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# Does cortical violation improve pedicle screw fixation? a narrative review of the biomechanical evidence

**Abstract**

The belief that cortical breach during pedicle screw insertion may enhance biomechanical stability persists in some surgical settings, largely owing to misinterpretation of bicortical fixation principles and anecdotal experience. This focused narrative review critically examines the biomechanical and clinical evidence addressing whether cortical violation improves pedicle screw stability. Available evidence indicates that fixation strength primarily depends on controlled cortical engagement and preservation of the bone-implant interface rather than on cortical breach. Selected biomechanical studies suggest that controlled bicortical engagement may increase fixation strength in specific circumstances, particularly in compromised bone quality; however, this should be distinguished from unintended or excessive cortical violation. Cortical breach has been associated with loss of pedicular containment, reduced fixation strength in experimental models, and increased neurovascular and visceral risk. Overall, the available evidence does not support cortical violation beyond anatomical boundaries as a routinely advantageous biomechanical or clinically justifiable strategy.

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## Introduction

Pedicle screw fixation is the cornerstone of modern spinal instrumentation, providing immediate and durable segmental stability across degenerative, traumatic, neoplastic, and deformity-related conditions.[1–3] While the importance of cortical bone engagement is well established, the belief that cortical violation, particularly anterior cortical breach, may improve screw stability continues to persist in surgical practice (Figure 1).[4]

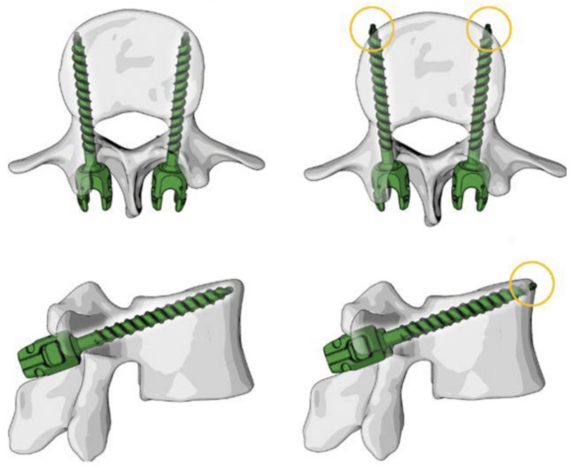


**Figure 1** Schematic comparison between controlled cortical bone trajectory (CBT) and bicortical screw positioning. Left: pericortical trajectory demonstrating intraosseous containment with circumferential bone-implant contact. Right: bicortical configuration demonstrating controlled engagement of the anterior vertebral cortex. The schematic illustrates the conceptual distinction between contained cortical engagement, controlled anterior cortical purchase, and transgression beyond the vertebral boundary. Potential biomechanical benefit from bicortical fixation should be attributed to controlled cortical engagement rather than assumed to result from cortical penetration itself.

For clarity, three related but biomechanically distinct concepts should be differentiated. Cortical engagement refers to intentional contact between the screw threads and cortical bone while the implant remains contained within the osseous boundaries of the pedicle and vertebral body. Bicortical fixation refers to deliberate engagement of an additional cortical boundary, most commonly the anterior vertebral cortex, with the aim of increasing terminal cortical purchase under controlled conditions. Cortical violation or breach, in contrast, refers to transgression of the intended cortical boundary with extension of the screw beyond the anatomical osseous envelope. These concepts should not be used interchangeably, as their biomechanical implications and clinical risk profiles differ substantially.

Pedicle screw stability depends on a complex interaction between bone quality, implant design, insertion trajectory, and preservation of the bone-implant interface.[1,2,5,6] Cortical bone contributes substantially to fixation strength because of its density and structural stiffness; however, this advantage depends on maintaining anatomical containment rather than violating cortical boundaries. Once cortical integrity is disrupted, the mechanical environment of the construct changes, compromising circumferential load transfer and fixation efficiency.[1] This misconception likely stems from conflating controlled cortical engagement with uncontrolled cortical breach and from extrapolating bicortical fixation techniques beyond their intended indications.[7–9] In osteoporotic bone, carefully controlled anterior cortical contact has been explored as a means of augmenting fixation. However, these techniques are highly selective, context-dependent, and aimed at achieving controlled cortical abutment rather than cortical penetration. They should therefore not be equated with inadvertent or excessive breach beyond the vertebral body.

Recent advances in spinal instrumentation, including cortical bone trajectory (CBT) and navigation-assisted techniques, have further reinforced the principle that fixation is optimised by maximising cortical engagement within anatomical boundaries rather than by violating them.[7,8,10,11] These developments highlight a fundamental concept: biomechanical stability is achieved through strategic cortical engagement and preservation of anatomical containment, not through cortical breach. Failure to distinguish between these concepts has contributed to the persistence of a misconception that remains unsupported by current evidence.

