

# Research Progress on Risk Factors for Post-operative Re-fracture after Osteoporotic Vertebral Compression Fracture Surgery

Keyu Zeng<sup>1,a</sup>, Xingda Cai<sup>1,b</sup>, Weijian Zhang<sup>1,c</sup>, Dingsheng Zha<sup>1,2,d,\*</sup>

<sup>1</sup>Department of Orthopedics, The First Affiliated Hospital of Jinan University, Guangzhou, 510623, China

<sup>2</sup>Department of Orthopedics, The Affiliated Shunde Hospital of Jinan University, Foshan, 528305, China

<sup>a</sup>zengkeyu0228@163.com, <sup>b</sup>caixingda678@163.com, <sup>c</sup>1021543634@qq.com, <sup>d</sup>zdsuser@126.com

\*Corresponding author

**Abstract:** Osteoporotic vertebral compression fractures (OVCF) are common among the elderly. <sup>[1]</sup>Percutaneous vertebroplasty (PVP) and percutaneous kyphoplasty (PKP) can quickly relieve pain, but the incidence of refracture after surgery will increase, which will affect the prognosis. <sup>[2]</sup>This article reviews the latest progress of refracture after OVCF surgery, pointing out that refracture is not just a single factor but a result of the interaction of multiple factors, such as patients, techniques, images, and management. <sup>[3]</sup>The core mechanisms include changes in biomechanics, reduced bone quality, and impaired healing. <sup>[4]</sup>Based on this, the article emphasizes the importance of individualized risk assessment and proposes the integration of imaging, biomechanical, and clinical data to construct predictive models, aiming to optimize surgical strategies and improve patients' long-term health outcomes.

**Keywords:** Osteoporotic Vertebral Compression Fracture (OVCF); Re-fracture; Vertebroplasty; Risk Factors

## 1. Introduction

Osteoporosis is a systemic skeletal disorder characterized by reduced bone mass and microarchitectural deterioration, leading to increased bone fragility and fracture susceptibility. With the global aging population, the incidence of osteoporotic vertebral compression fractures (OVCF) has risen substantially, posing a significant public health burden.<sup>[1]</sup> Percutaneous vertebroplasty (PVP) and percutaneous kyphoplasty (PKP) are the main minimally invasive surgical techniques for treating OVCF, which can quickly relieve pain, stabilize fractures, and facilitate early mobilization.<sup>[3]</sup>

However, the issue of post-operative re-fracture has received increasing attention. Re-fracture may present as re-collapse of the augmented vertebral body or fracture of an adjacent vertebral body. A study using French medical insurance data found that among individuals over 50 with severe osteoporotic fractures, 10.5% were readmitted for re-fracture within one year.<sup>[5]</sup> This increases medical costs and impairs quality of life. Approximately 24.4% of patients still experience low back pain after surgery. <sup>[6]</sup>Therefore, identifying patients at high risk for re-fracture is clinically important for optimizing treatment selection and improving long-term prognosis.

To reduce re-fracture risk after OVCF surgery, a thorough understanding of the underlying causes and risk factors is essential. Current evidence indicates that post-operative fractures are not attributable to a single cause but rather to multiple interacting factors, including patient characteristics, surgical technique, imaging findings, and post-operative care. Patient-specific assessment should include bone density, age, sex, comorbidities, and musculoskeletal health. Surgical factors include the choice of technique, as well as the volume, distribution, and leakage of bone cement. Imaging parameters, including the severity of preoperative vertebral collapse and the degree of spinal curvature correction, are also critical.<sup>[3]</sup>

Although numerous studies have identified individual risk factors, a comprehensive understanding of how these factors interact through underlying biological and mechanical mechanisms remains

elusive. This review aims to systematically examine re-fracture risk from patient, surgical, imaging, and post-operative perspectives, and to elucidate the underlying biomechanical mechanisms. By synthesizing current evidence, we seek to provide a mechanistic framework for individualized risk assessment and management, ultimately improving clinical outcomes in OVCF patients.

