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REVIEW

Comparison of Different Treatment Strategies for Long Head of Biceps Tendon in Rotator Cuff Repair: A Review

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Abstract: Rotator cuff injuries are frequently associated with lesions of the long head of the biceps tendon (LHBT), and the management strategies for LHBT significantly influence shoulder function recovery and pain relief in patients. This review provides a comprehensive overview of the anatomical features of the LHBT and its relationship with rotator cuff pathologies. It critically compares the clinical efficacy and complications of various treatment strategies for LHBT, including preservation, partial resection, complete tenotomy, and tendon transfer repair. By integrating recent advancements in imaging and anatomical studies, the review explores how LHBT lesions affect shoulder joint stability and function, as well as the mechanisms through which different surgical strategies impact the prognosis of rotator cuff repairs. Through a systematic analysis of the current literature, this review aims to provide a theoretical basis and practical guidance for clinicians in developing individualized treatment plans for patients with rotator cuff injuries involving the LHBT.

Keywords: rotator cuff injury, long head of biceps tendon, treatment strategies, efficacy comparison, shoulder function

Introduction

Shoulder injuries, particularly rotator cuff tears, are prevalent conditions that significantly impact patients' quality of life, leading to pain and functional disability. Among these injuries, rotator cuff tears often coexist with lesions of the LHBT, complicating the clinical picture and treatment strategies. The LHBT plays a crucial role in shoulder stability and function,[1] and its pathology can influence the outcomes of rotator cuff repair. Various treatment approaches have been proposed for managing LHBT injuries, particularly in the context of rotator cuff repair, including tenotomy, tenodesis, and transposition techniques. However, the efficacy of these strategies remains a topic of ongoing debate, and there is currently no consensus on the optimal management approach for LHBT lesions associated with rotator cuff injuries.[2,3] The recent studies further emphasized this controversy, noting that variations in patient selection criteria and outcome measures across studies contribute to inconsistent conclusions regarding the superiority of tenotomy versus tenodesis.[4,5]

The management of LHBT pathology is particularly relevant in the context of rotator cuff repairs, as the choice of intervention can significantly affect postoperative outcomes. Surgical techniques such as biceps tenodesis or tenotomy have been shown to alleviate pain and improve functional outcomes in patients with LHBT injuries. However, the decision-making process for selecting the appropriate procedure is influenced by various factors, including the extent of biceps tendon involvement, the presence of concurrent rotator cuff tears, and the specific anatomical considerations of the shoulder joint.[6,7] Recent studies have highlighted the importance of understanding the anatomical relationships and biomechanical implications of the LHBT in relation to rotator cuff repair techniques.[8]

Despite the advancements in surgical techniques and the growing body of literature, there remains a lack of uniformity in the clinical outcomes associated with different LHBT treatment strategies. For instance, while some studies report superior outcomes with biceps tenodesis compared to tenotomy, others suggest that tenotomy may be

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sufficient in certain patient populations.[9] Additionally, the potential for complications, such as the "Popeye" deformity associated with tenotomy, raises concerns about the long-term implications of these surgical choices.[10,11]

Recent advancements in imaging techniques, such as ultrasound elastography, have provided valuable insights into the assessment of shoulder pathologies, including LHBT injuries.[12] These imaging modalities allow for the evaluation of tissue stiffness and integrity, aiding in the diagnosis and monitoring of conditions affecting the LHBT and rotator cuff. However, further research is needed to establish standardized protocols for imaging and to correlate these findings with clinical outcomes.[13]

This review aims to systematically compare the various treatment strategies for LHBT lesions in the context of rotator cuff repair. By synthesizing the latest research findings and clinical data, we seek to elucidate the efficacy of different management approaches, thereby providing clinicians with evidence-based recommendations to enhance treatment strategies and improve patient prognoses. Ultimately, the goal is to optimize the management of shoulder injuries involving the LHBT, ensuring better functional recovery and quality of life for affected patients.