The implications of cortical violation extend beyond biomechanics. Anterior breach of the vertebral body may expose major vascular and visceral structures to injury, with potentially devastating consequences.[12,13] Thus, from both biomechanical and clinical perspectives, intentional or inadvertent violation of cortical boundaries warrants careful scrutiny.

This review critically evaluates the hypothesis that cortical violation enhances pedicle screw stability by integrating the available biomechanical evidence with relevant clinical considerations. Particular attention is given to distinguishing controlled cortical engagement, selective bicortical fixation, and true cortical violation, and to identifying the circumstances in which additional cortical purchase may provide biomechanical benefit without implying that cortical transgression itself is advantageous. The aim is to provide an evidence-based framework for the interpretation and safe application of these distinct fixation principles.

## Methodological approach

This study was conducted as a focused narrative review of the biomechanical and clinical literature addressing cortical engagement, bicortical fixation, and cortical violation during pedicle screw placement. A structured literature search was performed in PubMed, Scopus, and Google Scholar, including publications available through February 2026. Search terms were used individually and in combination and included “pedicle screw”, “cortical breach”, “cortical violation”, “bicortical fixation”, “cortical engagement”, “cortical bone trajectory”, “pull-out strength”, “malposition”, “cyclic loading”, and “complications”.

Studies were considered relevant when they provided biomechanical, anatomical, radiological, or clinical data directly addressing screw trajectory, cortical purchase, pedicle wall violation, anterior vertebral cortical engagement or breach, fixation strength, or complications associated with screw malposition. Particular attention was given to experimental studies directly comparing contained and breached trajectories, studies evaluating pull-out strength or cyclic loading, and clinical or radiological series documenting the consequences of cortical violation. Studies addressing controlled bicortical fixation were also included to evaluate circumstances in which additional cortical engagement may provide biomechanical benefit.

Seminal studies were retained where necessary to establish anatomical and biomechanical principles, while contemporary publications were included to reflect developments in cortical bone trajectory, navigation, screw placement accuracy, fixation in compromised bone quality, and complication profiles. Reference lists of relevant publications were also reviewed to identify additional pertinent studies.

Given the heterogeneity of experimental models, screw designs, anatomical levels, bone quality, definitions of cortical breach, and biomechanical endpoints, quantitative pooling was not considered appropriate. The objective was therefore not to perform a systematic review or meta-analysis, but to provide a focused critical synthesis of the evidence most directly relevant to the biomechanical and clinical question under investigation.

## Biomechanical principles of pedicle screw fixation

The pull-out strength and overall stability of pedicle screws are determined by a complex interplay of factors, including bone mineral density, screw dimensions, thread design, insertion technique, and trajectory.[1,2,9] Among these, the integrity of the bone-implant interface remains a principal determinant of fixation strength. Cortical bone engagement plays a pivotal role owing to its greater density, elastic modulus, and resistance to deformation compared with cancellous bone.[1]

From a biomechanical perspective, pedicle screw fixation depends not simply on insertion depth or maximal penetration, but on achieving effective three-dimensional purchase within a confined osseous envelope.[1] The pedicle serves as the primary anchoring corridor, consisting of a dense cortical shell surrounding a cancellous core.[1,3] This unique architecture provides circumferential support for the implant, allowing optimal load distribution when the screw remains centred within the pedicle and vertebral body.

Effective cortical engagement is achieved when the screw maintains appropriate purchase within the anatomical confines of the pedicle and vertebral body. Preservation of cortical integrity maintains a continuous osseous envelope around the screw threads, promoting uniform load transfer[1–3] and increasing resistance to both axial pull-out and cyclic micromotion.[1,2] Consequently, the principle of anatomical containment is fundamental: pedicle screw stability depends not merely on contact with bone, but on preservation of an effective bone-implant interface (Figure 2).

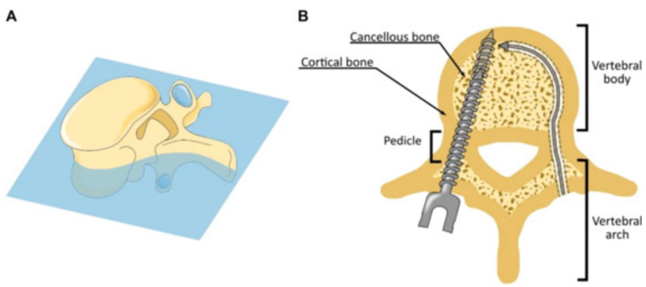


**Figure 2** Axial schematic of pedicle screw fixation demonstrating the anatomical relationship between cortical and cancellous bone. The pedicle acts as a cortical conduit, providing a dense osseous envelope that contributes to circumferential bone-implant contact. A contained intraosseous trajectory within this cortical shell preserves the structural contribution of the pedicle and supports effective screw fixation, highlighting the biomechanical importance of pedicular integrity.