## 2. Patient-Specific Risk Factors

### 2.1 Bone Mineral Density and Hounsfield Unit Values

Bone mineral density (BMD) measurement is a fundamental tool for assessing osteoporosis severity and predicting re-fracture risk. Multiple meta-analyses have confirmed that low BMD is a significant risk factor for re-fracture after percutaneous vertebroplasty (PVP) or percutaneous kyphoplasty (PKP). A review of nine studies involving 3,821 patients with osteoporotic vertebral compression fractures (OVCF) reported that low preoperative BMD is a key predictor of post-operative re-fracture.<sup>[3]</sup> Another review of 27 studies and 8,806 patients found that low preoperative BMD not only increases re-fracture risk but also serves as a strong indicator of residual low back pain after surgery.<sup>[6]</sup> Changes in BMD can affect the risk of re-fracture. Long-term use of denosumab increases BMD and reduces fracture incidence. However, discontinuation of this drug accelerates bone turnover and induces a rapid BMD decline, thereby increasing the likelihood of spontaneous vertebral fractures. This risk is particularly pronounced in patients with a history of vertebral fractures or those who experienced substantial BMD gains during treatment.<sup>[7]</sup> A Swiss cohort study reported that 10.3% of patients sustained spinal fractures within two years after discontinuing denosumab; this risk was significantly mitigated when patients were switched to bisphosphonates following withdrawal.<sup>[8]</sup>

From a biomechanical perspective, low BMD leads to a reduction in trabecular number and connectivity, which diminishes the compressive strength of the vertebral body. Although bone cement itself possesses high strength, the integrity of the cement-bone interface depends critically on the anchorage of cement into the surrounding trabecular network. In regions of low bone density, sparse and disconnected trabeculae provide insufficient interdigitation, impairing effective stress transfer from the cement to the bone. This results in focal stress concentrations at the interface and the accumulation of microdamage under cyclic loading, ultimately predisposing the augmented vertebra to re-collapse.<sup>[9]</sup>

CT-derived Hounsfield unit (HU) values offer a complementary approach to assess local bone quality and predict fracture risk in the augmented vertebra or adjacent vertebral bodies. Compared with BMD, HU values provide more specific site-related information and can be obtained from routine CT scans without additional cost or radiation exposure, making them a practical tool for clinical application.<sup>[10]</sup> A study of 279 patients undergoing PVP demonstrated that each 1-unit decrease in preoperative HU value was associated with an approximately 5.8% increase in the risk of vertebral re-fracture.<sup>[11]</sup> Furthermore, a high HU ratio between the augmented vertebra and the adjacent vertebral body (>15.18) combined with a low HU value in the adjacent vertebra (<66.9) significantly increases the risk of adjacent vertebral fracture. Such a ratio indicates a substantial stiffness gradient between segments, causing a disproportionate transfer of load to the adjacent level. Under physiological loading, this overload exceeds the mechanical capacity of the adjacent vertebral body, leading to its eventual failure.<sup>[12]</sup> HU values thus reflect not only bone density but also local mineralization and microstructural integrity; areas with low HU values exhibit sparser trabeculae and are prone to cement leakage or uneven distribution during injection.<sup>[11]</sup>

### 2.2 Demographic Characteristics

Age is an independent risk factor for post-operative re-fracture. Epidemiological data show that the incidence of vertebral fractures increases with age. In the NHANES cohort, the prevalence of vertebral fractures in adults aged  $\geq 50$  years increased from 2.2% to 4.6%, especially in the population aged 50–64 years, women, and non-Hispanic whites. Aging leads to a decrease in bone mineral density, directly increasing fracture risk.<sup>[13]</sup> Aging also predisposes the spine to degenerative changes, such as degenerative scoliosis, which further impairs spinal stability. Studies have shown that a Cobb angle exceeding  $10^\circ$  is a risk factor for adjacent vertebral fractures after percutaneous vertebroplasty.<sup>[4]</sup>

Women, particularly postmenopausal women, constitute the majority of patients with osteoporotic vertebral compression fractures (OVCF). After menopause, declining estrogen levels disrupt the balance between bone resorption and formation, resulting in accelerated bone loss and reduced bone mineral density (BMD). A meta-analysis of OVCF patients demonstrated that female sex is an

independent risk factor for re-fracture after PVP.<sup>[3]</sup> Furthermore, a large-scale CT study involving 538,946 scans revealed that the CT attenuation value of trabecular bone in the vertebral bodies of women over 50 years old decreases more steeply with age than that of age-matched men. This sex-based difference in bone microarchitecture may explain why women are more susceptible to adjacent vertebral fractures after surgery.<sup>[14]</sup>

