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Beyond Bankart: A contemporary algorithmic approach to anterior shoulder instability based on glenoid track and bone loss

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A R T I C L E I N F O

Keywords:
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Latarjet
Remplissage
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GTIMS
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A B S T R A C T

Background: Anterior shoulder instability is a prevalent orthopedic condition, particularly in young athletes, where recurrence after soft-tissue repair remains a major challenge. Traditional approaches have been insufficient in addressing cases with bipolar bone loss. The evolution of the glenoid track concept and lesion-specific algorithms has significantly improved surgical decision-making.
Purpose: To provide a comprehensive narrative review of current strategies for managing anterior shoulder instability, with emphasis on the integration of glenoid track analysis, radiographic quantification of bone loss, and an algorithmic approach to guide surgical treatment.
Study design: Narrative review.
Methods: A systematic literature search was conducted across PubMed, Embase, Scopus, and Web of Science (2000–2024). Key topics included glenoid bone loss, Hill-Sachs lesions, glenoid track, Bankart repair, remplissage, Latarjet, and Eden-Hybinette procedures. Articles were included based on clinical relevance, biomechanical contribution, and level of evidence. Emphasis was placed on studies introducing or validating the glenoid track concept and algorithmic decision models.
Results: Lesions were stratified into on-track or off-track categories based on glenoid track calculations. Subcritical glenoid defects (<13.5 %) with on-track lesions were effectively managed with Bankart repair. Off-track lesions and/or borderline bone loss (13.5–20 %) required remplissage or augmentation. Glenoid defects >20 % necessitated bony procedures such as Latarjet or Eden-Hybinette. The proposed algorithm, supported by biomechanical and clinical data, optimizes outcomes by aligning treatment with anatomical pathology. Predictive scores (ISIS, GTIMS) further refine surgical planning.
Conclusion: Personalized treatment of anterior shoulder instability, guided by glenoid track classification and bone loss quantification, represents a paradigm shift from the traditional soft-tissue-only paradigm. This review supports the use of a reproducible algorithmic framework that improves decision-making and outcomes. Future integration of biomechanical simulations and artificial intelligence may further enhance surgical precision.

1. Introduction

Anterior shoulder instability represents a significant clinical burden, particularly in young, active populations. It is the most common form of glenohumeral instability, accounting for over 90 % of all dislocations. The incidence of first-time traumatic anterior dislocations is estimated at approximately 11.2 per 100,000 person-years, with a bimodal distribution affecting predominantly males in their second and sixth decades of life. Athletes engaged in contact or overhead sports face disproportionately higher risks, and recurrence is especially prevalent in those under 20 years old, with reported rates exceeding 70 % following nonoperative management. Beyond its acute impact, anterior instability contributes to long-term sequelae including cartilage damage, labral degeneration, and glenohumeral arthropathy, thereby imposing both

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functional limitations and substantial healthcare costs.[13](see Table 1, Figs. 1–3)

The evolution of our understanding of shoulder instability has paralleled advancements in arthroscopic imaging and biomechanical modeling. The foundational work of Bankart in the early 20th century established the concept that detachment of the anteroinferior labrum from the glenoid rim was the principal lesion underlying recurrent instability. Surgical techniques subsequently centered on anatomical repair of this capsulolabral injury, either via open or arthroscopic means, with generally favorable short-term outcomes.[2–4]

However, despite technically successful Bankart repairs, recurrence persisted in a subset of patients—particularly those with underlying bony defects. This observation prompted a paradigm shift from a purely soft-tissue perspective to an integrated model of *bipolar bone loss*. The Hill-Sachs lesion, first described as a compression fracture of the posterosuperior humeral head following impaction against the glenoid rim, was found to be a critical contributor to engagement and instability. Similarly, anterior glenoid bone loss, particularly when exceeding 20–25 % of the inferior glenoid width, was shown to compromise the glenoid arc and undermine the stability conferred by labral repair alone.[3–5]

To address this complex interplay, Burkhart and De Beer introduced the concept of the *engaging Hill-Sachs lesion*, a biomechanically relevant finding characterized by the alignment of the lesion with the anterior glenoid rim during functional positions of abduction and external rotation. Building upon this, Yamamoto et al. and later Di Giacomo et al. refined the model by proposing the *glenoid track* concept—a dynamic representation of the contact zone between the glenoid and the humeral head during shoulder motion. This framework stratifies Hill-Sachs lesions into *on-track*(contained within the glenoid track and unlikely to engage) and *off-track* (extending medially beyond the glenoid track and prone to engagement), offering a predictive tool for surgical planning.[3–5]

This evolution from the classic Bankart paradigm to a comprehensive assessment of bipolar bone defects has transformed clinical decision-making. Current algorithms now integrate radiographic quantification of glenoid and humeral head bone loss with lesion orientation to guide tailored interventions, including soft-tissue repair, remplissage, and bone augmentation procedures such as the Latarjet or Eden-Hybinette techniques. Such algorithmic precision is critical to reducing failure rates and optimizing long-term outcomes in patients with anterior shoulder instability.[3–6]

2. Methods

This article was designed as a narrative review with the aim of synthesizing and critically analyzing the current evidence on anterior shoulder instability, with a particular focus on bone loss assessment and the application of the glenoid track concept in preoperative decision-making. The review adhered to rigorous methodological standards to ensure comprehensiveness, clinical relevance, and accuracy in reporting.