Experimental studies generally support the importance of preserving the cortical envelope for maintaining fixation strength, although the magnitude of this contribution varies according to bone quality, screw design, trajectory, and the biomechanical model employed.[1,2]

Screw trajectory is equally important. Optimal trajectories maximise engagement with dense cortical bone while preserving the internal architecture of the pedicle. Techniques such as cortical bone trajectory (CBT) were specifically developed to increase cortical contact within anatomical boundaries.[7,8,10,14] Rather than promoting cortical violation, these techniques reinforce the principle that fixation is enhanced through strategic intraosseous cortical engagement.

The relationship between screw length and fixation strength further illustrates this concept. Increasing screw length may

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improve fixation while additional threads continue to engage bone effectively.[2,9] As the screw approaches the anterior vertebral cortex, the potential contribution of additional cortical purchase depends on factors including bone quality, screw design, trajectory, and whether controlled bicortical engagement is achieved.[8,9] This should be distinguished from uncontrolled penetration beyond the vertebral boundary.

Biomechanical performance should also be considered under cyclic loading, which more closely reflects physiological conditions than static pull-out testing. Under repetitive loading, preservation of the bone-implant interface contributes to construct stability. Cortical breach may alter load distribution and compromise fixation, although its mechanical consequences depend on the location and magnitude of the breach, bone quality, screw characteristics, and testing conditions.[2,5,15] Studies evaluating screw malposition similarly suggest that pedicle wall breach may reduce fixation strength, particularly when substantial cortical support is lost.[2,15]

Collectively, these findings demonstrate that the pedicle functions as an anatomical containment unit, in which preservation of cortical integrity rather than cortical violation is an important determinant of biomechanical stability.

In summary, pedicle screw stability depends on maximising effective bone-implant contact through an appropriate trajectory while preserving the structural contribution of the pedicle. The available biomechanical evidence supports controlled cortical engagement as an important determinant of fixation strength. Additional cortical purchase may provide benefit under selected conditions, particularly when cancellous bone quality is compromised; however, such controlled engagement should be distinguished from cortical breach beyond the intended osseous boundaries.[1,2,9]

## Cortical breach and pull-out strength

While the biomechanical principles of pedicle screw fixation emphasise the importance of anatomical containment, experimental models of screw malposition provide more direct evidence regarding the consequences of cortical breach.[2,15] These studies allow the mechanical effects of pedicle wall violation to be examined under controlled conditions. Most available experimental data indicate that medial or lateral pedicle wall breach reduces pull-out strength relative to an equivalent contained trajectory, although the magnitude of this reduction depends on the direction and extent of breach, screw characteristics, bone quality, and testing methodology (Figure 3).[2,15]

The pedicle functions as the principal structural anchoring corridor, contributing to fixation through its dense cortical envelope.[1,3] Once this envelope is violated, the construct loses part of its anatomical containment, which may result in altered load distribution, localised stress concentration, and reduced biomechanical stability. Consequently, both immediate fixation strength and resistance to cyclic loading may be compromised, depending on the characteristics of the breach and the biomechanical conditions.[15]

Experimental studies further indicate that redirection of a misplaced screw may not fully restore the original biomechanical properties of the pedicle.[2,15] Repeated instrumentation can enlarge the cortical defect, further disrupting the bone-implant interface and potentially reducing fixation strength while increasing susceptibility to micromotion and subsequent mechanical failure.

Not all cortical breaches have equivalent biomechanical or clinical implications. Medial breaches may threaten neural structures, whereas lateral, superior, or inferior violations may compromise pedicular containment to varying degrees.[12,13] The consequences depend on the direction and magnitude of breach, the amount of residual cortical support, and the relationship of the screw to adjacent anatomical structures.

