement in the sagittal plane by more than 4.5 mm or 15% according to functional (2 points) or static (2 points) radiography; vertebral angulation during static radiography of more than 22° (2 points); change in the angulation angle during functional radiography of more than 15° above the L4, more than 20° at the L4–L5, and more than 25° at the L5–S1 (2 points); damage to cauda equina, neurological deficit (3 scores); and expected high spinal load (1 point). A total of 5 points or more can be considered as instability. Of these criteria, only neurological deficit is a clinical one.

Later, Simmonds et al. [7] developed a system for assessing instability using a combination of clinical and radiological

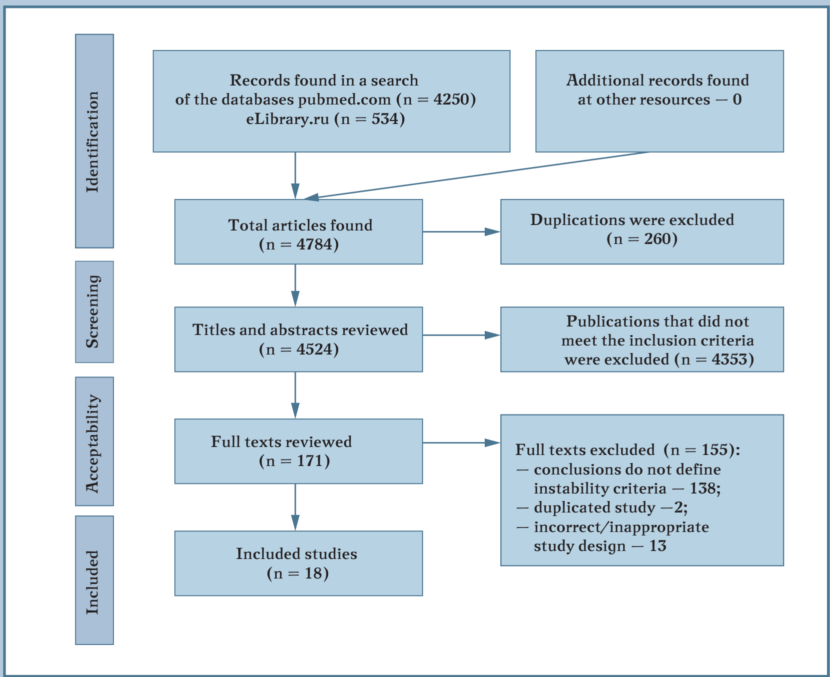

Fig. 1
Scheme for selecting publications for analysis in accordance with the PRISMA protocol

criteria based on a systematic review, with the following 3 groups: stable segment, potentially unstable segment, and unstable segment. The following criteria were used to assess instability grade: lumbar pain (none, not a main complaint, a main complaint), signs of restabilization (disc height and osteophytes), disc angulation (lordotic, neutral, kyphotic), displacement on functional radiological images (<3 mm, 3–5 mm, >5 mm), facet joint effusion (none, effusion with no distension, effusion with distension).

Generally, it can be concluded that there are no major studies of clinical instability criteria that are assessed only in combination with other, mainly radiological, parameters. Neurological deficit does not provide high specificity in determining segment instability, especially in patients with severe degenerative stenosis associated with significant ossification. Thus, the assessment of clinical criteria is not considered a preferred parameter for determining segmental instability.

Radiological instability criteria are often used in clinical practice, however, the sensitivity of this technique is lower because of muscular defense, pain syndrome, lack of an integrated examination protocol (what flexion should be achieved during functional radiography, etc.), and different body measurements of patients.

Fig. 2 and 3 [8] provide normal values of lumbar segment mobility obtained by Pearcy et al. [8] from the results of functional spondylography in 14 asymptomatic patients. The greatest vertebral displacements (translations) and rotations were observed in the sagittal plane (Z-axis in Fig. 2 and 3). In other planes, there were no displacements or angular deformations in a stable SMS, or they were minimal.