### **2.3 Underlying diseases**

Many studies have shown that type 2 diabetes mellitus (T2DM) is a key risk factor for re-fracture after vertebral augmentation. A meta-analysis reported that those with type 2 diabetes who underwent percutaneous vertebroplasty (PVP) had a significantly higher risk of re-fracture.<sup>[3]</sup> Of note, some diabetic patients have normal or even high bone density yet remain at elevated fracture risk—a condition known as "diabetic bone disease" or "poor bone quality." Hyperglycemia accelerates the formation of advanced glycation end products (AGEs), which cross-link collagen fibers. This cross-linking increases bone stiffness but reduces its toughness, ultimately diminishing the bone's ability to absorb energy. As a result, bone tissue becomes more susceptible to rapid microcrack accumulation and propagation under post-operative physiological loading, potentially leading to brittle fractures at the cement-bone interface or in adjacent vertebral bodies.<sup>[15]</sup> In patients with diabetic osteoporosis, the use of SGLT-2 inhibitors has been linked to an increased risk of vertebral fracture within six months after the initial spinal fracture. This may be due to weight loss, reduced plasma volume, or shifts in calcium-phosphorus balance. Clinicians should therefore carefully weigh the risks and benefits when prescribing these drugs.<sup>[16]</sup>

Chronic kidney disease (CKD) is associated with skeletal complications, resulting in reduced bone mass and impaired bone quality. Even in the absence of significant BMD reduction, fracture risk is elevated. The pathological mechanisms mainly involve hyperphosphatemia, hypocalcemia, active vitamin D deficiency, and secondary hyperparathyroidism, which lead to abnormal bone turnover and compromised bone microstructural integrity. Additionally, CKD patients often require long-term glucocorticoid therapy for their primary disease, further exacerbating bone loss.<sup>[17]</sup> Regarding treatment, renal impairment limits the efficacy of anti-osteoporosis drugs such as bisphosphonates, resulting in significantly higher post-operative re-fracture risk, particularly in advanced CKD patients in whom the incidence of vertebral fractures is markedly increased.<sup>[18]</sup> Importantly, increased bone fragility is closely linked to vascular calcification and cardiovascular events. This reflects a systemic "bone-vascular axis" pathology in CKD patients, suggesting that re-fracture risk is not merely a local mechanical issue but a manifestation of systemic disease.<sup>[17]</sup>

### **2.4 Sarcopenia**

Sarcopenia is an age-related musculoskeletal condition characterized by loss of muscle mass, strength, and function. It is relatively common in the elderly, has a high prevalence in patients with OVCF, and often occurs together with osteoporosis. Paraspinal muscles are very important for spinal stability. Sarcopenia can weaken this support, change the mechanical load distribution on the vertebral body, and increase the risk of initial fractures and postoperative fractures. Sarcopenia is present in 72.5% of OVCF patients; the risk of re-fracture in these patients is 2.78 times that of non-sarcopenic patients.<sup>[19]</sup> Another study found that sarcopenic patients have a shorter interval to re-fracture and higher post-fracture mortality.<sup>[20]</sup>

From a biomechanical perspective, the erector spinae muscles are crucial for maintaining spinal stability. Sarcopenia can reduce muscle strength, weaken the support for the vertebral body, and increase the load borne by the vertebra during daily activities. Fatty infiltration further impairs the efficiency and coordination of muscle contraction, leading to altered load transfer patterns. Normally, forces generated by muscle contraction are distributed across multiple vertebrae via fascia and ligaments. When muscle function is compromised, load becomes concentrated on individual vertebral bodies—particularly at weight-bearing regions or adjacent levels—predisposing them to fracture.<sup>[21]</sup>

### **2.5 Previous Fracture History and Genetic Susceptibility**

A prior fragility fracture is one of the strongest predictors of subsequent fracture. A meta-analysis of more than 7,000 patients demonstrated that individuals with a history of osteoporotic spinal fractures had a 2.55-fold higher risk of re-fracture compared with those without such a history.<sup>[19]</sup> Among patients undergoing PVP, a history of non-vertebral fractures is also an independent risk factor for

re-fracture. <sup>[22]</sup>Prior fractures lead to bone loss, disrupt the balance between bone formation and resorption, and alter spinal alignment and postural mechanics. If the post-operative spinal curvature is not adequately restored, it may compromise overall dynamic balance. Reduced physical activity, compounded by pain after fracture, accelerates muscle loss, creating a vicious cycle of fracture, immobilization, sarcopenia, and re-fracture.<sup>[21]</sup>

