10.48047/jocaaa.2024.33.06.83

Biomechanical and Anatomical Foundations of Dynamic Anterior Stabilization Techniques in Anterior Shoulder Instability: Current Concepts and Future Directions

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ABSTRACT

Background: Anterior shoulder instability remains a significant clinical challenge, particularly among young, active individuals and athletes. Traditional static stabilization procedures—such as arthroscopic Bankart repair or the Latarjet procedure—are associated with distinct limitations, especially in cases of subcritical bone loss or when optimizing dynamic function is crucial. Over the past decade, a deeper understanding of glenohumeral joint biomechanics and the functional anatomy of dynamic stabilizers, including the long head of the biceps tendon, has catalyzed the development of novel dynamic anterior stabilization techniques. These techniques aim not only to restore structural integrity but also to replicate or enhance the physiological sling effect, offering potential improvements in functional stability and joint preservation. This review synthesizes current knowledge on the anatomical and biomechanical underpinnings of the glenohumeral joint relevant to dynamic stabilization, details the evolution and principles of dynamic anterior stabilization procedures, and discusses the rationale for their application in anterior instability. Recent biomechanical and preclinical studies are examined, comparing dynamic stabilization approaches with traditional static techniques. Additionally, this review highlights current gaps in evidence, limitations of existing procedures, and emerging directions for future research, including advanced surgical strategies and individualized patient selection. By clarifying the foundational principles and emerging innovations, this article aims to inform clinical practice and stimulate further investigation into optimizing outcomes for patients with anterior shoulder instability..

Keywords*: Biomechanical and Anatomical Foundations , Anterior Stabilization Techniques, Anterior Shoulder Instability*

Introduction

Anterior shoulder instability is one of the most common problems encountered in orthopedic sports medicine, frequently affecting young, active populations and athletes [1]. Despite advances in surgical techniques, recurrence and persistent instability remain substantial concerns, particularly in the context of high-demand activities or underlying anatomic risk factors [2,3]. Traditionally, management

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strategies have focused on static stabilization techniques, such as the Bankart repair or Latarjet procedure, which restore or reinforce the structural integrity of the anterior glenoid and capsulolabral complex [4,5]. However, these approaches may not address the dynamic, functional demands placed on the glenohumeral joint during everyday and athletic movements, nor do they always replicate the physiological mechanisms that contribute to shoulder stability [6].

Recent advances in our understanding of shoulder biomechanics have highlighted the critical role of dynamic stabilizers—including the rotator cuff, periscapular muscles, and the long head of the biceps tendon—in maintaining glenohumeral stability, particularly in positions of abduction and external rotation [7,8]. The evolution of dynamic anterior stabilization techniques reflects a paradigm shift, emphasizing restoration of normal functional anatomy and biomechanics alongside traditional static repair [9]. Techniques such as dynamic anterior stabilization using the long head of the biceps tendon have shown promise in replicating the so-called "sling effect," potentially reducing the risk of recurrence, preserving native anatomy, and allowing for earlier rehabilitation [10,11].

This review article aims to comprehensively synthesize the anatomical and biomechanical foundations underlying these dynamic stabilization strategies, explore their surgical rationale, and highlight the current concepts and future directions in their clinical application. By bridging fundamental scientific principles with evolving surgical techniques, we seek to provide clinicians and researchers with an integrated perspective to inform best practices and stimulate further inquiry in this rapidly developing field [12].

Anatomy of the Glenohumeral Joint

The glenohumeral joint is the most mobile joint in the human body, permitting a wide range of motion at the expense of intrinsic stability [13]. The osseous architecture consists of the humeral head and the shallow, pear-shaped glenoid fossa of the scapula, providing only about one-third coverage of the humeral head and inherently predisposing the joint to instability [14]. The glenoid is deepened and broadened by the fibrocartilaginous labrum, which acts as both a chock-block to translation and an attachment site for the joint capsule and glenohumeral ligaments [15,16].

Stability of the joint is achieved through the interplay of static and dynamic stabilizers. The static stabilizers include the bony congruity, the labrum, the capsule, and the glenohumeral ligaments, each providing restraint to translation in specific ranges of motion and positions [17]. Notably, the inferior glenohumeral ligament complex (IGHL) is particularly critical in preventing anterior dislocation when the arm is abducted and externally rotated [18].