Such stability is achieved due to the specific spatial arrangement of the lumbar facet joints (sagittal or more oblique in the lower sections) and the ligamentous apparatus [9]. The ligaments in the lumbar spine provide its stability in the EZ-elastic zone. The tensile strength and ultimate elongation of separate ligaments is clearly provided by Chazal et al. [10] and White et al. [11] (Table 2).

Elmose et al. [12] tried to identify other criteria for SMS stability based on a systematic review of 118 surgical and non-surgical articles. Sagittal vertebral displacement (during functional spondylography) of more than 3 mm was the most common for many articles. With this value, most researchers refer to the article by Boden and Wiesel [13] who measured vertebral sagittal displacement based on the functional spondylograms of 40 healthy male subjects and found the maximum vertebral sagittal displacement of 3 mm and the lateral displacement of 8% of the vertebral body width. These criteria were historically taken as the standard ones.

Experimental criteria of instability. There are a number of more sensitive instability parameters, which are not currently measured in routine clinical practice because of the lack of required technical aids. These include the segment elasticity coefficient and the ratio of its neutral and elastic zones for its motion. These parameters can currently only be measured during cadaveric biomechanical research or by mathematical simulation using the finite element method.

Elasticity is the force that must be applied to a SMS to change its length by 1 mm. The elasticity coefficient is measured in N/mm. Mean elasticity coefficients for intact segments were obtained during *in vitro* tests [11, 14–17]:

- cervical spine: lateral extension – 33 N/mm, compression – 1,317 N/mm;
- thoracic spine: lateral extension – 100 N/mm, anteroposterior extension – 900 N/mm, compression – 1,250 N/mm;
- lumbar spine: extension – 100–200 N/mm, compression – 600–700 N/mm;
- sacroiliac joints: extension – 100–300 N/mm.

The data obtained by Berkson et al. [14] using 42 freshly prepared cadaveric SMS are of the utmost interest. Angular deformations, longitudinal displacements, and increase in intradiscal pressure in response to loading were measured. Angular deformation was measured with

Table 1
Articles analyzed in this systematic review

Article	Type of study	Study content	Study assessment	Level of evidence by Melnyk and Fineout-Overholt
Mushkin A.Yu. et al.[1]	Analytical review	Identification of the main groups of articles related to spinal biomechanics	All types of indicators are considered	7
Panjabi [6]	Analytical review	Description of the facet joints anatomy, clinical assessment of instability	Clinical, radiological and experimental criteria	7
Simmonds et al. [7]	Systematic review (23 publications)	A scheme for segmental instability assessment based on clinical and radiological criteria is proposed	Clinical and radiological criteria	5
Pearcy et al. [8]	*In vivo* experimental study (14 patients)	The limits of normal values of displacement and rotation of lumbar vertebrae in three planes were found based on a group of asymptomatic patients.	Radiological indicators	3
Krutko et al. [33]	Analytical review	Analysis of articles on the issue of segmental instability of the spine	Clinical, radiological and experimental criteria	7
Chazal et al. [10]	*In vitro* experimental study on cadaver material (46 lumbar spine specimens)	Identification of the ultimate elongation of ligaments and tensile strength in an experiment on 46 cadaver specimens	Experimental criteria	3
Berkson et al. [14]	*In vitro* experimental study on cadaver material (42 lumbar spine specimens)	Measurement of angular deformations, longitudinal displacement and intradiscal pressure changes in response to loading with gradation depending on the degree of disc degeneration on 42 cadaveric specimens	Experimental criteria	3
Panjabi [19]	Experimental study on cadaver material (*in vitro*), animal material (*in vivo*) supplemented by mathematical simulations	A correlation has been found between the size of the neutral zone and other instability parameters.	Experimental criteria	3
Yamamoto et al. [21]	*In vitro* experimental study on cadaver material (10 lumbar spine specimens)	Clarification of the size of the neutral zone, elastic zone and the angle of movements in normal conditions in an experiment on 10 cadaver specimens	Experimental criteria	3
Crisco [23]	PhD thesis (5 experimental studies)	Comparison of spinal stability *in vitro* and *in vivo* and determination of the stabilizing role of muscles	Experimental criteria	3