### **2.6 Use of Anti-osteoporosis Medications**

Bisphosphonates (BPs) and denosumab are the main drugs for post-operative osteoporosis. Anti-osteoporosis drugs can increase local BMD, enhance the interdigitation of cement with trabecular bone, improve interface strength, optimize stress distribution, and reduce postoperative micromotion, ultimately lowering the risk of re-fracture. The U.S. Preventive Services Task Force reported that both drugs reduce fracture risk in high-risk women over 65 with favorable safety profiles. <sup>[23]</sup>Korean medical insurance data show no significant difference between the two in preventing all fractures and major osteoporotic fractures. However, drug selection requires a personalized approach.<sup>[24]</sup>

The risk of spinal fractures increases within two years after discontinuation. Following denosumab withdrawal, the rebound in osteoclastic activity leads to rapid loss of trabecular connectivity and compromised bone strength. This fragile bone, combined with the high stiffness of bone cement, creates a stiffness gradient within the augmented vertebra, predisposing it to re-fracture under minimal or physiological loading.<sup>[25]</sup> Switching to bisphosphonates after withdrawal reduces this risk, yet only 6% of patients receive subsequent treatment following discontinuation.<sup>[26]</sup>

## **3. Surgical Technique-Related Risk Factors**

### **3.1 Choice of Vertebral Augmentation Procedure**

Both PVP and PKP can relieve pain, improve quality of life, and restore spinal alignment in OVCF patients. The main difference between them is that PKP uses a balloon to elevate the fractured vertebral body and correct the kyphotic curvature. Currently, there is no consensus on which technique has a higher risk of post-operative fracture. A systematic review suggested that the re-fracture rate of PKP may be higher than that of PVP, but the quality of evidence is limited, and higher-quality studies are needed to further clarify. <sup>[27]</sup>In randomized trials, patients in the PVP group reported better pain scores and quality of life at 12 months compared with those receiving local analgesic injections. However, the observed functional improvement did not reach statistical significance. This suggests that the specific surgical approach may be less important than the technical details of its execution.<sup>[28]</sup>

### **3.2 Factors Related to Bone Cement**

#### **3.2.1 Bone Cement Volume**

Multiple studies have shown that excessive bone cement volume may increase the risk of re-fracture. For example, a study of 245 patients found that the cement volume-to-bone volume ratio was an independent risk factor for adjacent vertebral fractures. When this ratio exceeds 13.82%, the risk increases significantly. <sup>[29]</sup>A meta-analysis of 39 studies (8,047 patients) further confirmed that both insufficient and excessive cement volume are risk factors for post-operative adjacent vertebral fractures, exhibiting a U-shaped risk relationship.<sup>[30]</sup>

Insufficient cement cannot restore the load-bearing capacity of the vertebral body, leaving it mechanically compromised. Under daily loading, microdamage accumulates, ultimately leading to vertebral re-collapse. Excessive cement creates supra-physiological stiffness in the augmented vertebra, generating a stiffness gradient with adjacent levels. This transfers excessive load to adjacent vertebral bodies, leading to fatigue fracture of the endplate or cancellous bone and subsequent re-fracture.<sup>[25]</sup>

#### **3.2.2 Bone Cement Distribution**

A study of over 100 PVP patients found that patients with cement contacting both endplates had a lower re-fracture rate than those with cement contacting only one or no endplate. <sup>[31]</sup>Another study of 170 patients showed that well-distributed cement significantly reduced pain scores at 1 and 12 months post-operatively, as well as the fracture rates of the augmented vertebra and overall fractures. Well-distributed cement results in uniform stress distribution without focal stress concentrations,

minimizing excessive load transfer to adjacent segments.<sup>[32]</sup> Overall, cement distribution is a key determinant of fracture risk after vertebral augmentation. Optimal cement distribution is characterized by contact with both endplates, extension across the midline, and minimal leakage. Contact with both endplates creates a continuous load path from the superior to the inferior endplate, reducing intravertebral bending moments and ensuring uniform stress distribution at the cement-endplate interface, thereby lowering the risk of post-operative fracture.

### **3.2.3 Bone Cement Leakage**

A retrospective study showed that bone cement leakage was an independent risk factor for vertebral re-fracture.<sup>[33]</sup> A review reported that bone cement leakage is a risk factor for post-operative vertebral fracture. The proposed mechanism is that cement leakage into the intervertebral disc forms rigid inclusions within this normally compliant structure, disrupting its shock-absorbing function. This creates focal stress concentrations on the adjacent endplate during spinal motion, eventually leading to endplate fatigue fracture and subsequent vertebral collapse.<sup>[34]</sup>