A comprehensive literature search was performed using multiple electronic databases, including PubMed/MEDLINE, Embase, Scopus, and Web of Science, covering the period from January 2000 to December 2024. Search terms included combinations of the following keywords: *anterior shoulder instability*, *glenoid bone loss*, *Hill-Sachs lesion*, *glenoid track*, *Bankart repair*, *Latarjet procedure*, *remplissage*, and *bone augmentation*. Boolean operators (AND/OR) were applied to optimize search sensitivity and specificity.

Eligible sources included original clinical studies (prospective and retrospective cohorts, case-control series), randomized controlled trials, systematic reviews, biomechanical cadaveric studies, and expert consensus statements. Articles were included if they addressed one or more of the following: pathoanatomy of bipolar bone loss, diagnostic imaging techniques for quantifying osseous defects, biomechanical rationale behind the glenoid track model, surgical planning algorithms incorporating on-track/off-track classification, or indications for augmentation procedures such as Latarjet or Eden-Hybinette. Editorials, narrative commentaries, and publications lacking primary data or technical relevance were excluded.

Two independent reviewers (authors of this manuscript) screened the titles and abstracts for relevance, followed by full-text review. The methodological quality of the selected articles was assessed informally based on study design, sample size, reproducibility of results, and applicability to current clinical practice. Discrepancies in study inclusion were resolved through consensus.

In addition, particular emphasis was placed on landmark publications that have contributed to the evolution of the glenoid track concept and its clinical application, including the foundational work by Yamamoto et al., Burkhart and De Beer, and Di Giacomo et al. These studies were reviewed in depth to elucidate the biomechanical underpinnings and practical utility of the on-track/off-track classification system.

Where applicable, radiographic assessment techniques such as best-fit circle analysis, three-dimensional computed tomography (3D-CT), and magnetic resonance imaging (MRI) protocols were also evaluated. The extracted content was synthesized thematically across five domains:

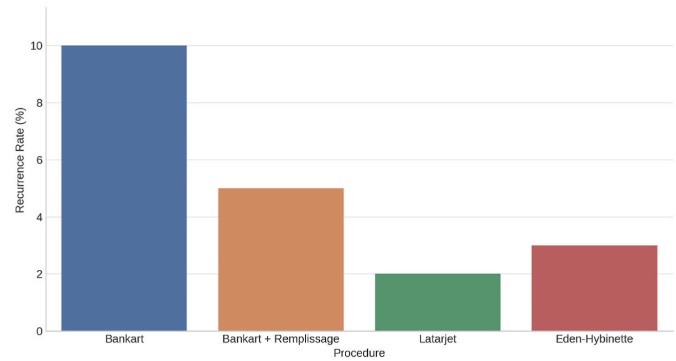

Fig. 1. Recurrence rate by surgical procedure.

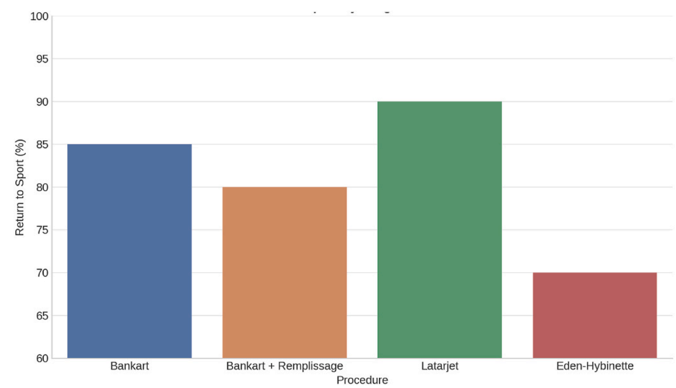

Fig. 2. Return to sport by surgical procedure.

Table 1
Recurrence ratio.