Ending of the Table 1

Articles analyzed in this systematic review

Article	Type of study	Study content	Study assessment	Level of evidence by Melnyk and Fineout-Overholt
Nachemson, Morris [24]	*In vivo* experimental study (16 patients)	Determination of intradiscal pressure *in vivo*	Experimental criteria	3
McNally, Adams [28]	*In vitro* experimental study (7 lumbar spine specimens)	Features of distribution of intradiscal pressure in the disc in normal and pathological conditions *in vitro*	Experimental criteria	3
McNally et al. [29]	*In vivo* experimental study (10 patients)	Features of distribution of intradiscal pressure in the disc in normal and pathological conditions *in vivo*	Experimental criteria	3
Brown et al. [30]	*In vivo* experimental study (298 patients)	Measurement of elasticity of spinal motion segments at different stages of disc degeneration *in vitro*	Experimental criteria	3
Di Pauli von Treuheim [27]	In vivo experimental study on animal material	Comparison of neutral zone calculation methods	Experimental criteria	3
Cannella et al. [26]	*In vitro* experimental study on cadaver material (17 lumbar spine specimens)	Comparison of the neutral zone size and the angle of motion of the segment before and after discectomy	Experimental criteria	3
Cornaz et al. [31]	*In vitro* experimental study on cadaver material (5 lumbar spine specimens)	Determination of segment stability by determining elasticity using a proprietary surgical device for instability quantification	Experimental criteria	3
McAfee et al. [32]	*In vitro* experimental study (1 specimen)	Determination of segment stability by determining elasticity using a proprietary robotic tool for measuring segment elasticity	Experimental criteria	3

a torque of 10.6 Nm (the measurement value of the torque is 1 Nm; it is a force of 1 Newton applied to a torque lever 1 m long), and displacement was measured with a force of 145 N. Measurements were performed with a vertical preloading of 400 N which imitated the weight of the human body, with differentiation of the analyzed segments by age, sex, disc level, and degeneration grade. The data obtained are provided in Fig. 4. Significant differences were found only when differentiating by sex: female subjects turned out to be somewhat more flexible compared to male ones. However, this study is of interest for us in regard to the conception of the normal values of vertebral displacement and angular vertebral deformation in response to the load. For these purposes, we may only consider the row with the disc degeneration grade 0, 1, 2, which included 39 out of 42 analyzed preparations.

The same paper provides data on the change in intradiscal pressure during the same loads (the values are provided in kilopascals). Also, only data from the row with degeneration grade 0, 1, 2 may be used (Fig. 5).

Panjabi et al. [17] were conducted a very large number of studies of spinal biomechanics in the late 1980s at Yale University. They developed the concept of neutral zone and elastic zone in the spinal motion that is of great interest for the further development of the SMS stability determination techniques. Neutral zone width and its relation to the

	N	Movement in degrees Mean (SD)		
		Flex	Ext	Flex/ext
L1/2	6	8 (5)	5 (2)	13 (5)
L2/3	11	10 (2)	3 (2)	14 (2)
L3/4	11	12 (1)	1 (1)	13 (2)
L4/5	11	13 (4)	2 (1)	16 (4)
L5/S1	11	9 (6)	5 (4)	14 (5)

Fig. 2
Vertebral displacement (mm) during flexion and extension [8]

full range of segmental motion have the potential to become the most sensitive parameters for determining instability.

It was found that the SMS motion in any direction in response to the load is non-linear, and the vertebral displacement is not proportional with an increase in the applied force. At the very beginning, the motion occurs easy, the vertebra seems to simply slide along the intervertebral disc without applying significant force. However, when ligament resistance comes in action, the load required for vertebral displacement by the same distance starts to increase exponentially.