### **3.2.4 Modified Bone Cements**

To address re-fracture risk at the material level, researchers have modified traditional PMMA cement through various approaches. The main goals are to reduce stiffness, enhance biocompatibility, and improve osseointegration. Low-stiffness PMMA containing silicone resin reduces polymerization exotherm and final stiffness, which may lower the risk of adjacent vertebral fractures.<sup>[25]</sup> Adding SIS material to PMMA (SIS-PMMA) reduces stiffness and polymerization heat, promotes osteogenic differentiation, and enhances mechanical strength and osseointegration.<sup>[35]</sup> PMMA-mSIS exhibits low stiffness, supports stem cell-mediated osteogenesis, and enhances bone integration. These modified materials exhibit favorable biocompatibility and may reduce re-fracture risk, although further research is still needed.<sup>[36]</sup>

### **3.3 Characteristics of the Operated Segment**

The vertebral level significantly influences post-operative biomechanics. T11-L2 (thoracolumbar junction) is a high-risk area for adjacent vertebral fracture. This region represents a transitional zone between the relatively rigid thoracic spine and the more mobile lumbar segments, bearing the highest bending moments during flexion and extension. Augmentation in this area creates a focal stiffness change, leading to stress concentration in adjacent vertebrae and increasing the risk of re-fracture.<sup>[37]</sup>

The risk of re-fracture within two years after surgery increases with the number of initially fractured vertebrae.<sup>[38]</sup> Multiple initial vertebral fractures indicate global compromise of the trabecular network. Each augmented vertebra alters the local mechanical environment, redistributing stress along the spine and creating multiple high-stress zones, leading to a cumulative increase in re-fracture risk.<sup>[39]</sup>

### **3.4 Surgical Timing**

Early surgical intervention can significantly reduce the risk of post-operative re-fracture. A study found that in patients with thoracic OVCF, early surgery was associated with a 50% reduction in re-fracture risk within two years compared with delayed surgery.<sup>[40]</sup> Another retrospective study also showed that the re-fracture rate was lower in the early surgery group than in the delayed surgery group.<sup>[41]</sup> While surgical timing may not be a direct risk factor, it influences re-fracture risk through multiple mechanisms. First, timing affects the quality of spinal balance restoration, which is an independent risk factor. Second, delayed surgery may aggravate fatty infiltration of the paravertebral muscles, which is associated with higher fracture risk. Third, early intervention facilitates optimal bone cement distribution and height restoration, thereby reducing stress on adjacent vertebral bodies. Advances in Imaging Assessment Indicators<sup>[21, 34]</sup>

## **4. Advances in Imaging Assessment Indicators**

### **4.1 Preoperative Vertebral Compression Severity Grading Systems**

A higher ratio of anterior to posterior vertebral height and a larger Cobb angle before surgery are significantly associated with an increased risk of re-fracture after PVP. This indicates that greater preoperative vertebral compression severity predicts higher subsequent re-fracture risk. A retrospective

study found that vertebral compression  $\geq 38.5\%$  was associated with significant loss of height restoration after surgical stabilization of thoracolumbar fractures, further supporting the link between compression severity and re-fracture.<sup>[33]</sup> Severe compression causes extensive damage to the trabecular network. Even when surgery partially restores vertebral height, the continuity and load-bearing capacity of trabecular bone are rarely fully recovered. Consequently, vertebral compression leads to height loss, altered spinal alignment, increased kyphotic angle, shifted load axis, and elevated stress on adjacent vertebral segments.<sup>[42]</sup>

#### **4.2 Cobb Angle Correction Rate and Biomechanical Changes**

Cobb angle correction is a key indicator of sagittal balance restoration in vertebral augmentation surgery. The degree of correction is closely associated with post-operative spinal stability. Multiple retrospective studies have demonstrated that excessive correction is a risk factor for post-operative re-fracture. A study of 495 patients who underwent PKP found that re-fracture risk increased proportionally with the degree of Cobb angle correction. Excessive correction may compromise optimal bone cement distribution and increase re-fracture risk. When correcting the Cobb angle, the balance of the entire spine needs to be considered.<sup>[43]</sup> From a biomechanical perspective, overcorrection disrupts the original spinal alignment, subjecting adjacent vertebral segments to abnormal loads. Furthermore, the muscles and ligaments of elderly patients have adapted to the long-term kyphotic posture. Sudden correction may exceed the adaptive capacity of these soft tissues, compromising their ability to maintain the new spinal alignment.<sup>[44]</sup>