Procedure	Indication	Recurrence Rate (%)	Return to Sport (%)
Bankart	On-track lesion + <20 % glenoid bone loss	10	85
Bankart + Remplissage	Off-track lesion + <20 % glenoid bone loss	5	80
Latarjet	On/Off-track + >20 % glenoid bone loss	2	90
Eden-Hybinette	Revision or severe glenoid defect	3	70

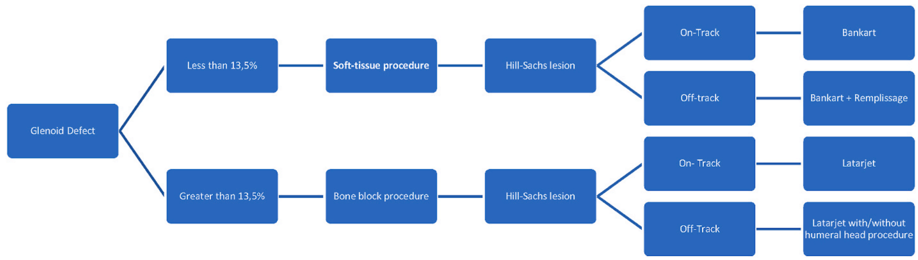

Fig. 3. Algorithm.

epidemiology, imaging and bone loss quantification, pathomechanics, surgical indications, and clinical outcomes.

No attempt was made to perform a meta-analysis, as the heterogeneity of study designs, definitions of instability, and variability in imaging protocols precluded quantitative pooling of data. Rather, this review was structured to provide a clinically oriented synthesis of the most influential evidence to support algorithm-based surgical planning in anterior shoulder instability.

3. Pathoanatomy and imaging

The structural integrity of the glenohumeral joint relies on a delicate balance between static and dynamic stabilizers, including the capsulolabral complex, glenohumeral ligaments, osseous contours, and surrounding musculature. Disruption of any of these elements—particularly following traumatic anterior dislocation—can initiate a cascade of instability that is both biomechanically and clinically significant.[4–6]

4. Capsulolabral lesions

The classic *Bankart lesion*, defined as the avulsion of the anteroinferior labrum with detachment of the inferior glenohumeral ligament complex from the glenoid rim, remains the most frequently encountered soft-tissue injury in anterior shoulder instability. Variants include the *ALPSA lesion* (anterior labroligamentous periosteal sleeve avulsion), in which the labrum is medially displaced but remains attached to an intact periosteum, and the *HAGL lesion* (humeral avulsion of the glenohumeral ligaments), wherein the inferior glenohumeral ligament is avulsed from its humeral insertion. Less commonly, *GLAD lesions* (glenolabral articular disruption) involve labral tears with associated cartilage damage. Each of these lesions alters capsular tension and compromises the concavity-compression mechanism critical for joint stability.[6–8]

5. Osseous lesions

Concomitant bone loss is a pivotal factor in recurrent instability. The *Hill-Sachs lesion*—a posterolateral humeral head compression defect resulting from impaction against the anterior glenoid during dislocation—occurs in up to 90 % of recurrent cases. Anterior glenoid bone loss, especially involving the anteroinferior quadrant, compromises the glenoid arc and directly reduces the containment function of the glenoid fossa. While isolated small defects may not provoke engagement, their combination with a large Hill-Sachs lesion can lead to bipolar bone loss and mechanical failure following standard soft-tissue repair.[6–8]

6. Advanced imaging and bone loss quantification

High-resolution three-dimensional computed tomography (3D-CT) is the gold standard for quantifying osseous defects. It permits precise measurement of glenoid bone loss via the *best-fit circle* method, comparing the injured glenoid to either the contralateral side or an idealized circular model. Glenoid defects exceeding 20–25 % of the inferior diameter are considered critical and warrant bone augmentation. Similarly, 3D-CT allows for characterization of Hill-Sachs lesions in terms of width, depth, volume, and orientation.[9–14]

Magnetic resonance imaging (MRI) and MR arthrography provide superior visualization of soft-tissue pathology, including labral tears, capsular redundancy, and ligamentous elongation. In select cases, MR-based measurement of glenoid bone loss using oblique sagittal images and circle-fit reconstruction has been validated against CT.[10–12]

7. The glenoid track concept

Yamamoto et al. introduced the *glenoid track* concept to reconcile the functional interplay between humeral and glenoid lesions. This model defines a zone of contact on the posterior humeral head that articulates with the glenoid during maximal abduction and external rotation. The width of the glenoid track is calculated as 83 % of the glenoid diameter in an intact glenoid ($GT = 0.83 \times D$). When glenoid bone loss is present, the track narrows proportionally.[10–12]

To assess the potential for engagement, the *Hill-Sachs interval (HSI)* is measured—defined as the distance from the medial margin of the rotator cuff footprint to the medial margin of the Hill-Sachs lesion, including the bone bridge. If HSI exceeds the calculated glenoid track (i.e., $GT < HSI$), the lesion is considered *off-track* and at risk of engaging the anterior glenoid rim during motion. Conversely, an *on-track* lesion remains safely within the glenoid track and is less likely to cause recurrent instability.