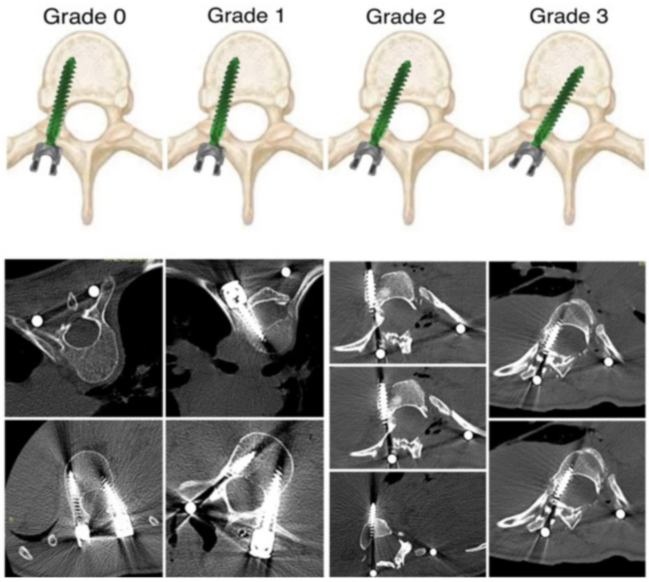


**Figure 3** Grading of pedicle screw placement accuracy. Schematic representation (top row) illustrating progressive degrees of cortical breach from Grade 0 (fully contained intraosseous trajectory) to Grade 3 (significant cortical violation with extravertebral extension). Corresponding axial CT images (bottom panels) demonstrate representative clinical examples of screw malposition. Increasing grades of cortical breach illustrate progressive loss of pedicular containment and potential compromise of the bone-implant interface, the biomechanical consequences of which depend on the direction and magnitude of the breach and the amount of residual cortical support.

The misconception that cortical violation improves fixation largely arises from studies evaluating alternative trajectories or larger-diameter screws.[7–9] The apparent biomechanical advantage reported for some alternative trajectories or longer or larger screws should therefore be interpreted according to the mechanism responsible for improved purchase. In these settings, increased fixation strength is generally attributable to greater intraosseous bone contact or engagement of denser cortical regions rather than to cortical transgression itself.[7–9] Available comparative evidence does not demonstrate an independent biomechanical advantage from uncontrolled cortical breach.[1,2,5,15]

These biomechanical considerations become particularly relevant under cyclic loading, which more closely reflects physiological conditions than static pull-out testing. Cortical breach may impair fatigue resistance and contribute to progressive degradation of the bone-implant interface, although the magnitude of this effect depends on the characteristics of the breach and the experimental model employed.[5,15]

Anterior cortical violation deserves particular attention because its biomechanical implications must be balanced against substantial clinical risk. Controlled engagement of the anterior cortex may provide additional fixation in selected circumstances, particularly in compromised bone.[8,9] This should be distinguished from uncontrolled extension of the screw beyond the vertebral boundary, which exposes adjacent vascular and visceral structures to potential injury.[12,13]

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Collectively, the available biomechanical evidence does not demonstrate an independent fixation advantage from cortical breach. Rather, breach results in loss of anatomical containment and may compromise the strength and durability of the construct, depending on its location, magnitude, bone quality, and biomechanical conditions. Cortical violation should therefore be distinguished from controlled cortical engagement and regarded as a deviation from the intended screw trajectory rather than as an established strategy for improving fixation.

## The misconception of bicortical fixation

Bicortical fixation has been described primarily in the setting of osteoporotic bone, where carefully controlled anterior cortical engagement may increase pull-out resistance by compensating for reduced cancellous bone quality.[8,9] Under these circumstances, the diminished mechanical contribution of trabecular bone shifts greater biomechanical importance towards cortical structures, prompting the development of techniques aimed at maximising cortical purchase.

Importantly, the potential benefit of bicortical fixation should not be dismissed when evaluating the broader question of cortical purchase. In severely osteoporotic or otherwise compromised bone, where cancellous purchase is reduced, controlled engagement of an additional cortical boundary may increase resistance to axial pull-out by transferring a greater proportion of load to structurally stronger cortical bone.[8,9] This represents a legitimate biomechanical principle and may be clinically relevant in carefully selected cases. Its potential advantage, however, derives from planned cortical purchase under controlled anatomical conditions rather than from uncontrolled extension of the screw beyond the vertebral body.

Bicortical fixation therefore requires careful contextualisation. As described in the available literature, it is neither broadly applicable nor conceptually equivalent to cortical violation. Rather, it represents a selective technique intended for specific clinical situations and performed under strict anatomical and technical control.[8,9]

Its potential application is particularly relevant in severely osteoporotic or otherwise compromised bone, where conventional pedicle screw fixation may provide reduced purchase.[9] The objective is controlled engagement of the anterior vertebral cortex rather than uncontrolled penetration beyond the intended vertebral boundary. Consequently, the potential biomechanical benefit of bicortical fixation should not be extrapolated to imply that cortical violation itself is advantageous.