Anatomical Basis of the Long Head of the Biceps Brachii Tendon

Anatomy of the Long Head of the Biceps Tendon and Its Relationship with the Rotator Cuff Tendons

The LHBT originates from the supraglenoid tubercle of the scapula and traverses the intertubercular groove of the humerus. This anatomical positioning is crucial as it places the LHBT in close proximity to the rotator cuff tendons, particularly the supraspinatus and subscapularis tendons. The anatomical relationship between these structures is further complicated by the presence of fibrous connections that exist between the LHBT and the rotator cuff tendons, creating a complex functional unit that plays a significant role in shoulder stability and movement. Recent studies have highlighted that these fibrous connections may enhance the mechanical stability of the shoulder by distributing forces across the joint, thereby reducing the risk of injury to both the LHBT and the rotator cuff tendons during dynamic activities.[14]

Moreover, the transverse humeral ligament, which spans the intertubercular groove, has been a subject of debate regarding its structural composition and functional significance. Emerging evidence suggests that this ligament may actually be a continuation of the subscapularis tendon, which could have implications for the stability of the LHBT within the groove.[15] This anatomical insight is particularly relevant when considering surgical interventions for shoulder injuries, as the integrity of the transverse humeral ligament and its relationship with the LHBT can influence the outcomes of procedures such as biceps tenodesis or rotator cuff repairs.

The anatomical variations of the LHBT are not merely academic; they have real clinical implications. For instance, agenesis of the LHBT, although rare, underscores the importance of understanding the anatomy of this tendon and its relationships with surrounding structures, as its absence can lead to compensatory mechanisms that may affect shoulder function.[16] Furthermore, the interaction between the LHBT and the rotator cuff is particularly significant in the context of rotator cuff pathology.[17] Studies have shown that disorders of the LHBT are often concomitant with rotator cuff injuries, highlighting a well-established synergistic relationship where damage to one structure can predispose to and exacerbate injuries in the other.[18,19]

In summary, the anatomy of the long head of the biceps tendon and its interconnections with the rotator cuff tendons are critical for maintaining shoulder stability and function. Understanding these relationships can inform clinical practices and surgical approaches, particularly in the context of repairing shoulder injuries and managing biceps-related pathologies. The ongoing research into the anatomical and functional dynamics of these structures will likely continue to refine our understanding and enhance the effectiveness of interventions aimed at restoring shoulder health.

Anatomical and Functional Relationship Between the Rotator Cuff Tendons and the Long Head of Biceps Tendon (LHBT)

The anatomical relationship between the rotator cuff tendons and the LHBT is critical for the stability and function of the shoulder joint. Rotator cuff injuries are often accompanied by LHBT subluxation or tears, which can significantly impact shoulder stability. The LHBT plays a vital role in maintaining the position of the humeral head within the glenoid cavity, particularly during dynamic movements. Anatomical studies have demonstrated that the LHBT and rotator cuff tendons share a complex interrelationship, with overlapping tendon fibers and connective tissue that contribute to shoulder stability and motion control.[14] The interaction between these structures is essential for effective glenohumeral joint function, as they work synergistically to stabilize the shoulder during various activities, such as lifting and throwing. The LHBT is not merely a passive structure; rather, it actively participates in the dynamic stabilization of the shoulder, particularly in the context of rotator cuff injuries. In cases of rotator cuff tears, the LHBT may exhibit compensatory hyperactivity, which can lead to further pathology if not addressed appropriately.[18] Furthermore, the anatomical positioning of the LHBT, along with its connections to the rotator cuff, underscores the importance of considering both structures during surgical interventions aimed at repairing rotator cuff injuries. Failure to adequately address the LHBT during rotator cuff repair can result in suboptimal outcomes, as the stability provided by the LHBT is crucial for maintaining proper shoulder mechanics.[20] Therefore, understanding the anatomical and functional relationship between the rotator cuff and the LHBT is imperative for orthopedic surgeons when planning surgical strategies for shoulder injuries, as it can influence both the immediate and long-term outcomes of shoulder surgeries.