This classification has direct surgical implications. On-track lesions with minimal bone loss may be treated with soft-tissue Bankart repair alone. Off-track lesions, particularly when coupled with subcritical or critical glenoid bone loss, often necessitate augmentation procedures such as remplissage or Latarjet to restore containment and prevent engagement.[6,11,12]

Incorporating glenoid track analysis into preoperative planning ensures a biomechanically sound, individualized approach to anterior shoulder instability—one that aligns lesion characteristics with the appropriate surgical strategy to optimize long-term outcomes.[10–12]

8. Surgical planning: The Di Giacomo algorithm

The management of anterior shoulder instability has undergone a significant transformation with the introduction of algorithmic decision-making that incorporates both soft-tissue and osseous pathology. At the forefront of this evolution is the Di Giacomo algorithm, which synthesizes the glenoid track concept with quantification of bipolar bone loss to guide surgical intervention in a structured, reproducible, and biomechanically sound manner.[6,11,16]

9. Stepwise planning framework

The algorithm begins with a thorough clinical evaluation and advanced imaging assessment, followed by step-by-step radiographic analysis:

1. **Quantify Glenoid Bone Loss (GBL):**
   The width of the intact glenoid is estimated using the best-fit circle method on 3D-CT reconstructions. The amount of bone loss (d) is then calculated as a percentage of the estimated original glenoid width (D), using the formula: GBL (%) $= (d/D) \times 100$[6,11,16]
   Defects are categorized as:
   - *Subcritical:* <13.5 % (historically regarded as non-surgical, though recent evidence suggests functional impact).
   - *Borderline:* 13.5–20 % (may compromise stability depending on concurrent lesions).
   - *Critical:* >20–25 % (significantly destabilizing, mandates augmentation).[6,11,16]
2. **Calculate the Glenoid Track (GT):**
   For an intact glenoid, the GT is 83 % of its width. In the presence of bone loss: GT $= 0.83 \times (D - d)$
   This reflects the remaining articular surface available to engage with the humeral head during functional motion.[6,11,16]
3. **Measure the Hill-Sachs Interval (HSI):**
   The HSI includes the width of the Hill-Sachs lesion plus the bone bridge from the rotator cuff insertion to the medial margin of the lesion: HSI = HS width + Bone Bridge
4. Classify the Hill-Sachs Lesion (on-track vs. off-track):
   - *On-track:* GT ≥ HSI → lesion is contained and unlikely to engage.
   - *Off-track:* GT < HSI → lesion exceeds glenoid coverage and poses engagement risk.

This classification dictates whether a soft-tissue-only repair is sufficient or whether bone augmentation is necessary.[6,11,16]

10. Surgical implications based on algorithm

The Di Giacomo algorithm branches into treatment pathways based on lesion classification:

- **On-Track + Subcritical GBL (<13.5–17 %):**
  Isolated Bankart repair is typically sufficient. The capsulolabral complex is restored without additional procedures.[6,11,16]
- **On-Track + Borderline GBL (13.5–20 %):**
  Bankart ± remplissage depending on capsular laxity, sport demands, and recurrence risk. High-demand athletes may benefit from reinforcement even in the absence of engagement.[6,11,16]
- **Off-Track + Subcritical or Borderline GBL:**
  Bankart + remplissage is recommended to convert the off-track Hill-Sachs into an on-track configuration, effectively neutralizing engagement risk.[6,11,16]
- **Off-Track + Critical GBL (>20–25 %):**
  Bony procedure required: either a Latarjet, which augments the glenoid with a coracoid graft and reinforces the anteroinferior capsule, or Eden-Hybinette in revision or failed Latarjet cases. These procedures restore glenoid concavity and re-establish the glenoid track.[6,11,16]
- **Combined Severe Bipolar Bone Loss:**
  May require both Latarjet + remplissage, particularly in contact athletes or patients with highly unstable shoulders.[6,11,16]

11. Clinical value

This algorithmic framework provides a personalized surgical roadmap, minimizes recurrence, and avoids overtreatment. It empowers the surgeon to match pathology with the least invasive yet most biomechanically stable technique available. Studies have shown that applying this approach reduces graft failure, enhances return-to-play rates, and improves long-term shoulder function.