Dynamic stabilizers, including the rotator cuff muscles, the long head of the biceps tendon, and the periscapular musculature, contribute to joint stability by actively centering the humeral head within the glenoid during movement. The coordinated activation of these muscles generates a compressive

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force across the joint and resists translation in the presence of external stress [19]. The functional anatomy and synergy between these static and dynamic elements are essential for understanding both the mechanisms of instability and the rationale for advanced stabilization techniques [20].

Passive Stabilizers of the Glenohumeral Joint

The passive stabilizers of the glenohumeral joint consist of non-contractile structures that contribute to maintaining joint congruity and resisting translation, particularly at the extremes of motion. The primary passive stabilizers include the osseous structures (glenoid and humeral head), the glenoid labrum, the joint capsule, and the glenohumeral ligaments [21].

The glenoid labrum is a fibrocartilaginous rim that deepens the articular surface of the glenoid, enhancing stability by increasing the surface area and acting as a buttress against humeral head translation. The integrity of the labrum is vital; detachment or injury, as seen in Bankart lesions, significantly compromises joint stability and is a hallmark of traumatic anterior dislocation [22,23]. The joint capsule envelops the glenohumeral articulation and provides additional restraint through its anteroinferior thickening, which forms the glenohumeral ligaments.

Among these, the inferior glenohumeral ligament complex (IGHL) is the most important static stabilizer against anterior and inferior displacement, especially when the arm is abducted and externally rotated. The middle and superior glenohumeral ligaments contribute to stability in midrange positions, and variations in their development can influence individual predisposition to instability [24]. The concavity-compression effect, generated by the labrum and the negative intra-articular pressure of the capsule, also plays a significant role in passive stability, acting to "suction" the humeral head into the glenoid fossa [25].

In cases of traumatic dislocation or repetitive microtrauma, injury or attenuation of these passive stabilizers increases reliance on dynamic mechanisms to maintain joint stability. Understanding the interplay between passive and dynamic stabilizers is crucial for tailoring surgical strategies, especially when considering techniques designed to restore or augment deficient static restraints [26].

Dynamic Stabilizers of the Shoulder

Dynamic stabilizers are the contractile structures that actively maintain glenohumeral joint stability, particularly during motion and functional loading. Chief among these are the rotator cuff muscles—supraspinatus, infraspinatus, teres minor, and subscapularis—which envelop the humeral head and provide a compressive “squeezing” force that keeps the humeral head centered within the glenoid throughout a wide range of movements [27]. Their coordinated contraction is essential for balancing forces and preventing excessive translation, especially during abduction and external rotation.

The long head of the biceps tendon (LHBT) is another critical dynamic stabilizer. Originating from the supraglenoid tubercle and the superior labrum, it traverses the bicipital groove before entering the arm.

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During overhead activities and positions of abduction and external rotation, the LHBT acts as a humeral head depressor and resists anterior translation, particularly when the static restraints are compromised [28,29]. This unique positioning and tensioning ability have formed the foundation for its use in novel stabilization techniques.

In addition to the rotator cuff and LHBT, the periscapular muscles—including the trapezius, serratus anterior, rhomboids, and levator scapulae—contribute indirectly by maintaining scapular positioning and optimizing glenoid orientation. Efficient scapulothoracic motion is fundamental for shoulder function and stability, as dyskinesis can alter glenohumeral biomechanics and predispose to instability episodes [30].

Dynamic muscle control is not only important in preventing acute dislocations but also in mitigating microinstability during repetitive athletic movements. Loss of muscle coordination, fatigue, or injury can tip the balance toward instability, especially in patients with anatomical deficits or prior capsulolabral injury. Rehabilitation protocols targeting these dynamic stabilizers are a mainstay in both non-operative and post-surgical management of anterior shoulder instability [31].

Anatomy and Biomechanics of the Long Head of the Biceps Tendon in Shoulder Instability

The long head of the biceps tendon (LHBT) originates from the supraglenoid tubercle and the superior aspect of the glenoid labrum, blending with the superior labral fibers and extending intra-articularly before exiting through the bicipital groove of the humerus [32]. This unique anatomical course allows the LHBT to play a dual role in shoulder stability, functioning both as a secondary static restraint and a dynamic stabilizer, particularly during abduction and external rotation.