### **5. Key Strategies in Surgical Management**

Refractures following OVCF surgery result from a complex interplay of risk factors, necessitating precise identification of high-risk patients and comprehensive, multidisciplinary management throughout their care continuum to improve long-term outcomes. Preoperatively, integrating assessments of bone mineral density (BMD), spinal muscle atrophy, Hounsfield unit (HU) value disparities, and spinal alignment can help develop personalized risk prediction models. Intraoperatively, adopting innovative materials like low-stiffness bone cement and meticulously controlling cement volume and distribution are crucial for optimizing biomechanical compatibility. Postoperatively, initiating standardized anti-osteoporosis therapy promptly—tailoring drug selection (e.g., zoledronic acid or teriparatide) to individual patient profiles—while reinforcing core muscle strengthening and postural correction exercises is essential. At the institutional level, implementing geriatric orthopedics-led care pathways ensures seamless integration of early comprehensive evaluations and rehabilitation interventions, enhancing treatment adherence and addressing modifiable risk factors to fundamentally reduce re-fracture risk.

### **6. Conclusion and Future Perspectives**

Re-fracture after OVCF is not caused by a single factor but results from a complex interplay of patient-specific, surgical, imaging, and post-operative factors. The core mechanisms include biomechanical alterations, structural deterioration, and impaired reparative capacity. Understanding this multifactorial mechanistic framework is essential for advancing clinical care.

Future efforts should focus on two key areas. First, future efforts should develop next-generation bone cements that combine stiffness optimization with bioactivity, featuring gradual degradation and enhanced osseointegration, to mitigate stress shielding and improve long-term stability. Second, future efforts should integrate multi-dimensional data—including imaging biomarkers (HU values, muscle fat fraction), serum markers (bone turnover, inflammation), and biomechanical parameters (spinal alignment)—into machine learning-based prediction models to enable truly personalized risk stratification.

We are shifting from a factor-based to a mechanism-based paradigm in personalized medicine. By tailoring surgical techniques, pharmacological interventions, and rehabilitation protocols to each patient's unique risk profile, this approach can reduce re-fracture risk and improve long-term quality of life in elderly OVCF patients.