	N	Translations (mm) Mean (SD)		
		X	Y	Z
Movements during flexion				
L1/2	6	0 (1)	1 (1)	3 (1)
L2/3	11	1 (1)	1 (1)	2 (1)
L3/4	11	1 (1)	0 (1)	2 (1)
L4/5	11	0 (1)	0 (1)	2 (1)
L5/S1	11	0 (1)	1 (1)	1 (1)
Movements during extension				
L1/2	6	1 (1)	0 (0)	1 (1)
L2/3	11	0 (1)	0 (1)	1 (1)
L3/4	11	1 (1)	0 (1)	1 (1)
L4/5	11	0 (1)	0 (1)	1 (1)
L5/S1	11	1 (1)	0 (0)	1 (1)

Fig. 3
Rotation of vertebrae (degrees) during flexion and extension [8]

Fig. 6 demonstrates the load-displacement curve, which summarizes Panjabi's understanding of the SMS motion. The curve demonstrates that the minimum load (N) is required at the beginning of the motion. This segment of the curve corresponds to the neutral zone (NZ). It is followed by the elastic zone, where the load required for vertebral displacement sharply increases because of the resistance of spinal joints and ligaments. These zones together constitute the range of motion (ROM). In case of SMS instability, the curve will shift to the right and become flatter; during stabilization, the shift in the opposite direction will occur [19].

Panjabi et al. and Yamamoto et al. [20, 21] provided normal values of NZ, EZ, and ROM for different segments (Fig. 7). A cadaver spinal specimen was analyzed using a dynamic machine. A physiological load was applied; after its removal, the SMS did not return to its initial position, and a residual displacement persisted. This phenomenon was used to determine the neutral zone value. Three cycles of applying and removing the physiological load were carried out, with a break of 30 s. The residual displacement was measured just before the beginning of the third cycle. Thus, the displacement was measured during flexion and extension. The values obtained together characterized the neutral zone. Accordingly, the elastic zone was defined as the difference between the segmental motion range and the neutral zone. However, no definition of physiological load was provided, though it is different for each individual.

The neutral zone value and the neutral zone ratio will increase with the development of SMS instability. The neutral zone value will decrease with its stabilization due to a natural or surgical bone block.

Busscher et al. [22] provided a slightly clearer description of determining the load value for the neutral zone: the neutral zone boundary is defined as the point of maximum change in the load-displacement curve.

Spinal and abdominal muscles are of high importance in maintaining lumbar stability. The critical load value may be used to demonstrate their effect: it is the minimum force that must be applied to the top of a column to cause its minimal flexion. Experimental studies revealed that the critical load for the lumbar spine is 90 N [23]. This is significantly less than the load of 1,500 N or more used in *in vivo* experiments [24]. This difference can be explained by the stabilizing effect of the core muscles. Panjabi et al. [25] assessed the effect of muscles on spinal stability under acute injury conditions and found that when simulating a 60 N stabilizing muscular force for a specimen

Table 2
Strength and elasticity of spinal ligaments [10, 11]

Ligament	Tensile strength	Ultimate elongation
Anterior longitudinal	450	26
Posteriot longitudinal	324	26
Flaval	285	26
Interspinous	125	13
Supraspinal	150	32

Classification	Rotations (°) due to 10.6Nm moment				Displacements (cm) due to 145N shear		
	Flexion	Extension	Lateral bend	CW* torsion	Anterior shear	Posterior shear	Rt. lateral shear
Degeneration							
Grades 0, 1, 2	5.5	2.9	5.6	1.5	.12	.08	.10
Grades 3, 4				[illegible]	[illegible]	[illegible]	[illegible]

Fig. 4
Angular deformation and displacements obtained in the study by Berkson et al. [14]

Classification of segments	Increase Due to 10.6Nm Moment (kPa)				Increase due to 145N shear (kPa)		
	Flexion	Extension	Rt. lateral bend	Torsion	Anterior	Posterior	Rt. lateral
Degeneration							
Grades 0, 1, 2	267	58	279	30	39	6	44
Grades 3, 4				18(3)	26(3)		39(3)

Fig. 5
Changes in intradiscal pressure obtained in the study by Berkson et al. [14]

with an injured vertebra, the ROM value remains significantly higher than in a not injured one, however, the NZ value returns almost to the initial. This allows concluding that muscles are important in maintaining the neutral zone within normal condition and extrapolating the results obtained to degenerative lesions of the spine.

Sensitivity of the NZ parameter was confirmed by Cannella et al. [26] in their experiment using 12 cadaver specimens with measurement of biochemical parameters before and after partial damage to the intervertebral disc (simulation of the degenerative process or discectomy): a significant increase in the neutral zone and the motion angle after disc damage was obtained.

