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BIOMECHANICAL AND CLINICAL ASPECTS OF LUMBOSACRAL SPINAL INSTABILITY: DIAGNOSTICS, CLASSIFICATION, AND CONTEMPORARY TREATMENT STRATEGIES

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Abstract. Lumbosacral spinal instability represents a complex biomechanical and clinical condition that plays a key role in the pathogenesis of chronic low back pain and degenerative spinal disorders. Despite extensive investigation, the absence of standardized diagnostic criteria and heterogeneous clinical presentation continue to limit optimal patient management. Spinal instability is characterized by the inability of the vertebral motion segment to maintain physiological alignment and controlled motion under normal mechanical loads without provoking pain, neurological dysfunction, or progressive deformity. Degenerative disc disease, facet joint arthropathy, trauma, infection, and iatrogenic factors are considered major contributors to segmental instability. This article provides a comprehensive analysis of the biomechanical foundations, clinical manifestations, diagnostic methods, and modern treatment strategies for lumbosacral spinal instability. Special attention is given to dynamic radiographic assessment, magnetic resonance imaging, and scoring systems for instability evaluation. Surgical management options, including rigid fusion and motion-preserving stabilization techniques, are discussed in the context of sagittal balance and adjacent segment degeneration. The findings highlight the necessity of an integrated, individualized approach to diagnosis and treatment, emphasizing the role of biomechanical restoration and vertebral-pelvic alignment correction in improving long-term outcomes.

Key words: lumbosacral spine, spinal instability, biomechanics, degenerative disc disease, functional radiography, spinal fusion.

БИОМЕХАНИЧЕСКИЕ И КЛИНИЧЕСКИЕ АСПЕКТЫ НЕСТАБИЛЬНОСТИ ПОЯСНИЧНО-КРЕСТЦОВОГО ОТДЕЛА ПОЗВОНОЧНИКА: ДИАГНОСТИКА, КЛАССИФИКАЦИЯ И СОВРЕМЕННЫЕ ПОДХОДЫ К ЛЕЧЕНИЮ

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Аннотация. Нестабильность пояснично-крестцового отдела позвоночника представляет собой сложное биомеханическое и клиническое состояние, играющее ключевую роль в патогенезе хронической боли в пояснице и дегенеративных заболеваний позвоночника. Несмотря на значительное количество исследований, отсутствие унифицированных диагностических критериев и вариабельность клинических проявлений существенно затрудняют выбор оптимальной лечебной тактики. Нестабильность характеризуется утратой способности позвоночно-двигательного сегмента сохранять

физиологические взаимоотношения и контролируемую подвижность под воздействием обычных нагрузок без развития болевого синдрома, неврологических нарушений или прогрессирующей деформации. В статье представлен комплексный анализ биомеханических основ, клинической картины, диагностических методов и современных подходов к лечению нестабильности пояснично-крестцового отдела позвоночника. Особое внимание уделено функциональной рентгенографии, магнитно-резонансной томографии и балльным системам оценки нестабильности. Рассматриваются хирургические методы лечения, включая ригидную фиксацию и динамическую стабилизацию, с учетом параметров сагиттального баланса и риска дегенерации смежных сегментов. Подчеркивается необходимость индивидуализированного междисциплинарного подхода к диагностике и лечению данной патологии.

Ключевые слова: нестабильность позвоночника, пояснично-крестцовый отдел, биомеханика, дегенеративные заболевания, диагностика, хирургическое лечение.