**References**

- [1] WIKLUND P, BUCHEBNER D, GEIJER M. Vertebral compression fractures at abdominal CT: underdiagnosis, undertreatment, and evaluation of an AI algorithm [J]. *J Bone Miner Res*, 2024, 39(8): 1113-1119.
- [2] LI J, XIE Y, SUN S, et al. Regional differences in bone mineral density biomechanically induce a higher risk of adjacent vertebral fracture after percutaneous vertebroplasty: a case-comparative study [J]. *Int J Surg*, 2023, 109(3): 352-363.
- [3] MARSELOU E, KELEKIS A, DIMITRIADIS Z, et al. Risk factors for refracture or new vertebral compression fractures after percutaneous vertebroplasty: a systematic review and meta-analysis [J]. *Osteoporos Int*, 2025, 36(8): 1297-1311.
- [4] YU P, TANG Z, CHANG W, et al. Degenerative scoliosis may trigger higher incidence of adjacent vertebral fractures following percutaneous vertebroplasty: a clinical evidence-based biomechanical research [J]. *Osteoporos Int*, 2026, 37(1): 133-143.
- [5] THOMAS T, TUBACH F, BIZOUARD G, et al. The Economic Burden of Severe Osteoporotic Fractures in the French Healthcare Database: The FRACTOS Study [J]. *J Bone Miner Res*, 2022, 37(10): 1811-1822.
- [6] LYU F F, ZHANG M, DENG Y F, et al. Incidence and predictors of residual back pain after percutaneous vertebral augmentation in osteoporotic vertebral compression fracture: a systematic review and meta analysis [J]. *Osteoporos Int*, 2025, 36(10): 1781-1794.
- [7] KUMAR S, WANG M, KIM A S, et al. Denosumab discontinuation in the clinic: implications of rebound bone turnover and emerging strategies to prevent bone loss and fractures [J]. *J Bone Miner Res*, 2025, 40(9): 1017-1034.
- [8] BURCKHARDT P, FAOUZI M, BUCLIN T, et al. Fractures After Denosumab Discontinuation: A Retrospective Study of 797 Cases [J]. *J Bone Miner Res*, 2021, 36(9): 1717-1728.
- [9] OHMAN-MAGI C, HOLUB O, WU D, et al. Density and mechanical properties of vertebral trabecular bone-A review [J]. *JOR Spine*, 2021, 4(4): e1176.
- [10] SOLLMANN N, LOFFLER M T, EL HUSSEINI M, et al. Automated Opportunistic Osteoporosis Screening in Routine Computed Tomography of the Spine: Comparison With Dedicated Quantitative CT [J]. *J Bone Miner Res*, 2022, 37(7): 1287-1296.
- [11] WAN S, WU Z, LI H, et al. Poor bony density can independently trigger higher incidence of adjacent vertebral fracture after percutaneous vertebralplasty: a mono-center retrospective study [J]. *Langenbecks Arch Surg*, 2025, 410(1): 87.
- [12] MATSUMOTO K, HOSHINO M, SAWADA H, et al. The Risk of Adjacent Vertebral Fracture Following Balloon Kyphoplasty in Patients With Previous Adjacent Vertebral Fracture [J]. *Cureus*, 2024, 16(10): e72627.
- [13] HAN C S, HANCOCK M J, DOWNIE A, et al. Red flags to screen for vertebral fracture in people presenting with low back pain [J]. *Cochrane Database Syst Rev*, 2023, 8(8): Cd014461.
- [14] WESTERHOFF M, GYFTOPOULOS S, DANE B, et al. Deep Learning-based Opportunistic CT Osteoporosis Screening and the Establishment of Normative Values [J]. *Radiology*, 2025, 317(2): e250917.
- [15] WOLFEL E M, SCHMIDT F N, VOM SCHEIDT A, et al. Dimorphic Mechanisms of Fragility in Diabetes Mellitus: the Role of Reduced Collagen Fibril Deformation [J]. *J Bone Miner Res*, 2022, 37(11): 2259-2276.
- [16] CHANG Y, CHI K Y, CHEN C M, et al. Association between SGLT2 inhibitor use and the risk of vertebral augmentation after initial osteoporotic vertebral fracture in patients with type 2 diabetes [J]. *Osteoporos Int*, 2026.
- [17] HSU S, BANSAL N, DENBURG M, et al. Risk factors for hip and vertebral fractures in chronic kidney disease: the CRIC study [J]. *J Bone Miner Res*, 2024, 39(4): 433-442.
- [18] WU M, LI H, SUN X, et al. Aerobic exercise prevents renal osteodystrophy via irisin-activated osteoblasts [J]. *JCI Insight*, 2025, 10(5).
- [19] LIN Y H, LIN J, XU J Y, et al. What Risk Factors Are Associated With Recurrent Osteoporotic Vertebral Compression Fractures After Percutaneous Vertebral Augmentation? A Meta-analysis [J]. *Clin Orthop Relat Res*, 2025, 483(8): 1528-1539.
- [20] NGUYEN B T T, NGUYEN T T, KUO Y J, et al. Impact of sarcopenia on outcomes following vertebral augmentation for osteoporotic vertebral compression fracture: a systematic review and meta-analysis [J]. *Asian Spine J*, 2025, 19(3): 476-489.
- [21] WEN Q, WANG J, TAN G, et al. Association between lumbar disc degeneration at L4-L5 level and atrophy of paraspinal muscles and gluteus medius: a cross-sectional study using 3T quantitative magnetic resonance imaging [J]. *BMC Med Imaging*, 2025, 26(1): 60.