Importantly, the Di Giacomo algorithm is not static—it is adaptable based on evolving patient factors, intraoperative findings, and future biomechanical insights. Its adoption represents a milestone in precision surgery for shoulder instability.[10–12]

12. Reinforcement techniques beyond Bankart

While isolated Bankart repair remains the cornerstone for managing anterior shoulder instability in the absence of significant bone loss, the recurrence rates in select patient populations have highlighted the need for augmentation procedures. These reinforcement techniques aim to address the biomechanical shortcomings of soft-tissue repair alone, particularly in cases involving off-track Hill-Sachs lesions, borderline or critical glenoid bone loss, or high-demand functional requirements.[13–16]

13. Remplissage

13.1. Indications

Remplissage is indicated in patients with off-track Hill-Sachs lesions and subcritical (<20 %) or borderline glenoid bone loss. It is most effective when the humeral defect poses an engagement risk but the glenoid architecture remains largely preserved. This procedure is commonly employed in young athletes, especially those participating in collision or overhead sports, where restoration of joint stability is paramount.[16–18]

13.2. Technique

Remplissage involves posterior capsulotenodesis of the infraspinatus tendon and posterior capsule into the Hill-Sachs defect via arthroscopic suture anchors. This converts an engaging lesion into a non-engaging one by effectively “filling in" the defect and limiting its articulation with the anterior glenoid.[16–18]

13.3. Biomechanical evidence

Biomechanical studies have demonstrated that remplissage significantly increases the force required for dislocation and decreases humeral head translation in off-track shoulders. It restores humeral containment without the need for bone grafting and avoids compromising the subscapularis or anterior capsule.[16–18]

13.4. Clinical outcomes

Clinical series have reported excellent recurrence rates, with instability recurrence as low as 5–7 %. While a mild restriction in external rotation may be observed postoperatively, particularly in overhead athletes, patient-reported outcomes remain favorable, with high rates of return to sport.[18–20]

14. Latarjet procedure

14.1. Indications

The Latarjet procedure is indicated in cases of critical glenoid bone loss (>20–25 %), failed soft-tissue stabilization, or persistent instability in high-risk patients with an off-track Hill-Sachs lesion and glenoid insufficiency. It is also recommended when the instability severity index score (ISIS) is elevated (≥6), reflecting multiple risk factors for failure of Bankart repair.[20,36]

14.2. Technique

The procedure involves transfer of the coracoid process, along with the attached conjoined tendon, to the anteroinferior glenoid. This achieves a triple-blocking effect: (1) bony augmentation of the glenoid arc, (2) dynamic stabilization via the sling effect of the conjoined tendon, and (3) capsular reinforcement.[20,36]

14.3. Biomechanical evidence

Cadaveric and finite element analyses confirm that the Latarjet procedure significantly restores anterior stability, even in shoulders with large bipolar defects. It increases the contact area between the glenoid and the humeral head, thereby redistributing joint forces and preventing engagement of Hill-Sachs lesions.[20,36]

14.4. Clinical outcomes

Multiple long-term series report high success rates, with stability restored in over 95 % of cases. Return to play is typically achieved within 4–6 months. Although complications such as graft osteolysis, nonunion, or neurologic injury have been described, modern refinements in technique have reduced their incidence. Functional scores remain high, particularly in athletes.[20,36]

15. Eden-Hybinette procedure

15.1. Indications

This procedure is reserved for revision cases following failed Latarjet, poor-quality coracoid graft, or when the glenoid bone loss is so extensive that additional augmentation is required. It is also employed in patients with epilepsy or hyperlaxity, where recurrent instability has destroyed the anterior glenoid rim.[20–22]

15.2. Technique

The Eden-Hybinette procedure involves free bone block augmentation using autograft (iliac crest) or allograft (distal tibia) to reconstruct the anterior glenoid. The graft is secured with screws or buttons, and may be performed open or arthroscopically.[20–22]

15.3. Biomechanical evidence

The procedure effectively reconstructs the glenoid arc and is biomechanically comparable to the Latarjet in terms of contact pressure and glenohumeral stability. It allows for customization of graft size and contour to match the native anatomy.[20–22]

15.4. Clinical outcomes

Though limited by smaller series, available data show reliable mid-to long-term stability, particularly in revision settings. The procedure avoids the need for coracoid harvest, preserving deltopectoral anatomy. Functional outcomes are generally positive, though return to sport may be more variable due to the complexity of the underlying pathology.[20–22]

Together, these reinforcement techniques extend the armamentarium beyond the Bankart repair, allowing the surgeon to match the patient's anatomical and functional profile with the most appropriate intervention. The careful application of biomechanical principles—guided by imaging and algorithmic planning—has redefined the standard of care in anterior shoulder instability.[20–22]

16. Open vs. arthroscopic approach

The evolution of surgical management for anterior shoulder instability has paralleled advances in arthroscopic instrumentation, imaging, and fixation techniques. Over the past two decades, arthroscopic repair has become the dominant approach, favored for its minimally invasive nature, superior visualization of intra-articular pathology, and reduced morbidity. However, the choice between arthroscopic and open techniques must be individualized, particularly in the context of bone loss, lesion complexity, and revision scenarios.[22–24]

17. Evidence from the literature

Randomized and comparative cohort studies have demonstrated that arthroscopic Bankart repair yields comparable outcomes to open stabilization in select populations with isolated soft-tissue lesions and minimal bone loss. Reported redislocation rates after arthroscopic repair in appropriately selected patients range from 5 % to 15 %, with consistently high functional outcome scores and rapid return to activity.