BEL-DUMG‘AZA UMURTQA POG‘ONASI BEQARORLIGINING BIOMEKANIK VA KLINIK JIHATLARI: DIAGNOSTIKA, TASNIFLASH VA ZAMONAVIY DAVOLASH STRATEGIYALARI

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Annotatsiya. Bel-dumg‘aza umurtqa pog‘onasi beqarorligi surunkali bel og‘rig‘i va degenerativ umurtqa kasalliklari patogenezida muhim o‘rin tutuvchi murakkab biomekanik va klinik holat hisoblanadi. Tadqiqotlar sonining ko‘pligiga qaramay, yagona diagnostik mezonlarning yo‘qligi va klinik belgilarning turlicha namoyon bo‘lishi bemorlarni davolashda optimal taktika tanlashni qiyinlashtiradi. Umurtqa beqarorligi pozvonka-harakat segmentining fiziologik holatini va nazorat qilinadigan harakatchanligini odatiy yuklama sharoitida og‘riq, nevrologik buzilishlar yoki deformatsiya rivojlanmasdan saqlay olmasligi bilan tavsiflanadi. Mazkur maqolada bel-dumg‘aza umurtqa pog‘onasi beqarorligining biomekanik asoslari, klinik ko‘rinishlari, diagnostika usullari va zamonaviy davolash strategiyalari batafsil tahlil qilinadi. Funktsional rentgenografiya, magnit-rezonans tomografiya va beqarorlikni baholash uchun ball tizimlariga alohida e’tibor qaratilgan. Sagittal muvozanat va qo‘shni segmentlar degeneratsiyasi xavfini hisobga olgan holda jarrohlik davolash usullari muhokama qilinadi. Individual va kompleks yondashuvning ahamiyati ta’kidlanadi.

Kalit so’zlar: umurtqa beqarorligi, bel-dumg‘aza bo‘limi, biomekanika, degenerativ kasalliklar, diagnostika, jarrohlik davolash.

Introduction. Lumbar and lumbosacral spinal instability remains one of the most debated and clinically challenging concepts in modern vertebrology, spinal surgery, and musculoskeletal biomechanics. Despite decades of investigation, the absence of a universally accepted diagnostic gold standard and the heterogeneity of clinical manifestations continue to complicate both conservative and surgical decision-making. Segmental instability of the lumbar spine is widely recognized as a major contributor to chronic low back pain, functional disability, and progressive neurological impairment, affecting a substantial proportion of the working-age population and elderly individuals alike [1-3]. From a biomechanical perspective, spinal stability represents the capacity of the vertebral column to maintain physiological alignment and controlled motion under axial load, shear forces, and torsional stress, while simultaneously protecting neural and vascular structures. Loss of this capacity leads to abnormal intervertebral motion, redistribution of mechanical loads, accelerated degenerative cascades, and eventual failure of compensatory neuromuscular mechanisms. White and Panjabi’s classical definition conceptualized spinal

instability as the inability of the spine to maintain vertebral relationships within physiological limits under normal loads without producing neurological compromise, structural damage, or incapacitating pain [16]. This definition remains foundational but insufficiently captures the complexity of modern clinical observations, particularly in degenerative and postoperative contexts.

The lumbosacral junction represents a biomechanically vulnerable transition zone between the mobile lumbar spine and the rigid pelvis. This region is subjected to high compressive and shear forces, especially during upright posture, flexion-extension movements, and rotational activities. Degenerative changes of the intervertebral disc, facet joints, and ligamentous structures progressively alter load transmission patterns, leading to hypermobility or paradoxical rigidity at the affected motion segment. Numerous studies report that radiological signs of segmental instability are present in 12-40% of patients with chronic lumbar pain syndromes, although clinical correlation remains inconsistent [1, 4]. The concept of instability has evolved from a purely mechanical construct toward a multidimensional clinical entity incorporating biomechanical failure, neuromuscular compensation, pain modulation, and psychosocial factors. Degenerative disc disease, facet arthropathy, spondylolisthesis, postoperative destabilization, trauma, infection, and neoplastic processes all contribute to the disruption of normal segmental kinematics. Importantly, instability should not be equated solely with degenerative spondylolisthesis, as this oversimplification obscures alternative pathogenic pathways such as discogenic hypermobility or iatrogenic destabilization following decompressive procedures [7].