- [22] HUANG W, CAI X H, LI Y R, et al. The association between paraspinal muscle degeneration and osteoporotic vertebral compression fracture severity in postmenopausal women [J]. *J Back Musculoskelet Rehabil*, 2023, 36(2): 323-329.
- [23] KAHWATI L C, KISTLER C E, BOOTH G, et al. Screening for Osteoporosis to Prevent Fractures: A Systematic Evidence Review for the US Preventive Services Task Force [J]. *Jama*, 2025, 333(6): 509-531.
- [24] PARK C, KIM C, PARK R W, et al. Comparative effectiveness and safety outcomes between denosumab and bisphosphonate in South Korea [J]. *J Bone Miner Res*, 2024, 39(7): 835-43.
- [25] KIM M J, PARK S Y, KANG S, et al. Low modulus PMMA-based bone cement for the reduction of adjacent vertebral fractures after vertebroplasty [J]. *Acta Biomater*, 2025, 203: 399-411.
- [26] SENDHIL S R, CADARETTE S M, AGGARWAL S, et al. Follow-on osteoporosis therapy after denosumab discontinuation among Medicare beneficiaries [J]. *Osteoporos Int*, 2026, 37(1): 81-91.
- [27] EVANS A R, NIZNIK T, LI C, et al. Spinal augmentation for vertebral body fractures in the elderly population [J]. *Geroscience*, 2025.
- [28] CARLI D, VENMANS A, LODDER P, et al. Vertebroplasty versus Active Control Intervention for Chronic Osteoporotic Vertebral Compression Fractures: The VERTOS V Randomized Controlled Trial [J]. *Radiology*, 2023, 308(1): e222535.
- [29] ZHOU C, HUANG S, LIAO Y, et al. Correlation analysis of larger side bone cement volume/vertebral body volume ratio with adjacent vertebral compression fractures during vertebroplasty [J]. *Front Endocrinol (Lausanne)*, 2023, 14: 1072087.
- [30] HE L, LI W, ZHAI X, et al. Risk factors for adjacent vertebral fracture after kyphoplasty or percutaneous vertebroplasty in osteoporotic vertebral systematic review and meta-analysis compression fractures [J]. *Eur Spine J*, 2025, 34(11): 5126-5141.
- [31] HAIBIER A, JIE Y, YUSUFU A, et al. Effect of different cement distribution on the clinical efficacy of vertebral compression fractures in unilateral percutaneous vertebroplasty [J]. *Eur Spine J*, 2025, 34(5): 1673-1684.
- [32] YUNTAO L, HAIBIER A, KAYIERHAN A, et al. Clinical effect analysis of unilateral percutaneous vertebral cement distribution in the repair of osteoporotic thoracolumbar vertebral compression fractures [J]. *BMC Surg*, 2025, 25(1): 90.
- [33] DAI C, LIANG G, ZHANG Y, et al. Risk factors of vertebral re-fracture after PVP or PKP for osteoporotic vertebral compression fractures, especially in Eastern Asia: a systematic review and meta-analysis [J]. *J Orthop Surg Res*, 2022, 17(1): 161.
- [34] XIE S, CUI L, WANG C, et al. Contact between leaked cement and adjacent vertebral endplate induces a greater risk of adjacent vertebral fracture with vertebral bone cement augmentation biomechanically [J]. *Spine J*, 2025, 25(2): 324-336.
- [35] ZHANG C, CAI X, LI M, et al. Preclinical Evaluation of Bioactive Small Intestinal Submucosa-PMMA Bone Cement for Vertebral Augmentation [J]. *ACS Biomater Sci Eng*, 2024, 10(4): 2398-2413.
- [36] MIAO X, YANG S, ZHU J, et al. Bioactive mineralized small intestinal submucosa acellular matrix/PMMA bone cement for vertebral bone regeneration [J]. *Regen Biomater*, 2023, 10: rbad040.
- [37] PARK J S, PARK Y S. Survival analysis and risk factors of new vertebral fracture after vertebroplasty for osteoporotic vertebral compression fracture [J]. *Spine J*, 2021, 21(8): 1355-1361.
- [38] LIN X B, YE H, HE L J, et al. Analysis of changes in serum high t-PINP/beta-CTX ratio and risk of re-fracture after vertebral osteoporotic fracture surgery [J]. *Eur Rev Med Pharmacol Sci*, 2023, 27(22): 10860-10867.
- [39] YOKOYAMA K, IKEDA N, TANAKA H, et al. Changes in spinal sagittal balance after a new osteoporotic vertebral compression fracture [J]. *Osteoporos Int*, 2024, 35(4): 645-651.
- [40] RAMESH A, KO A, PATEL P K, et al. Early Percutaneous Kyphoplasty Is Associated with Reduced Risk of Subsequent Thoracic Vertebral Compression Fracture [J]. *Spine Surg Relat Res*, 2026, 10(1): 105-111.
- [41] HE B, ZHAO J, ZHANG M, et al. Effect of Surgical Timing on the Refracture Rate after Percutaneous Vertebroplasty: A Retrospective Analysis of at Least 4-Year Follow-Up [J]. *Biomed Res Int*, 2021, 2021: 5503022.
- [42] WALLE M, YERITSYAN D, ABBASIAN M, et al. A graph model to describe the network connectivity of trabecular plates and rods [J]. *Front Bioeng Biotechnol*, 2024, 12: 1384280.
- [43] WU Y, ZHU S, LI Y, et al. Analysis of Risk Factors for Augmented Vertebral Refracture After Percutaneous Kyphoplasty in Osteoporotic Vertebral Compression Fractures [J]. *J Clin Med*, 2025, 14(2).
- [44] DAHER M, SEBAALY A, SAKR I, et al. Diagnosis and Management of Osteoporotic Vertebral Compression Fractures [J]. *J Bone Joint Surg Am*, 2025.