Nonetheless, meta-analyses have indicated higher recurrence rates in high-risk populations—particularly young, male, contact athletes—when treated with arthroscopic Bankart repair alone. In these cases, failure is often attributed not to technical error, but to unrecognized or undertreated osseous pathology. As such, reliance on arthroscopy without thorough radiographic assessment may underestimate the extent of glenoid or humeral bone loss, leading to suboptimal outcomes.[24–27]

The open Latarjet procedure, in contrast, has shown superior stability in patients with critical glenoid bone loss or off-track Hill-Sachs lesions. Several systematic reviews have confirmed lower recurrence rates and higher return-to-sport levels in patients undergoing open bone block procedures compared to arthroscopic soft-tissue repair. Moreover, the Latarjet's dynamic sling effect adds an element of muscular stabilization that is particularly beneficial in athletes with multidirectional stress on the joint.

Arthroscopic Latarjet, while technically demanding, has emerged as a hybrid alternative, offering the advantages of minimally invasive access with bone augmentation. Early results show promising outcomes comparable to the open technique, though operative times, learning curves, and complication profiles remain areas of active research.[26,27]

18. Indications for open approach

Open stabilization should be strongly considered in the following scenarios:

- **Critical Glenoid Bone Loss (>20–25 %)**: Open Latarjet or Eden-Hybinette procedures are preferred to restore glenoid arc and stability. 26-28
- **Off-Track Hill-Sachs Lesion with Concomitant Glenoid Defect**: Open procedures permit graft placement with direct visualization and may be combined with remplissage if required. 26-28
- **Failed Prior Arthroscopic Repair**: Revision cases, especially with bone loss or scarring, often necessitate open access for adequate mobilization and reconstruction. 26-28
- **Hyperlaxity or Epileptic Shoulder Instability**: These patients benefit from robust bone block procedures which are more reliably executed through an open approach. 26-28
- **Severe Capsular Redundancy or Poor Tissue Quality**: Open capsular shift and anterior plication allow for precise tensioning under direct control.

In summary, while arthroscopic repair offers substantial benefits in selected cases, the open approach retains a critical role in managing complex or revision scenarios, particularly when bony architecture is compromised. An evidence-based, lesion-specific strategy—guided by glenoid track classification and radiographic bone loss—ensures optimal selection between techniques. Ultimately, the surgeon's experience with both approaches remains essential to achieving durable outcomes tailored to the individual patient.[26–28]

19. Risk factors for failure and recurrence

Despite advances in imaging, surgical technique, and rehabilitation protocols, a subset of patients continues to experience recurrent instability following anterior shoulder stabilization. Identification and stratification of risk factors for failure are essential to guide surgical decision-making, optimize treatment selection, and counsel patients appropriately.[28–30]

20. Patient-specific risk factors

- **Age at First Dislocation:**
  Age is one of the most powerful predictors of recurrence. Patients under 20 years of age at the time of their first dislocation exhibit recurrence rates exceeding 70 % when treated conservatively, and up to 25 % even after arthroscopic Bankart repair. This has been attributed to high ligamentous laxity, immature capsular healing response, and greater exposure to high-risk activities.[28–30]
- **Ligamentous Laxity and Generalized Hypermobility:**
  Increased capsular elasticity and joint laxity reduce the efficacy of soft-tissue repair alone. In these individuals, even a technically sound capsulolabral reconstruction may fail under functional loads due to insufficient passive restraint. Objective measures of hypermobility, such as the Beighton score, may assist in preoperative identification.[16,18,30]
- **Contact and Overhead Sports Participation:**
  Athletes engaged in collision sports (e.g., rugby, football, martial arts) or repetitive overhead motions (e.g., baseball, volleyball) are exposed to forces that exceed the threshold for soft-tissue repair. Recurrence and failure rates in this population are consistently higher unless augmentation techniques are employed, even in the absence of overt bone loss.[12,16,30]
- **Previous Surgery and Failed Stabilization:**
  Revision cases carry an inherently higher risk due to altered anatomy, scarred or deficient capsulolabral tissue, and unaddressed bony defects. Careful re-evaluation with advanced imaging and consideration of bone-block procedures is imperative in this setting.[20,30]

21. Predictive scoring systems

To better stratify patients at risk for failure, several preoperative scoring systems have been developed:

- **Instability Severity Index Score (ISIS):**
  Introduced by Balg and Boileau, the ISIS is a six-point score incorporating patient age, degree of sports participation, type of sport, shoulder hyperlaxity, and radiographic findings of Hill-Sachs and glenoid bone loss. A score ≥ 6 is associated with a significantly increased risk of recurrence after arthroscopic Bankart repair, and typically warrants consideration of a Latarjet or other augmentation procedure.[18,31]
- **Glenoid Track Instability Management Score (GTIMS):**
  This recently proposed modification integrates the glenoid track concept into preoperative assessment. It considers radiographic measurements of glenoid bone loss and Hill-Sachs engagement status to guide treatment selection. GTIMS enhances the predictive accuracy of ISIS by incorporating objective imaging-based thresholds, effectively bridging biomechanical principles with clinical decision-making.[18,31]

22. Combined risk profiles and surgical implications

Patients exhibiting multiple risk factors—such as a young athlete with an off-track lesion and borderline glenoid bone loss—represent a high-risk phenotype that frequently necessitates reinforcement beyond isolated labral repair. Recognition of these cumulative risks is crucial to avoid under-treatment and to reduce the likelihood of graft failure, persistent instability, or premature return to surgery.

A structured preoperative evaluation incorporating both clinical parameters and advanced imaging stratification tools allows for a tailored approach to stabilization. When used appropriately, tools such as ISIS and GTIMS support algorithm-based surgical planning and have been shown to correlate with improved outcomes and lower recurrence rates across diverse patient populations.[18,31]

23. Treatment algorithm (Diagram)

The incorporation of structured algorithms into the surgical planning of anterior shoulder instability represents a pivotal advance in precision medicine. As our understanding of bipolar bone loss and its biomechanical implications has evolved, so too has the need for standardized, evidence-based decision-making tools. The treatment algorithm presented here synthesizes the glenoid track classification, quantitative bone loss assessment, and lesion-specific surgical indications into a streamlined clinical framework.[32–34]

The algorithm begins with the identification of recurrent anterior shoulder instability, prompting comprehensive imaging with high-resolution 3D computed tomography and/or magnetic resonance arthrography. These modalities enable accurate quantification of glenoid bone loss and characterization of Hill-Sachs lesions in terms of size, orientation, and engagement potential.[32–34]

The first branching point in the algorithm is the evaluation of glenoid bone loss. If the osseous defect is less than 20 % of the glenoid width, the case is classified as subcritical, and soft-tissue stabilization may suffice. If the defect exceeds 20–25 %, it is considered critical, and bony augmentation—typically via a Latarjet or Eden-Hybinette procedure—is indicated to restore the articular arc and prevent further instability.[32–34]

Subsequently, the Hill-Sachs lesion is assessed through the lens of the glenoid track concept. The lesion is classified as either on-track (contained within the glenoid track) or off-track (extending medially beyond the track). This classification directly informs the surgical approach:

- In patients with subcritical glenoid loss and an on-track lesion, an isolated Bankart repair is typically sufficient.
- In those with subcritical glenoid loss but an off-track lesion, a Bankart repair combined with remplissage is recommended to address the humeral defect and prevent engagement.
- In the presence of critical glenoid bone loss with an on-track Hill-Sachs lesion, a Latarjet procedure is generally performed, as it both reconstructs the anterior glenoid and provides a dynamic sling effect via the conjoined tendon.
- When both glenoid loss is critical and the Hill-Sachs lesion is off-track, a Latarjet procedure with or without a concomitant humeral head procedure (such as remplissage or allograft reconstruction) is required, depending on the extent of the humeral defect and its biomechanical impact.[32–35]

This decision tree is further enhanced through integration with clinical tools such as the Instability Severity Index Score (ISIS) and the Glenoid Track Instability Management Score (GTIMS), which stratify patients based on demographic, activity-related, and radiographic risk factors. When used in conjunction with this algorithm, these tools improve surgical planning and support individualized treatment strategies.

The algorithm's visual format facilitates rapid interpretation and intraoperative utility, serving as both a teaching tool and a surgical roadmap. Its adoption in clinical practice has been associated with reduced recurrence rates, improved functional outcomes, and greater reproducibility of treatment results across diverse surgical teams.

Ultimately, the algorithmic approach to anterior shoulder instability integrates modern imaging, biomechanical modeling, and risk stratification into a unified platform for decision-making—transforming complex pathology into predictable and personalized care.[32–35]

24. Discussion

The management of anterior shoulder instability has undergone a paradigm shift in the past two decades, transitioning from a one-sizefits-all approach based on Bankart repair to a nuanced, anatomy-specific strategy guided by the quantification of bone loss and the glenoid track concept. This evolution has enabled surgeons to more accurately stratify patients based on biomechanical risk and to tailor interventions that address the true etiology of recurrent instability.[36–38]

A key insight driving this change is the recognition that soft-tissue repair alone is insufficient in the presence of significant osseous defects. Numerous biomechanical and clinical studies have demonstrated that glenoid bone loss >20–25 % or off-track Hill-Sachs lesions independently compromise shoulder stability and are associated with high recurrence rates following isolated Bankart repair. The Di Giacomo algorithm and its modifications provide a practical, reproducible framework for integrating these variables into surgical planning. By systematically evaluating glenoid bone loss and Hill-Sachs engagement status, surgeons can confidently determine when to proceed with augmentation procedures such as remplissage, Latarjet, or Eden-Hybinette.