By now, the neutral zone concept by Panjabi has not yet received the final features. Several different methods were developed to determine the boundaries between the neutral and elastic zones on the load-displacement curve. These include the trilinear method, the double sigmoid method, the zero load method, the stiffness threshold method, and the extrapolated elastic zone method. When comparing these methods, Di Pauli von Treuheim et al. [27] concluded that there was no significant conformance between them: data with significant differences were obtained after calculations. The double sigmoid method and the stiffness threshold method were the most coincident ones.

McNally and Adams [28] analyzed intradiscal pressure in normal and severely degenerated discs *in vitro* measuring it by profilometry: a needle with a sensor was placed into the disc, and values were obtained at each point of its moving through the disc. The results are provided in Fig. 8, with the upper diagram demonstrating the technique for inserting a needle with a pressure sensor. Graph A demonstrates the pressure distribution for a normal disc. The points of intradiscal pressure values obtained from the posterior sections of the fibrous ring through the nucleus pulposus to the anterior sections of the fibrous ring are distributed along the X-axis. According to this graph, the most pressure in a normal disc is exercised on the nucleus pulposus in the center, and the fibrous ring (posterior and anterior sections) actually experiences no load. In contrast, there is a re-distribution of pressure in degeneration because of the decreased size of the nucleus pulposus. Graph B provides profilometry results obtained for degenerated discs. There is a significant decrease in the load on the nucleus pulposus, and increased load on the fibrous ring, primarily, on its posterior sections.

In 1996, a group of researchers has published materials of the similar in vivo study [29]. Profilometry of degenerated lumbar discs was performed in symptomatic patients with severe lumbar pain. After measuring the pressure, the association between the pain and the analyzed disc was confirmed by provocative discography (injection of a contrast agent into the disc caused an increase in pain in the lumbar spine and was registered on radiological images). The data obtained were similar to the prior *in vitro* study, and the theory on the association between lumbar pain and overload of the posterior sections of the fibrous ring was confirmed.

It is rational to select the fixation technique based on intraoperative measurement of the SMS stability. Specialists from the Orthopedics and Rehabilitation Department of the University of Miami (USA) have developed a device for intraoperative assessment of spinal stability. This device is placed between the spinous processes of the vertebrae and measures the deformation that occurs in response to the load applied. Thus, it is possible to obtain the most accurate data on the elasticity of a specific SMS in a particular patient (Fig. 9) [30].

Another device for intraoperative measurement of spinal stability was proposed by Cornaz et al. [31]. It registers the anteroposterior displacement of vertebrae in response to a load applied through placed pedicle screws (Fig. 10).

Currently, a robotic pneumatic system for intraoperative measurement of segment elasticity and assessment of its stability is already used in the USA. The robotic system has a pneumatic drive and provides the application of the required tensile force to the placed pedicle screws. At the same time, change in the distance between vertebral endplates is registered using an electron-optical converter. Fig. 11 demonstrates the results of such a measurement before and after discectomy. The assessment is made for tension in the sagittal plane [32].

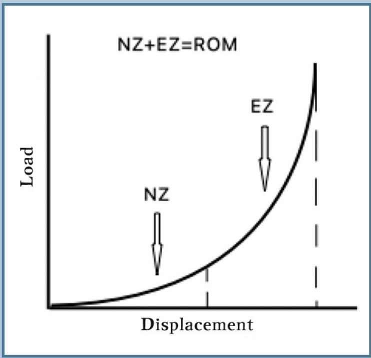

Fig. 6
Load-displacement curve [19]

	Flexion				Extension				One-side lat. bend				One-side ax rotation			
	NZ	EZ	ROM	NZR	NZ	EZ	ROM	NZR	NZ	EZ	ROM	NZR	NZ	EZ	ROM	NZR
C0–C1	1.1	2.4	3.5	31.4	1.1	19.9	21.0	5.2	1.5	4.0	5.5	27.3	1.6	5.6	7.2	22.2
C1–C2	3.2	8.3	11.5	27.8	3.2	7.7	10.9	29.4	1.2	5.5	6.7	17.9	29.6	9.3	38.9	76.1
Low cervical	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Lumbar	1.5	6.1	7.6	19.7	1.5	2.3	3.8	39.5	1.6	5.0	6.6	24.2	0.7	1.7	2.4	29.2
L5–S1	3.0	7.0	10.0	30.0	3.0	4.8	7.8	38.5	1.8	3.7	5.5	32.7	0.4	1.0	1.4	28.6