Imaging Findings and Diagnosis of Long Head of Biceps Tendinopathy

Application of MRI and X-Ray in the Diagnosis of LHBT Lesions

Magnetic Resonance Imaging (MRI) has emerged as a superior diagnostic modality for evaluating lesions of the LHBT, particularly in cases of tears and dislocations, compared to conventional X-ray imaging. MRI provides detailed visualization of soft tissue structures, allowing for accurate assessment of the LHBT's integrity and associated pathologies, such as rotator cuff tears. Studies have demonstrated that MRI can effectively identify not only the presence of LHBT tears but also their extent and associated pathological changes, thereby guiding treatment decisions. For instance, a retrospective review indicated that MRI measurements of the acromiohumeral interval (AHI) were significantly smaller in patients with rotator cuff tears, highlighting the close relationship between LHBT lesions and rotator cuff pathology.[21] This relationship underscores the importance of MRI in diagnosing LHBT lesions, as it can reveal underlying shoulder pathologies that X-ray may miss due to its reliance on indirect signs. While X-ray can provide some information regarding bony structures and alignment, it is limited in its ability to assess soft tissue injuries, which are critical in the context of LHBT lesions. The indirect signs on X-ray, such as changes in the AHI, are less specific and can lead to misdiagnosis or delayed treatment. Therefore, MRI not only enhances diagnostic accuracy but also aids in the comprehensive evaluation of shoulder conditions, making it an indispensable tool in the clinical setting.

The acromiohumeral interval (AHI) is a valuable radiographic parameter that reflects the integrity of the rotator cuff, particularly in massive or posterosuperior tears. In such cases, the loss of muscular stabilization and force couple can lead to superior migration of the humeral head, resulting in a decreased AHI—a condition often described as "superior escape".[21] This superior instability and the associated narrowing of the subacromial space create a pathological environment that predisposes the LHBT to secondary injury. The tendon is subjected to increased mechanical abrasion, inflammation, and potential instability within the bicipital groove. Consequently, while a reduced AHI is not a direct diagnostic criterion for LHBT lesions, it serves as a critical indirect marker. It identifies patients with advanced cuff deficiency, who are at a significantly higher risk of concurrent LHBT pathology. Given that MRI excels at visualizing both the bony AHI and the soft tissue status of the cuff and biceps tendon, it is the imaging modality of choice in this context. It allows for a comprehensive assessment, confirming the extent of rotator cuff tearing and evaluating the often-associated LHBT damage, thereby guiding appropriate surgical management.

Advantages and Limitations of Ultrasound in the Assessment of LHBT Injuries

Ultrasound imaging has emerged as a crucial tool in the evaluation of LHBT injuries, providing dynamic observation capabilities that enhance the diagnostic process. One of the key advantages of ultrasound is its ability to visualize tendon movement in real-time, allowing clinicians to assess the sliding abnormalities and partial tears that may not be apparent through static imaging modalities such as MRI. This dynamic assessment is particularly beneficial in identifying conditions such as bicipital tendinopathy and tenosynovitis, which are common in athletes and individuals engaged in repetitive overhead activities. Studies have demonstrated that ultrasound can effectively detect various pathologies associated with the LHBT, including subluxation, bursitis, and tendon ruptures, thereby facilitating timely and accurate diagnoses.[22] Moreover, ultrasound is a cost-effective and accessible imaging modality that can be performed in an outpatient setting, making it a practical choice for many clinicians. However, the technique is not without its limitations. While ultrasound measurements have shown a high correlation with anatomical specimen measurements, there exists a risk of underestimating the size of the tendon or the extent of the injury due to operator dependence and the subjective nature of the imaging interpretation.[14] Additionally, the quality of the ultrasound image can be significantly affected by the patient's body habitus, the operator's skill level, and the equipment used. These factors can lead to variability in diagnostic accuracy, particularly in cases of subtle injuries or in patients with significant anatomical variations. Furthermore, while ultrasound can provide valuable information regarding the soft tissue structures surrounding the LHBT, it may not adequately visualize deeper structures or assess concurrent pathologies, such as rotator cuff tears, which may require additional imaging modalities like MRI for comprehensive evaluation. Thus, while ultrasound offers distinct advantages in the assessment of LHBT injuries, it is essential for clinicians to be aware of its limitations and to consider it as part of a multimodal approach to shoulder evaluation, integrating clinical findings and other imaging techniques to ensure optimal patient outcomes.[23]

Classification of Different Treatment Strategies for the Long Head of the Biceps Tendon

Preservation Strategy

The preservation strategy for the LHBT during shoulder surgery is particularly relevant for patients exhibiting mild LHBT pathology or those without significant symptoms. This approach is grounded in the understanding that the LHBT plays a crucial role in maintaining shoulder joint stability. By retaining the tendon, surgeons aim to preserve the anatomical and functional integrity of the shoulder, which can be especially beneficial in cases where the tendon is not severely compromised. Research indicates that retaining the LHBT can contribute to better outcomes in terms of functional recovery and pain management, as the tendon assists in the dynamic stabilization of the glenohumeral joint during movement.[3] However, it is important to note that while the preservation of the LHBT can be advantageous, it is not without risks. One of the primary concerns is the potential for disease progression, particularly if the tendon is already exhibiting signs of degeneration or injury. In such cases, the decision to preserve the tendon must be carefully weighed against the risk of exacerbating existing conditions, which could lead to further complications such as pain or reduced range of motion.