Biomechanically, the LHBT contributes to anterior stability by resisting anterior and superior translation of the humeral head, especially when the capsulolabral complex is deficient or compromised [33]. Electromyographic and cadaveric studies have shown that tensioning of the LHBT increases resistance to anterior translation in simulated positions of instability, underscoring its role as a functional “sling” during overhead and throwing activities [34]. Furthermore, the LHBT acts synergistically with the rotator cuff and deltoid muscles to center the humeral head within the glenoid, contributing to the overall compressive force that stabilizes the joint.

In cases of anterior shoulder instability, injury to the LHBT or its attachment may compromise this dynamic stabilizing effect, further predisposing to recurrent dislocation or subluxation. Conversely, surgical techniques that utilize the LHBT, such as dynamic anterior stabilization procedures, aim to replicate or enhance its native biomechanical function, thereby restoring a critical element of physiological stability [35].

Recognition of the LHBT’s anatomical and biomechanical contributions has spurred the development of new strategies for addressing anterior instability, particularly in scenarios where traditional static

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repairs may be insufficient or when subcritical bone loss is present. Understanding these principles is fundamental for appreciating the rationale behind emerging dynamic stabilization procedures [36].

Pathomechanics of Anterior Shoulder Instability

Anterior shoulder instability arises from a disruption in the delicate balance between static and dynamic stabilizers of the glenohumeral joint, leading to excessive translation or displacement of the humeral head relative to the glenoid. This instability most commonly results from traumatic events, such as a fall or direct blow to the arm in an abducted and externally rotated position, which can cause detachment of the anterior-inferior labrum (Bankart lesion), capsular stretching, and, in severe cases, osseous injury to the glenoid or humeral head (Hill-Sachs lesion) [37,38].

While traumatic injuries are the predominant cause, atraumatic instability may develop in the setting of generalized ligamentous laxity, repetitive microtrauma, or abnormal glenoid morphology, each of which can weaken the passive restraints and increase reliance on dynamic stabilizers for joint stability [39]. The extent of bone loss on the glenoid or humeral side is now recognized as a critical factor in both the risk of recurrence and the selection of appropriate surgical intervention. Even “subcritical” bone loss, previously considered insignificant, has been shown to adversely affect the success rates of traditional soft tissue repairs [40].

Biomechanically, instability is characterized by loss of the concavity-compression effect, failure of the capsulolabral complex to provide an adequate bumper, and disruption of the sling effect produced by the inferior glenohumeral ligament and the long head of the biceps tendon. As these static and dynamic stabilizers fail, the humeral head is permitted to sublux or dislocate anteriorly, particularly during activities involving overhead or forceful external rotation [41].

Understanding the pathomechanics of anterior shoulder instability is fundamental for developing and refining surgical strategies. Recent emphasis has shifted toward restoring both structural and functional stabilizers, with the aim of recreating the natural biomechanics of the shoulder. Dynamic anterior stabilization techniques seek to harness the patient’s own anatomy, particularly the long head of the biceps, to re-establish the sling effect and optimize functional stability in cases where traditional approaches may fall short [42].

Biomechanics of Dynamic Anterior Stabilization

Dynamic anterior stabilization techniques are designed to harness the functional contribution of native anatomical structures, primarily the long head of the biceps tendon (LHBT), to restore physiological stability to the anterior shoulder. Unlike static repairs that depend solely on capsulolabral reconstruction or bony augmentation, dynamic methods seek to replicate or enhance the "sling effect," wherein the transferred or tensioned LHBT acts as a dynamic restraint to anterior translation of the humeral head, particularly during positions of abduction and external rotation [43].

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Biomechanical studies have demonstrated that the LHBT, when rerouted or anchored in the anterior glenoid region, can significantly increase resistance to anterior displacement, mimicking the function of the native capsulolabral complex and the inferior glenohumeral ligament. This dynamic restraint is responsive to muscle activation and joint position, offering a more physiological stabilization mechanism that adapts to the demands of various activities [44]. In addition, the augmented sling effect helps maintain compressive forces across the glenohumeral joint, improving joint congruity and reducing the risk of redislocation.

Comparative cadaveric research has shown that dynamic anterior stabilization provides similar or even superior control of anterior translation compared to traditional Bankart repair, particularly in the presence of subcritical bone loss where static repairs are prone to failure. Furthermore, by utilizing the patient's own tendon tissue, these techniques may reduce the risk of graft-related complications and avoid alteration of glenoid or humeral anatomy, preserving options for future revision procedures if needed [45].