Recent advances in imaging, surgical instrumentation, and biomechanical modeling have renewed interest in refining diagnostic criteria and optimizing treatment strategies. Nevertheless, controversies persist regarding the relative roles of dynamic radiography, computed tomography, magnetic resonance imaging, and functional assessment tools in identifying clinically meaningful instability. Similarly, the choice between rigid fusion and motion-preserving stabilization remains a subject of ongoing debate, particularly in the context of adjacent segment degeneration and sagittal balance restoration [14, 15]. The present article aims to provide an in-depth, structured, and critically expanded analysis of lumbosacral spinal instability, synthesizing biomechanical theory, clinical presentation, diagnostic methodology, and contemporary treatment concepts. By adapting the discussion to the IMRAD framework, this work seeks to bridge the gap between descriptive clinical observation and evidence-based therapeutic decision-making, with particular emphasis on the pathophysiological mechanisms underlying instability and their implications for modern spinal surgery.

Materials and Methods. This work represents a comprehensive narrative and analytical reinterpretation of published clinical, biomechanical, and radiological data on lumbosacral spinal instability, with a primary conceptual foundation derived from peer-reviewed orthopedic and neurosurgical literature. The methodological approach integrates qualitative synthesis of classical definitions, modern imaging criteria, and surgical outcome studies, alongside biomechanical principles governing spinal motion segments. Source materials included original clinical studies, systematic reviews, biomechanical analyses, and national and international guidelines addressing lumbar segmental instability, degenerative spinal disease, and postoperative outcomes. Particular attention was paid to publications addressing dynamic instability, sagittal balance parameters, and vertebral-pelvic relationships. Emphasis was placed on studies describing functional radiographic assessment, angular and translational motion thresholds, and scoring systems for instability evaluation, including the White-Panjabi criteria [6, 9]. Radiological diagnostic methods were analyzed in terms of sensitivity, specificity, reproducibility, and clinical applicability. These included flexion-extension radiography, spiral computed tomography, magnetic resonance imaging with assessment of Modic changes, and emerging functional imaging modalities. Surgical treatment strategies were evaluated based on reported clinical outcomes, complication rates, biomechanical efficacy, and impact on adjacent segment degeneration. The synthesis process prioritized pathophysiological coherence, clinical relevance, and translational applicability. Concepts were integrated into a unified framework linking structural degeneration, biomechanical failure, and symptom generation. Selective in-text citations were incorporated using square brackets to reflect key theoretical or empirical contributions consistent with academic publishing standards.

Results. Analysis of the available literature demonstrates that lumbosacral spinal instability is a heterogeneous condition with multifactorial etiology and variable clinical expression. Degenerative disc disease emerges as the most frequent initiating factor, characterized by progressive dehydration of the nucleus pulposus, fissuring of the annulus fibrosus, and loss of disc height. These changes disrupt normal load sharing between anterior and posterior spinal elements, leading to increased stress on facet joints and ligamentous structures. In the early compensatory phase, hypertrophic changes and osteophyte formation may temporarily restore stability, whereas subsequent decompensation results in hypermobility and symptomatic instability [5]. Three principal types of instability can be distinguished based on the dominant structural failure within the motion segment. Discogenic instability is associated with primary disc degeneration and manifests as abnormal translational or angular motion without overt vertebral displacement. Discartrogenic instability, often presenting as retrolisthesis, involves posterior translation of the superior vertebra and is frequently accompanied by facet joint arthropathy and nerve root irritation. Discartroosteogenic instability, typically expressed as anterolisthesis, combines disc and facet degeneration with osseous defects such as spondylolysis, leading to progressive canal stenosis and neurological compromise [8]. Clinically, instability manifests as mechanical low back pain exacerbated by movement, prolonged sitting, or axial loading. Patients often report a sensation of spinal "giving way" or fatigue during static postures. Characteristic physical signs include increased lumbar lordosis, paraspinal muscle spasm, restricted range of motion, and altered gait patterns, such as the so-called "tightrope walker" gait observed in advanced deformity. Neurological symptoms vary depending on the degree of canal or foraminal compromise and may include radiculopathy, neurogenic claudication, or, in severe cases, cauda equina syndrome. Radiological assessment remains central to diagnosis, although no single modality provides definitive confirmation. Functional flexion-extension radiography continues to serve as the primary tool for detecting abnormal motion, with instability commonly defined as sagittal translation exceeding 3-4 mm or angular motion surpassing 10-15 degrees, depending on the spinal level [9, 7]. However, significant interobserver variability and dependence on patient cooperation limit reproducibility. Computed tomography offers superior visualization of osseous anatomy but lacks dynamic assessment capability, while magnetic resonance imaging excels in detecting disc degeneration, Modic endplate changes, and neural compression but may underestimate functional instability [2].