Moreover, the preservation strategy necessitates a thorough preoperative evaluation to assess the extent of LHBT pathology and its impact on shoulder function. Techniques such as imaging studies and clinical assessments can provide valuable insights into the condition of the tendon and inform surgical decisions. For example, patients with mild biceps tendinopathy may benefit from preservation, as the tendon can still function effectively in stabilizing the shoulder joint. Conversely, in cases where there is significant degeneration or associated injuries to the rotator cuff, a more aggressive approach may be warranted, potentially involving tenodesis or tenotomy.[24]

Additionally, the preservation of the LHBT allows for the maintenance of the muscle's anatomical length-tension relationship, which is critical for optimal muscle function and shoulder biomechanics. This is particularly important during rehabilitation, as preserving the tendon can facilitate a more natural recovery process and help patients regain strength and mobility more effectively.[25] However, the decision to preserve the LHBT should also consider individual patient factors, including age, activity level, and overall shoulder health, as these can influence both short-term and long-term outcomes.

In conclusion, the preservation strategy for the LHBT in shoulder surgeries presents a viable option for patients with mild pathology or asymptomatic conditions. While it offers the potential for enhanced shoulder stability and function, careful consideration of the risks associated with disease progression is essential. The decision-making process should be guided by a comprehensive evaluation of the tendon's condition and the specific needs of the patient, ensuring that the chosen approach aligns with the overarching goal of optimizing shoulder function and minimizing postoperative complications.

Partial Resection (Tendon Debridement)

Partial resection or tendon debridement is a surgical strategy primarily employed for managing localized tears or tendon pathologies within the rotator cuff, particularly when the goal is to alleviate symptoms while preserving tendon function. This technique is particularly beneficial for patients who present with partial thickness tears or tendinopathy, where the integrity of the tendon is not completely compromised. The rationale behind partial resection is to remove degenerated tissue, thereby reducing pain and improving shoulder mobility. Evidence suggests that this approach can lead to satisfactory outcomes, particularly in patients with lower functional demands or those who are older. For instance, arthroscopic debridement has been shown to relieve shoulder pain in elderly patients, allowing for a quicker return to daily activities compared to more invasive surgical options.[26] However, while the recovery time post-surgery is generally favorable, the recurrence rate of symptoms remains a critical consideration. Studies indicate that the retear rates for partial repairs can be significantly high, ranging from 18% to 94%, particularly in cases involving massive rotator cuff tears.[27] This underscores the importance of careful patient selection and realistic expectations regarding the outcomes of partial resection.

Moreover, the technique of tendon debridement can be particularly advantageous in specific patient populations. For example, younger patients with high functional demands may benefit from a more aggressive approach, such as complete repair or tendon transfer, while older patients or those with significant comorbidities may experience better outcomes with partial resection due to its less invasive nature.[26] The decision to pursue partial resection should also consider the quality of the remaining tendon tissue and the overall integrity of the rotator cuff. In cases where the tendon exhibits significant degeneration or retraction, a partial resection may not suffice, and alternative surgical strategies may be warranted.

The postoperative recovery trajectory following partial resection is typically characterized by a relatively rapid return to functional activities. Patients often report a decrease in pain and improvement in shoulder range of motion within weeks following the procedure. However, ongoing rehabilitation is crucial to maximize functional recovery and minimize the risk of re-injury. Physical therapy protocols should focus on restoring strength and stability to the shoulder joint, particularly emphasizing rotator cuff strengthening and scapular stabilization exercises.

Despite the advantages, it is essential to monitor patients closely for signs of recurrence or complications post-surgery. The potential for retear necessitates a proactive approach in both surgical technique and postoperative management. Regular follow-up assessments, including imaging studies when indicated, can help identify any issues early, allowing for timely interventions.