Fig. 7
Normal values of neutral zone (NZ), elastic zone (EZ), range of motion (ROM) and neutral zone ratio (NZR) in degrees for different segments [20, 21]

Discussion

Complex anatomy of the spine leads to great challenges in determining clear criteria for the SMS stability/instability.

The current criteria for segmental stability can be divided into large groups, clinical and biomechanical ones. Clinical criteria (pain on palpation, pain under loading or with certain movements, neurological deficit) may be associated not only with excessive vertebral mobility, stretching of the fibrous ring and spinal ligaments, but also with the nerve root or spinal cord compression. In this regard, clinical criteria have low specificity in most cases and are a low-effective method for clearly defining segmental instability.

Biomechanical stability parameters can be assessed using the following parameters:

1) radiological examination (functional radiography with the assessment of vertebral displacement);

2) experimental models (*in vitro* on cadaver specimen using a dynamometric device; in vivo intraoperatively – disc profilometry, elasticity measurement using specialized dynamometric devices).

Radiological criteria for assessing instability are currently very commonly used in clinical practice; however, their low sensitivity should be considered. The sensitivity of static methods may be limited by the impossibility of reliably assessing the formed bone block (for example, fixed spondylolisthesis). As for functional radiography, one should always consider the impossibility of its proper assessment in conditions of severe pain syndrome due to the muscle reflex action.

The neutral zone size should be emphasized among the experimentally measured biomechanical parameters, as it allows developing a very sensitive method for determining instability and indications for stabilization. The shortcoming of this parameter is the lack of scientific consensus on the issue of determining the neutral zone boundaries using the load-displacement curve. Other parameters (segment elasticity, vertebral displacement, and angular deformation) are also of high value in determining instability. The possibility of *in vivo* determining these measurements may be especially interesting. When analyzing the literature sources on experimental biomechanical criteria, no publications with level 1 evidence were found, however, high sensitivity and specificity of the neutral zone size and SMS elasticity in determining segmental instability have a significance level of expert consensus.

In the analytical review by A.V. Krutko et al. [33], publications on spinal segmental instability were reviewed in order to identify criteria for a clear definition of treatment strategy, and a conclusion was made on the current absence of an unequivocal method. The authors have an opinion that the development of a definite clinical and radiological algorithm is necessary for the further development of spinal surgery, and it generally supports the results of our research.

Conclusion

This literature data analysis allowed assessing the current state of medical science in the sphere of determining spinal segmental instability. We can mention that routine methods used in clinical practice are characterized with low sensitivity and specificity: pain assessment in motion, pain assessment during palpation, results of plain and functional radiography or CT. Available theoretical information on biomechanical parameters that can be experimentally measured (ROM, elasticity, neutral zone) demonstrates that these can be successfully used in clinical practice and serve for support for developing a sensitive technique to determine the SMS instability. However, at present, an integrated mechanism for determining the boundaries of the neutral zone is required, as well as technical developments for in vivo measuring these parameters in the operation room.

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The authors declare that they have no conflict of interest. The study was approved by the local ethics committees of the institutions.
All authors contributed significantly to the research and preparation of the article, read and approved the final version before publication.