The data supporting remplissage are compelling, particularly in patients with off-track lesions and preserved glenoid anatomy. This arthroscopic technique is minimally invasive and effectively converts an engaging defect into a non-engaging one, often without sacrificing range of motion or return to sport. Similarly, the Latarjet procedure has become the gold standard for treating instability with critical bone loss, with multiple long-term series confirming its biomechanical efficacy and clinical durability. While technically demanding, especially when performed arthroscopically, its utility in high-demand athletes and revision cases is well established.[38–40]

Our proposed treatment algorithm synthesizes this evidence into a structured decision-making pathway that reflects both radiographic precision and clinical judgment. Importantly, the algorithm accounts not only for the size of the defects but also for their interplay, as captured by the glenoid track classification. This is crucial in cases of bipolar bone loss, where the cumulative effect of glenoid and humeral defects exceeds the threshold for stability even if each lesion appears borderline in isolation.

Despite its strengths, the algorithm must be applied with awareness of patient-specific factors that can influence outcomes. Age, ligamentous laxity, sport-specific demands, and previous surgical history all modulate the risk of recurrence and may necessitate modification of the standard pathway. The integration of predictive tools such as the Instability Severity Index Score (ISIS) and Glenoid Track Instability Management Score (GTIMS) into preoperative assessment further enhances the personalization of care.

Limitations of this approach include variability in imaging quality and interpretation, as well as the absence of universally agreed-upon thresholds for what constitutes “subcritical" bone loss. Moreover, while the glenoid track model provides a useful biomechanical framework, it does not account for all dynamic factors affecting shoulder stability, such as capsular quality, proprioception, and neuromuscular control.[40–44]

In summary, the contemporary management of anterior shoulder instability demands a comprehensive approach that integrates radiographic assessment, biomechanical classification, and patient-specific risk stratification. The algorithm presented in this review offers a practical and clinically validated framework that can improve decision-making, reduce recurrence, and enhance functional outcomes. Future research should focus on refining the thresholds for intervention, validating algorithmic pathways prospectively, and incorporating emerging technologies such as machine learning and intraoperative navigation into the treatment paradigm.[44–48]

25. Conclusions

The surgical treatment of anterior shoulder instability has progressed from a uniform soft-tissue repair paradigm to a highly individualized, biomechanically informed approach. The integration of radiographic quantification of bone loss and the glenoid track concept into preoperative planning has enabled orthopedic surgeons to tailor interventions based on the unique anatomical and functional demands of each patient. This precision-guided model enhances surgical outcomes, minimizes recurrence, and aligns treatment with the specific risk profile of the individual.

Personalized planning is no longer optional—it is essential. The success of any stabilization procedure hinges on the surgeon’s ability to synthesize imaging data, classify lesions accurately, and anticipate mechanical failure points before they manifest clinically. The algorithmic framework presented in this review provides a clear and reproducible pathway for surgical decision-making that balances anatomical pathology with clinical risk stratification.

Looking forward, emerging technologies promise to further revolutionize this field. Artificial intelligence (AI) and machine learning models may enhance diagnostic accuracy by automating measurements of glenoid and humeral bone loss and predicting lesion behavior under dynamic conditions. Similarly, biomechanical simulations based on patient-specific imaging could allow surgeons to test surgical scenarios preoperatively—virtually evaluating the effect of different interventions on joint stability and load distribution.

As we move toward a more data-driven era in orthopedic surgery, the fusion of clinical expertise, biomechanical modeling, and intelligent systems will be pivotal in refining treatment algorithms and improving patient outcomes. Personalized, predictive, and precise medicine is not only the future—it is the new standard.

Ethical statement

This study was approved by the clinica arthros (ARTC No. 0036)

All procedures were performed in accordance with the ethical standards of the 1964 Helsinki Declaration and its later amendments.

Patient data were handled confidentially and anonymized before analysis to ensure privacy and compliance with institutional and international research ethics standards.

CRediT author statement

Edgar Barros: Conceptualization, Methodology, Supervision, Validation, Critical revision of the manuscript.

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Carlos Peñaherrera-Carrillo: Literature review, Validation, Manuscript editing.

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Declaration of competing interest

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