This distinction is fundamental. Controlled bicortical engagement seeks to maximise terminal cortical support under deliberate anatomical control. Cortical breach, in contrast, represents extension beyond the intended osseous boundary. These situations should therefore be considered biomechanically and clinically distinct.

Furthermore, bicortical fixation must be balanced against the anatomical risks associated with the close relationship between the anterior vertebral cortex and major vascular structures, particularly in the lumbar spine.[12,13] Alternative methods of improving fixation in osteoporotic bone, including cement augmentation, expandable screws, and modified trajectories that increase cortical engagement, may therefore be considered according to the individual clinical and anatomical circumstances (Figure 4).[2,9]

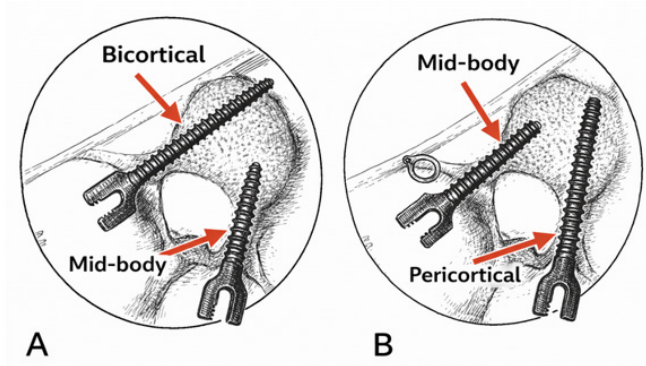


**Figure 4** Conceptual illustration of bicortical fixation in the lumbar spine and its distinction from cortical violation. Controlled bicortical fixation seeks additional purchase through deliberate engagement of the anterior vertebral cortex, whereas cortical violation represents unintended or excessive extension beyond the intended osseous boundary. The potential biomechanical benefit of bicortical fixation derives from controlled cortical purchase and should not be interpreted as evidence that cortical transgression itself improves fixation.

From a biomechanical perspective, the reported advantages of bicortical fixation should be interpreted within the conditions in which they were demonstrated. Experimental studies have reported increases in pull-out strength with controlled anterior cortical engagement, particularly in models of reduced bone quality.[8,9] The magnitude and clinical relevance of this benefit vary according to bone density, screw length and design, trajectory, vertebral level, and testing conditions, and static pull-out testing does not fully reproduce physiological cyclic loading. Thus, the evidence supports the possibility of a selective biomechanical advantage from controlled bicortical purchase, but it does not establish cortical penetration beyond the vertebral boundary as the mechanism responsible for that advantage.

The persistent confusion between bicortical fixation and cortical violation appears to arise from an overemphasis on cortical contact while underestimating the importance of anatomical control.[7,8] The available evidence therefore supports distinguishing deliberate bicortical engagement from unintended or excessive cortical breach rather than considering both situations as manifestations of the same biomechanical principle.

Accordingly, bicortical fixation, where appropriate, should be regarded as a controlled, context-specific technique intended to increase cortical purchase in selected circumstances. This concept should not be extrapolated to justify uncontrolled cortical violation during routine pedicle screw placement, which has no established independent biomechanical advantage and may expose adjacent structures to avoidable risk.[12,13]

## Clinical risks of anterior cortical violation

Beyond its biomechanical consequences, cortical violation during pedicle screw placement is associated with a spectrum of clinically relevant complications. The clinical significance of breach depends on its direction, magnitude, vertebral level, and relationship to adjacent neural, vascular, and visceral structures. Reviews of thoracolumbar pedicle screw instrumentation identify neurological, vascular, cerebrospinal fluid, visceral, and structural complications among the recognised consequences of clinically significant screw malposition.[4,12,16,17] Although major complications are uncommon in large series, their potential severity reinforces the importance of accurate screw placement and careful assessment of cortical breach (Figure 5).

 

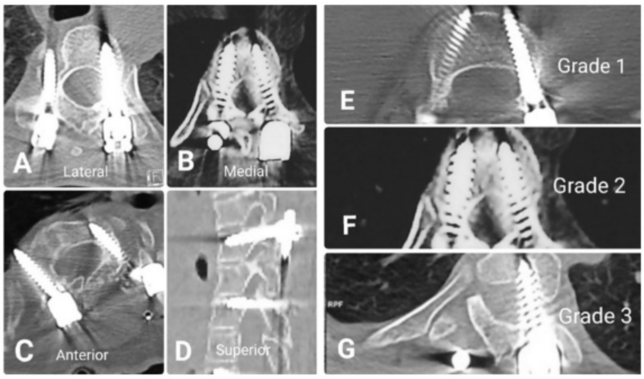


**Figure 5** CT-based classification of pedicle screw malposition according to direction and degree of cortical breach. Panels A-D illustrate representative examples of screw deviation relative to the pedicle walls, including lateral, medial, anterior, and superior breaches. Panels E-G depict progressive degrees of cortical violation, from Grade I (minor cortical encroachment) to Grade 3 (frank transgression beyond the vertebral boundaries). This framework illustrates that the clinical significance of cortical breach depends not only on its magnitude but also on its direction and relationship to adjacent anatomical structures. Anterior cortical violation is of particular clinical relevance because extravertebral extension may place major vascular and visceral structures at risk.