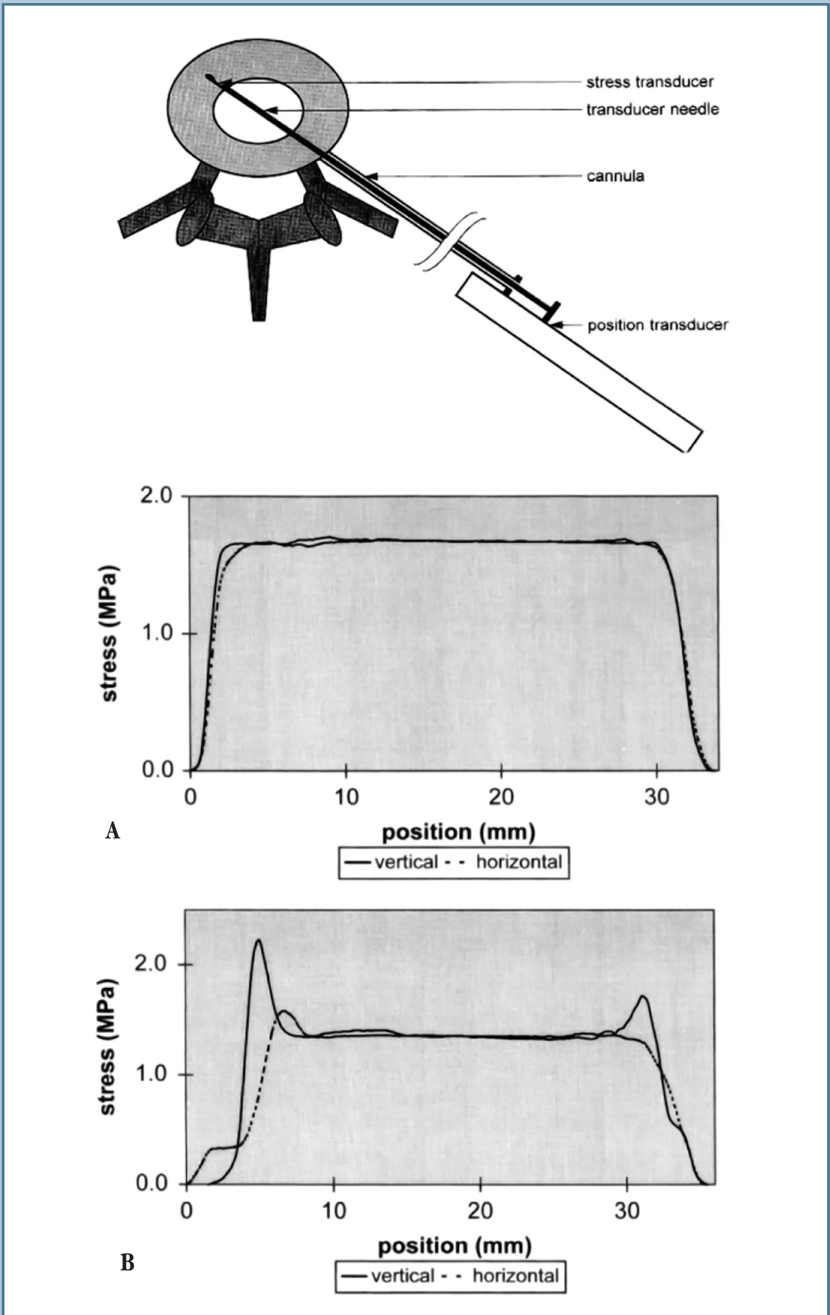

Fig. 8
Disc profilometry data obtained in the study by McNally and Adams on cadaver material [28]

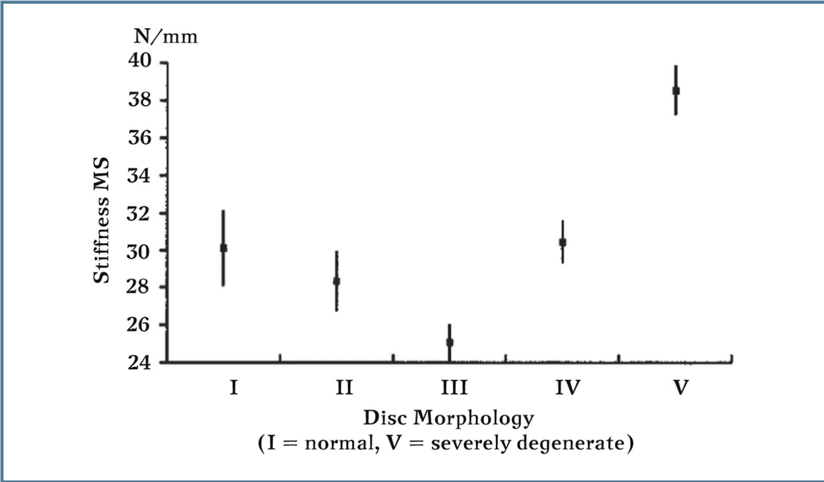

Fig. 9
Data on the elasticity value depending on the stage of disc degeneration, obtained intraoperatively using a special device described in the study by Brown et al. [30]