In summary, partial resection or tendon debridement serves as a viable option for treating localized rotator cuff injuries, particularly in patients with specific characteristics that align with this approach. While it offers a faster recovery and symptom relief, careful consideration of the potential for recurrence and the need for comprehensive rehabilitation is critical to achieving optimal outcomes. The ongoing evolution of surgical techniques and rehabilitation protocols will continue to enhance the effectiveness of this treatment modality in managing rotator cuff pathologies.

Complete Tenotomy (Tendon Division)

Complete tenotomy of the long head of the biceps tendon is a surgical procedure often employed in cases of severe biceps pathology or when associated rotator cuff injuries render the shoulder cuff irreparable. This technique is particularly beneficial for patients suffering from significant pain and dysfunction, as it effectively alleviates shoulder pain associated with biceps tendonitis or tears. The primary advantage of tenotomy is its simplicity and rapid execution compared to more complex procedures like tenodesis. Studies have shown that patients who undergo tenotomy experience a notable reduction in pain levels postoperatively, often reporting significant improvements on visual analog scales (VAS) within months of the procedure.[28,29] However, while pain relief is a critical outcome, the procedure is not without its complications. One of the most commonly reported issues following tenotomy is the development of the "Popeye sign," a cosmetic deformity characterized by the bulging of the biceps muscle due to tendon retraction.[10,30] This deformity, while generally not affecting functional outcomes, can lead to patient dissatisfaction, particularly among those who prioritize aesthetic considerations in their recovery. Furthermore, tenotomy may result in decreased biceps strength, particularly in elbow flexion and supination, which can impact the overall functional capacity of the upper limb.[31,32]

Research indicates that while tenotomy provides effective pain relief, it may also lead to long-term functional deficits in certain populations, especially among younger, more active patients who engage in sports or physically demanding occupations.[3,33] The decision to perform a tenotomy should therefore consider the patient's age, activity level, and personal aesthetic preferences. Moreover, the incidence of complications such as muscle cramps and persistent pain has been documented, suggesting that while tenotomy can be effective, it may not be the optimal choice for all patients.[34,35]

In summary, complete tenotomy of the long head of the biceps tendon serves as a viable option for managing severe biceps pathology, particularly when the rotator cuff is irreparable. It offers significant pain relief, but the potential for cosmetic deformity and functional decline necessitates careful patient selection and thorough preoperative counseling. Ultimately, the choice between tenotomy and alternative procedures, such as tenodesis, should be guided by a comprehensive assessment of the patient's specific condition, functional demands, and personal goals for recovery. Further studies are warranted to better understand the long-term implications of tenotomy and to refine patient selection criteria to optimize outcomes.

Long Head of Biceps Tendon Transfer Repair

The transfer of the LHBT to alternative anatomical sites has emerged as a significant strategy in the surgical management of complex shoulder pathologies, particularly in cases involving massive rotator cuff tears. This technique aims to restore tendon tension and enhance shoulder joint stability, which is crucial for optimal functional recovery. The rationale behind this approach lies in the anatomical and biomechanical properties of the LHBT, which can provide a dynamic stabilizing effect on the shoulder joint when repositioned appropriately. Studies have shown that transferring the LHBT can lead to improved shoulder function, especially in patients with extensive rotator cuff injuries where traditional repair methods may be insufficient. For instance, a mid-term follow-up study indicated that using the LHBT as an autograft for deep layer repair in delaminated rotator cuff tears resulted in significant improvements in pain relief and functional scores, highlighting the effectiveness of this technique in restoring shoulder mechanics and patient quality of life.[36]

However, the complexity of the surgical procedure must be acknowledged, as it requires a thorough understanding of shoulder anatomy and the intricacies of tendon transfer techniques. The potential for complications, such as neurovascular injury and tendon rupture, necessitates meticulous surgical planning and execution. Moreover, the selection of appropriate candidates for this procedure is critical; ideal candidates typically include younger patients with minimal degenerative changes and significant functional deficits due to irreparable rotator cuff tears.[27] The surgical complexity increases when addressing multifaceted shoulder issues, which may involve concomitant procedures such as acromioplasty or superior capsule reconstruction. As such, the decision to perform LHBT transfer should be made on a case-by-case basis, considering the patient's age, activity level, and specific shoulder pathology.