Neurological complications represent the most immediate consequence of pedicle screw malposition. Medial pedicle wall breach may result in direct irritation, compression, or injury of the nerve root, dural sac, or spinal cord, depending on the vertebral level involved.[12,18] Even in the absence of major neurological deficit, minor degrees of cortical violation may produce postoperative radicular pain, dysaesthesia, delayed neural irritation, or necessitate revision surgery.[12,16] These complications reflect the anatomical constraints of the pedicle, whose cortical boundaries define the safe relationship between the implant and adjacent neural structures. Once these boundaries are violated, the issue extends beyond fixation strategy to potential injury of critical neuroanatomical structures.

Dural injury and cerebrospinal fluid leakage represent additional potential consequences of medial cortical breach, particularly when associated with spinal canal intrusion or screw revision following an initially misplaced trajectory.[12,16] Such complications may increase the risk of wound problems, infection, persistent cerebrospinal fluid leakage, postoperative headache, pseudomeningocoele formation, and reoperation. Accordingly, clinically significant cortical violation should not be regarded solely as a radiological finding, but should be interpreted in relation to its anatomical location and potential clinical consequences.

Anterior cortical violation warrants particular attention because its potential biomechanical implications must be balanced against potentially severe clinical consequences. Once the anterior vertebral cortex is breached, the screw tip may extend into the prevertebral or retroperitoneal space, where major vascular and visceral structures can be at risk. In the thoracic spine, malpositioned screws may compromise the thoracic aorta, azygos system, pleura, lung, or oesophagus, depending on the vertebral level and trajectory.[13,19] In the lumbar spine, the abdominal aorta, inferior vena cava, common iliac vessels, lumbar arteries, sympathetic chain, ureter, and retroperitoneal viscera may be endangered.[13,19] Clinical reports and reviews have documented acute vascular injury, delayed vascular erosion or perforation, pseudoaneurysm formation, and retroperitoneal haemorrhage associated with pedicle screw malposition.[13,19]

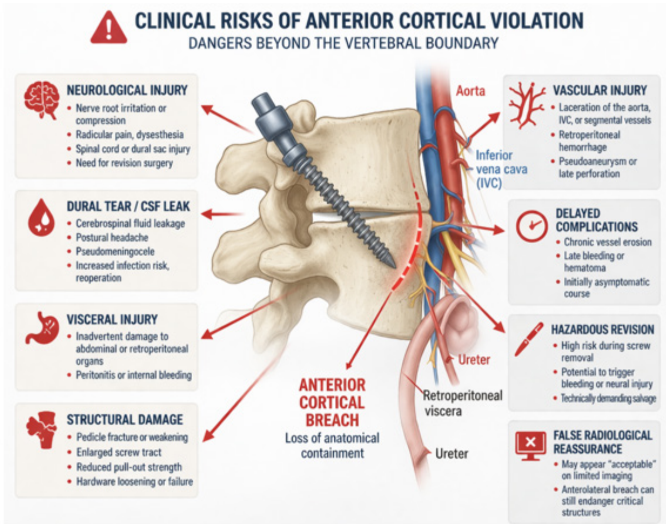


**Figure 6** Clinical risks of anterior cortical violation during lumbar pedicle screw placement. Schematic representation of a lumbar vertebra demonstrating anterior cortical breach with screw tip extending beyond the vertebral body into the retroperitoneal space. Importantly, the figure underscores that apparent radiological acceptability does not exclude clinically significant risk, reinforcing that anterior cortical violation represents a preventable technical error rather than a stability-enhancing strategy.