Surgical outcome data indicate that decompression alone in the presence of instability is associated with high rates of symptom recurrence and postoperative destabilization. Conversely, rigid fusion techniques provide reliable short-term pain relief but may accelerate degeneration of adjacent segments due to altered biomechanical load distribution [4]. Emerging evidence supports the role of dynamic stabilization systems and sagittal balance correction in reducing complication rates and improving long-term functional outcomes, although high-quality randomized trials remain limited.

Discussion. The findings underscore the necessity of conceptualizing lumbosacral spinal instability as a dynamic, continuum-based disorder rather than a binary radiological diagnosis. Instability represents the failure of a complex adaptive system involving passive structures, active neuromuscular control, and central pain modulation. This perspective aligns with contemporary biomechanical models describing phases of dysfunction, instability, and restabilization, as originally proposed by Kirkaldy-Willis and Farfan [10]. One of the central challenges in clinical practice lies in distinguishing symptomatic instability from incidental radiological hypermobility. Numerous studies demonstrate poor correlation between imaging findings and pain intensity, emphasizing the importance of comprehensive clinical evaluation. The presence of instability should therefore be interpreted within the broader context of patient-reported symptoms, functional impairment, and response to conservative management. The role of vertebral-pelvic parameters has gained increasing attention in recent years. Abnormal pelvic incidence, sacral slope, and lumbar lordosis mismatch have been implicated in both the development of instability and the progression of adjacent segment disease following fusion [12]. Restoration of sagittal alignment is now recognized as a critical determinant of surgical success, influencing postoperative biomechanics and long-term outcomes.

From a therapeutic standpoint, the traditional paradigm of rigid fusion as the universal solution for instability is being challenged. While fusion remains indispensable in cases of high-grade spondylolisthesis, severe deformity, or neurological compromise, its indiscriminate use may expose patients to unnecessary risks. Motion-preserving techniques, including dynamic stabilization and hybrid constructs, aim to restore physiological load sharing while maintaining segmental mobility. Preliminary data suggest potential benefits in selected patient populations, although long-term comparative evidence is still evolving. Importantly, postoperative instability represents a distinct clinical entity with unique pathophysiological mechanisms. Iatrogenic destabilization following excessive decompression, facetectomy, or laminectomy highlights the need for meticulous surgical planning and adherence to biomechanical principles. The integration of preoperative risk stratification tools and intraoperative decision algorithms may reduce the incidence of failed back surgery syndrome and recurrent instability [10, 11]. Future research should prioritize the development of standardized diagnostic criteria incorporating dynamic imaging, biomechanical modeling, and functional assessment. Advances in quantitative motion analysis, artificial intelligence-assisted imaging interpretation, and patient-specific finite element modeling hold promise for improving diagnostic accuracy and personalized treatment planning.

Conclusion. Lumbosacral spinal instability constitutes a complex, multifactorial disorder that occupies a central role in the pathogenesis of chronic low back pain and degenerative spinal disease. Its clinical significance extends beyond mere radiological hypermobility, encompassing biomechanical failure, neuromuscular dysfunction, and progressive structural degeneration. Accurate diagnosis requires an integrated approach combining clinical assessment with dynamic and static imaging modalities. Treatment strategies must be individualized, balancing the need for neural decompression, mechanical stabilization, and preservation of physiological motion. While rigid fusion remains the cornerstone of surgical management in advanced cases, growing evidence supports the selective use of motion-preserving and alignment-corrective techniques to mitigate long-term complications. A refined understanding of instability as a dynamic process rather than a static condition is essential for optimizing patient outcomes and advancing the field of spinal surgery.

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