The biomechanical rationale behind dynamic anterior stabilization extends to optimizing the balance between mobility and stability, with the goal of restoring near-normal shoulder kinematics while minimizing restrictions on range of motion. This principle has driven the innovation of multiple arthroscopic techniques that incorporate dynamic elements, emphasizing individualized, anatomic reconstruction over rigid fixation [46].

Indications for Dynamic Anterior Stabilization

Dynamic anterior stabilization (DAS) has emerged as a valuable option in the surgical management of anterior shoulder instability, particularly for select patient populations where traditional techniques may be insufficient or overly invasive. The most widely accepted indication for DAS is the presence of recurrent anterior instability in the setting of "subcritical" glenoid bone loss—generally defined as bone loss less than 20-25% of the glenoid width—where Bankart repair alone may have a higher failure rate, but bony augmentation with Latarjet is not yet warranted [47].

DAS is especially considered in young, athletic individuals who demand both stability and preservation of normal shoulder kinematics. It is also indicated in cases where patients have poor capsulolabral tissue quality, failed previous Bankart repair, or exhibit dynamic instability due to deficient dynamic stabilizers. Patients with engaging Hill-Sachs lesions but without significant glenoid bone loss may benefit from DAS, particularly when combined with other soft tissue or remplissage procedures [48].

Relative contraindications include cases of critical glenoid bone loss (>25%), significant humeral bone defects, generalized ligamentous laxity, or irreparable rotator cuff pathology, where dynamic procedures may not provide adequate stability. Additionally, chronic dislocations or patients with poor

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tendon quality may not be ideal candidates, as the effectiveness of the dynamic sling effect relies on the integrity and function of the transferred or rerouted long head of the biceps tendon [49].

Careful preoperative assessment is essential to determine candidacy for DAS, including advanced imaging to quantify bone loss, evaluate labral and capsular integrity, and assess the condition of the LHBT. Patient-specific factors, such as activity level, sport participation, and expectations, should also be considered in the decision-making process. The selection criteria continue to evolve as clinical experience and evidence accumulate, with ongoing research aimed at refining indications and optimizing patient outcomes [50].

Quantification Methods for Glenoid Bone Loss

Accurate assessment of glenoid bone loss is critical in the management of anterior shoulder instability, as it directly influences the choice of surgical technique and the likelihood of recurrent instability. Several imaging modalities and quantification methods have been developed to evaluate the extent of glenoid bone deficiency. Conventional radiographs provide a basic overview, but advanced imaging—particularly three-dimensional computed tomography (3D-CT)—offers superior accuracy and reproducibility in quantifying both the location and percentage of bone loss [51].

The “best-fit circle” method on en face 3D-CT images is widely accepted for estimating glenoid bone loss. This approach involves constructing a circle to match the inferior glenoid contour and calculating the area or width of the defect relative to the intact glenoid. Studies have shown that this technique correlates well with intraoperative findings and has become the standard for preoperative planning [52]. Alternative methods, such as the PICO method and the measurement of glenoid track, have also been described, providing clinicians with multiple options to tailor assessment based on available imaging and surgeon preference [53].

Magnetic resonance imaging (MRI) is valuable for assessing associated soft tissue pathology but is less reliable than CT for quantifying bone loss. Nevertheless, MRI-based protocols and computer-assisted measurements are being refined to improve bone assessment, especially in patients where radiation exposure is a concern [54]. The threshold for “subcritical” bone loss, generally regarded as between 13.5% and 20-25% of the glenoid width, is an area of ongoing debate and directly impacts whether dynamic or static stabilization procedures are recommended [55].

Accurate quantification is essential not only for guiding surgical decision-making but also for counseling patients regarding the risks of recurrence and the likelihood of needing more extensive procedures. As imaging technology evolves, efforts continue to standardize measurement techniques and improve interobserver reliability, further enhancing individualized patient care [56].

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Surgical Techniques Based on Biomechanics

The evolution of surgical techniques for anterior shoulder instability has increasingly emphasized biomechanical principles aimed at replicating physiological stability. Among these, dynamic anterior stabilization (DAS) using the long head of the biceps tendon (LHBT) has gained prominence for its ability to provide both a dynamic sling effect and anatomic reconstruction. The technique typically involves arthroscopic transfer or tenodesis of the LHBT to the anterior glenoid, creating a tensioned sling that resists anterior translation of the humeral head during abduction and external rotation [57].