The vascular implications of anterior cortical violation deserve particular attention because injury may occur either immediately or in a delayed fashion. Acute complications include intraoperative or early postoperative haemorrhage, whereas delayed presentations may result from chronic contact between the screw and the vessel wall, leading to erosion, pseudoaneurysm formation, or late vascular perforation.[13] A screw in contact with a major vessel may remain asymptomatic for a prolonged period. Nevertheless, vascular contact is a recognised complication, and decisions regarding observation or revision must balance the risks associated with continued screw-vessel contact against those of surgical removal or repositioning.[13,19]

Visceral injury is less frequently reported than neurological or vascular complications but remains a recognised consequence of pedicle screw malposition.[12,19] Once instrumentation extends beyond the vertebral body, the screw is no longer confined to the intended osseous environment and may compromise adjacent retroperitoneal or thoracic structures. Although uncommon, these complications reinforce the importance of distinguishing controlled cortical engagement from unintended extravertebral extension.

Cortical violation may also compromise the structural integrity of the pedicle itself. Pedicle fracture, enlargement of the screw tract, and weakening of the bone-implant interface may result from eccentric or repeated screw insertion attempts.[18,20] This is particularly relevant when an initial breach is managed by redirecting the screw through an already compromised pedicle. Although such manoeuvres may improve radiographic alignment, repeated instrumentation may further disrupt the cortical envelope and reduce the mechanical competence of the pedicle, potentially predisposing to loosening or construct-related failure.[15,18,20]

Revision of a malpositioned screw presents an additional challenge. Removal or repositioning of screws in close relationship to vascular or neural structures may itself precipitate serious injury.[13,19] Accordingly, the consequences of cortical violation extend beyond the

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initial placement and may create complex management decisions that increase surgical risk.

Radiological interpretation also deserves careful consideration. Cortical breach may appear acceptable on limited intraoperative imaging when gross alignment is preserved and no immediate neurological or haemodynamic complications are evident.[4,16] However, imaging studies and clinical reports demonstrate that breaches involving adjacent critical structures may remain clinically relevant even in asymptomatic patients.[11,19] Consequently, the absence of immediate complications should not necessarily be interpreted as evidence of appropriate screw placement.

Taken together, the available clinical evidence indicates that the significance of cortical violation depends on its direction, magnitude, vertebral level, and relationship to adjacent structures. Controlled cortical engagement and selective bicortical fixation should therefore be distinguished from unintended or excessive cortical breach. Although selected additional cortical purchase may provide biomechanical benefit under specific circumstances, extension beyond the intended osseous boundary may expose patients to neurological, vascular, visceral, and mechanical complications without an established independent biomechanical advantage.

## Discussion

The present review integrates biomechanical and clinical evidence to evaluate the persistent claim that cortical violation during pedicle screw placement enhances fixation strength. When examined in light of the available evidence, this assertion is not supported. However, interpretation of the literature requires a clear distinction between controlled cortical engagement, selective bicortical fixation, and true cortical violation, since these concepts represent different biomechanical conditions and should not be used interchangeably.

From a biomechanical perspective, the distinction between cortical engagement and cortical violation is structural rather than semantic. Pedicle screw stability depends on effective bone-implant purchase, appropriate trajectory, and preservation of the structural contribution of the pedicle. Maintenance of the cortical envelope promotes circumferential bone-implant contact, appropriate load distribution, and resistance to micromotion. Experimental studies evaluating pedicle wall breach generally demonstrate reduced pull-out strength and inferior mechanical performance compared with equivalent contained trajectories, although the magnitude of these effects varies according to bone quality, screw characteristics, direction and extent of breach, and the experimental model employed.[1,2,15,20]

The persistence of the opposite view appears to reflect, at least in part, extrapolation from studies evaluating alternative trajectories, increased cortical contact, longer or larger-diameter screws, or selective cortical purchase. Improved fixation reported with cortical bone trajectory and other techniques designed to maximise cortical contact results from increased engagement with structurally competent bone while maintaining deliberate anatomical control.[7,8,10] Such findings support the biomechanical value of cortical purchase but should not be interpreted as evidence that cortical transgression itself improves fixation.

The distinction becomes particularly relevant in the context of bicortical fixation. Controlled engagement of the anterior vertebral cortex has been investigated as a means of augmenting fixation, particularly in severely osteoporotic or otherwise compromised bone where cancellous purchase is reduced.[8,9] Under these circumstances, engagement of an additional cortical boundary may increase resistance to axial pull-out by transferring a greater proportion of load to structurally stronger cortical bone. This represents a legitimate biomechanical principle and may provide benefit in carefully selected cases. However, the magnitude and clinical relevance of this benefit depend on bone quality, vertebral level, screw design and trajectory, and the conditions under which fixation is tested.