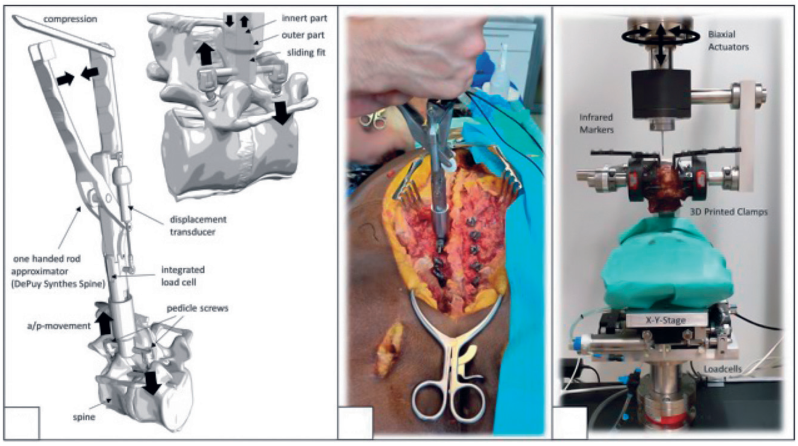

Fig. 10
Surgical device for direct real-time quantification of spinal segmental stability from the studies by Cornaz et al. [31]

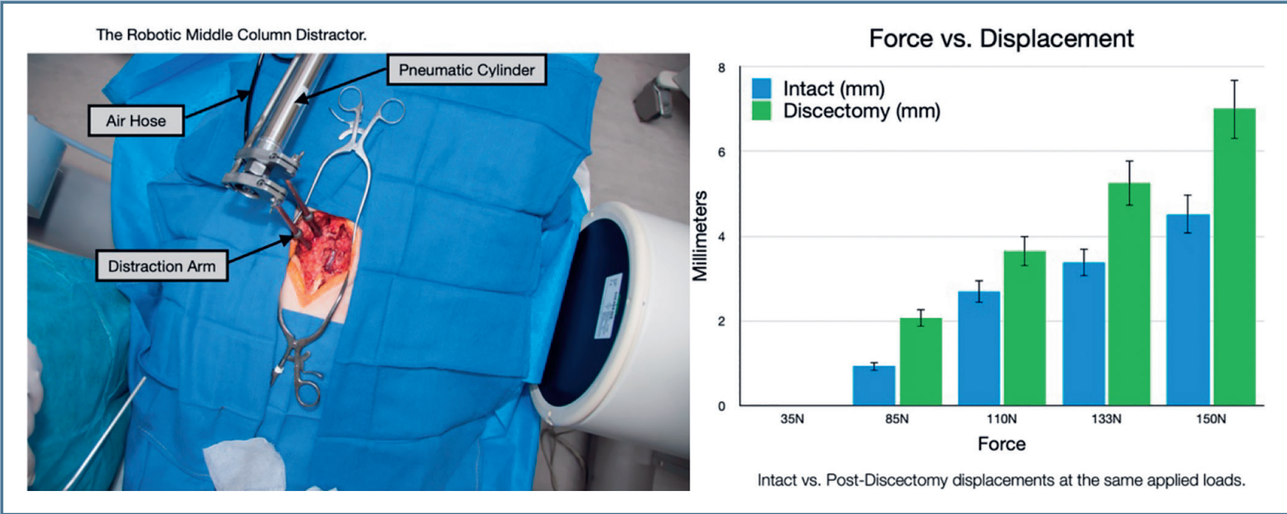

Fig. 11
Robotic system for measuring segment elasticity [32]

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