Variations on the DAS concept include the ASA-LHBT (Arthroscopic Subscapularis-Augmented Long Head Biceps Tendon) technique, where the LHBT is routed through or adjacent to the subscapularis tendon before fixation, further enhancing the sling effect and dynamic restraint. Other procedures utilize the LHBT in combination with Bankart repair or remplissage to address both soft tissue and bony deficiencies, offering a tailored approach based on patient-specific pathology [58].

Biceps autograft and associated reconstructions leverage the strength and biological compatibility of the patient's own tendon to augment anterior stability, particularly in patients with poor capsulolabral tissue or failed prior repairs. The BLS (Between Glenohumeral Ligaments and Subscapularis) approach represents another biomechanically informed variation, designed to optimize the position and tension of the sling for maximal functional benefit [59].

Comparative studies have shown that these dynamic techniques can restore resistance to anterior translation to levels approaching or exceeding those of intact shoulders, particularly when static stabilizers are compromised. Moreover, by avoiding or delaying bone block procedures such as the Latarjet, these approaches may preserve native anatomy and reduce the risk of procedure-specific complications [60]. The choice of technique is guided by careful preoperative assessment of bone loss, tissue quality, and patient activity level, underscoring the importance of individualized, biomechanics-based surgical planning.

Future Directions: Biomechanical Research and Technique Evolution

The landscape of anterior shoulder stabilization continues to evolve as ongoing biomechanical research refines our understanding of both pathology and repair. Future directions in dynamic anterior stabilization (DAS) focus on optimizing the functional replication of native anatomy, personalizing procedures based on patient-specific biomechanics, and integrating advanced surgical technologies. High-fidelity biomechanical models, both cadaveric and computational, are being developed to simulate various stabilization techniques and to predict outcomes under real-world loading conditions [61].

One promising avenue is the enhancement of imaging and surgical navigation, including intraoperative 3D imaging and augmented reality, to improve the accuracy of tendon positioning and tensioning in

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DAS procedures. Personalized, data-driven approaches that leverage patient-specific anatomical and functional data may enable surgeons to better match technique to individual risk profiles, maximizing stability while preserving range of motion [62]. Additionally, ongoing research is evaluating biologic augmentation—such as scaffold materials or growth factors—to improve tendon-to-bone healing and long-term durability of dynamic repairs.

Technique evolution is also being driven by increased clinical experience and long-term outcome studies, which are identifying optimal patient populations, ideal indications, and potential limitations of DAS. Hybrid procedures, combining elements of dynamic and static stabilization, may offer solutions for patients with borderline or complex pathology, further expanding the surgical armamentarium [63]. Collaboration between orthopedic surgeons, biomechanical engineers, and rehabilitation specialists will be essential to translate emerging research into improved clinical outcomes and to standardize best practices.

Ultimately, the integration of advanced biomechanics with individualized surgical planning and post-operative rehabilitation holds the promise of enhancing both functional and clinical results for patients with anterior shoulder instability. Continued innovation and high-quality research will be necessary to fully realize the potential of dynamic stabilization strategies [64].

Conclusion

Dynamic anterior stabilization represents a paradigm shift in the surgical management of anterior shoulder instability, moving beyond traditional static repairs to leverage the biomechanical contributions of native tissues such as the long head of the biceps tendon. By replicating the physiological sling effect and restoring functional stability, these techniques offer a promising alternative for patients with subcritical bone loss, poor soft tissue quality, or those seeking to maintain a high level of athletic function. The success of dynamic stabilization relies on a nuanced understanding of shoulder anatomy and biomechanics, as well as careful patient selection and individualized surgical planning.

Recent biomechanical and clinical studies have demonstrated that dynamic anterior stabilization can achieve outcomes comparable to or better than traditional repairs in select patient populations, with the added advantage of preserving bone stock and native anatomy. However, the optimal indications, technique variations, and long-term durability of these procedures remain areas of active investigation. Ongoing research into personalized surgical planning, enhanced imaging, and biologic augmentation will continue to advance the field and may further improve patient outcomes.

In summary, dynamic anterior stabilization offers an innovative, anatomy-based approach to shoulder instability that bridges the gap between static and functional repair. Continued integration of

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biomechanical insights, clinical evidence, and technological advancements will be key to refining these techniques and establishing their role in the future of shoulder surgery.

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