The available literature therefore supports a more nuanced interpretation than a simple opposition between cortical contact and cortical breach. Increased cortical purchase can be biomechanically advantageous, particularly when bone quality is poor and cancellous fixation is limited. Controlled bicortical engagement may represent one means of achieving this objective in selected circumstances. However, the biomechanical benefit reported in such studies should be attributed to deliberate engagement of structurally competent cortical bone rather than to cortical violation per se. Controlled bicortical engagement and uncontrolled extension beyond the intended vertebral boundary consequently represent biomechanically and clinically distinct situations.

This distinction is also important when interpreting experimental endpoints. Many biomechanical studies assess fixation using static axial pull-out testing, which provides a useful comparative measure but does not fully reproduce the multidirectional and repetitive forces acting on spinal constructs in vivo. Cyclic loading, bone quality, screw-bone interface characteristics, and anatomical variability may substantially influence mechanical behaviour. Consequently, findings obtained under specific experimental conditions should not automatically be extrapolated to all clinical situations, particularly when comparing contained fixation, controlled bicortical purchase, and cortical breach.

The clinical consequences of cortical violation must also be considered independently of its biomechanical effects. Neurological injury, dural tears, vascular compromise, visceral injury, pedicle damage, and construct-related complications are recognised consequences of clinically significant screw malposition.[12,16,18,19] The clinical relevance of a breach depends on its direction, magnitude, vertebral level, and relationship to adjacent anatomical structures. Although major complications are relatively uncommon, the absence of immediate clinical sequelae should not necessarily be interpreted as evidence of appropriate screw placement, since delayed vascular and mechanical complications have been reported.[13,19]

These considerations reinforce the importance of surgical precision and appropriate trajectory selection. Advances in navigation, intraoperative imaging, and trajectory optimisation have improved the ability to maximise bone purchase while maintaining anatomical control.[7,8,11,17] Within this context, the objective should not simply be to maximise screw length or cortical contact, but to optimise fixation according to bone quality and individual anatomy while avoiding unintended cortical transgression.

Taken together, the available biomechanical and clinical evidence indicates that pedicle screw stability is primarily determined by effective bone-implant purchase, appropriate trajectory, and preservation of the structural contribution of the pedicle. Controlled additional cortical engagement may enhance fixation in selected circumstances, particularly in compromised bone; however, current evidence does not demonstrate that uncontrolled cortical violation beyond the intended anatomical boundary provides an independent biomechanical advantage. The distinction between these mechanisms is therefore central to the interpretation of both experimental and clinical evidence.

This review has several limitations. First, the available evidence is heterogeneous and includes cadaveric investigations, synthetic bone models, biomechanical simulations, imaging-based analyses, and predominantly retrospective clinical series. Direct comparison between studies is limited by differences in screw design, vertebral level, insertion trajectory, bone mineral density, breach direction and magnitude, and definitions of cortical engagement and cortical violation. Second, biomechanical studies frequently use axial pull-out strength as their principal endpoint. Although useful for comparative testing, pull-out strength represents a surrogate measure and does not reproduce the multidirectional and cyclic loading experienced by spinal constructs in vivo. Third, evidence regarding controlled bicortical fixation is derived from heterogeneous experimental conditions and is particularly influenced by bone quality, making generalisation to patients with normal bone density inappropriate. Fourth, clinically significant cortical breach is relatively uncommon, and prospective clinical studies specifically designed to determine its independent mechanical consequences are limited. Finally, as a focused narrative rather than systematic review, study selection and interpretation are inherently susceptible to selection bias despite the structured literature search. These limitations preclude definitive quantitative conclusions regarding the magnitude of biomechanical effects and support a cautious interpretation of the available evidence.

## Conclusion

Current evidence does not support uncontrolled cortical violation during pedicle screw placement as a routinely advantageous biomechanical or clinically justifiable fixation strategy. Pedicle screw stability depends on appropriate trajectory, effective bone-implant purchase, and preservation of the structural contribution of the pedicle and vertebral body.

Controlled cortical engagement should be clearly distinguished from cortical breach. In selected circumstances, particularly in compromised or osteoporotic bone, deliberate bicortical engagement may provide additional fixation by increasing purchase in structurally competent cortical bone. This potential advantage reflects controlled cortical support and should not be extrapolated to imply that penetration beyond the intended vertebral boundary is itself beneficial.

The available biomechanical and clinical evidence therefore supports maximising cortical purchase while maintaining precise anatomical control. Cortical violation beyond the intended osseous envelope offers no established independent biomechanical advantage and may expose adjacent neural, vascular, and visceral structures to avoidable risk. Future studies using standardised definitions, physiological cyclic-loading models, and prospective clinical data are required to better define the circumstances in which additional cortical engagement provides a clinically meaningful advantage.

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## Conflicts of interest

The authors declare that there are no conflicts of interest.

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