In addition to the technical challenges, the postoperative rehabilitation process for patients undergoing LHBT transfer is also crucial for achieving optimal outcomes. A well-structured rehabilitation protocol that focuses on gradual strengthening and range of motion exercises is essential to maximize the functional benefits of the tendon transfer. Research has indicated that patients who adhere to a comprehensive rehabilitation program post-surgery experience better recovery trajectories, including enhanced range of motion and reduced pain levels.[26]

In conclusion, the transfer of the long head of biceps tendon represents a promising approach in the surgical treatment of complex shoulder injuries, particularly in cases of massive rotator cuff tears. While this technique can significantly improve shoulder stability and function, it is accompanied by increased surgical complexity and potential complications. Therefore, careful patient selection, thorough surgical technique, and diligent postoperative rehabilitation are paramount to achieving successful outcomes. As our understanding of shoulder biomechanics and surgical techniques continues to evolve, further research is warranted to refine these methods and establish standardized protocols for LHBT transfer in clinical practice.

Beyond its well-described pathologies and traditional treatments, the long head of the biceps tendon has garnered significant interest as a versatile autograft in reconstructive shoulder surgery. An emerging and promising application is

Table 1 Comparison Table of Different Treatment Strategies for the Long Head of Biceps Tendon (LHBT) in Rotator Cuff Repair

Treatment Strategy	Indication	Core Advantages	Main Risks/Complications	Clinical Outcomes
Preservation Strategy	Mild LHBT pathology, asymptomatic or minimally symptomatic patients	Maintains anatomical integrity of the shoulder joint, aids dynamic stability	Risk of disease progression, insufficient pain relief in some patients	Limited pain relief (depending on the severity of the pathology); Moderate functional recovery, requiring rehabilitation
Partial Resection (Tendon Debridement)	Partial tears, partial-thickness injuries, patients with low functional demands / elderly	Minimally invasive, quick recovery, relieves local pain	High recurrence rate (18–94%), limited efficacy in severe injuries	Significant short-term pain relief; Moderate functional recovery, requiring intensive postoperative rehabilitation
Complete Tenotomy	Severe LHBT pathology, irreparable rotator cuff tears, patients prioritizing pain relief	Simple procedure, significant short-term pain relief (improved short-term VAS scores)	"Popeye" deformity, decreased biceps muscle strength (elbow flexion / supination)	Optimal short-term pain relief; Quick early functional recovery, long-term muscle strength may be affected
Tendon Transfer Repair	Massive rotator cuff tears, complex shoulder pathology, young / high-functional-demand patients	Restores joint stability, excellent long-term functional recovery	Complex procedure, risk of neurovascular injury, requires precise operation	Significant pain relief; Best long-term functional recovery, dependent on standardized rehabilitation

its use as a dynamic stabilizer in the treatment of anterior glenohumeral instability.[37,38] The concept of dynamic anterior stabilization (DAS), which involves the trans-subscapular transfer of the LHBT to the anterior glenoid rim, has been developed as a soft-tissue solution for patients with subcritical bone loss, positioned between isolated soft-tissue repair and bony augmentation procedures.[38] Recent clinical series have begun to validate this approach, reporting satisfactory short-to-midterm outcomes with low recurrence rates and minimal compromise to range of motion.[39,40] This evolving body of literature solidifies the LHBT's expanding role from a source of pain to a key resource in the surgeon's armamentarium for addressing complex instability.

To systematically synthesize the key characteristics of the four LHBT treatment strategies (preservation, partial resection, complete tenotomy, and tendon transfer repair) discussed above, Table 1 summarizes their indications, core advantages, main risks/complications, and typical clinical outcomes. This comparison provides a concise reference for clinicians to quickly grasp the trade-offs of each strategy before delving into the subsequent analysis of clinical efficacy.

Comparison of Clinical Efficacy of Different Treatment Strategies

To objectively compare the clinical performance of the four LHBT treatment strategies, we evaluated five core indicators: short-term pain relief, long-term pain relief, early functional recovery, long-term functional recovery, and complication risk. The quantitative differences in these indicators across strategies are visualized in Figure 1, where higher scores represent better performance (for pain relief and functional recovery) or higher risk (for complications). This figure provides an intuitive overview of efficacy trends before analyzing each indicator in detail.

Pain Relief Effects

The comparison of pain relief outcomes between different surgical strategies for managing the LHBT during rotator cuff repair reveals significant differences in efficacy. As shown in Figure 1, complete tenotomy achieved the highest score in short-term pain relief (score = 5.0), followed by tendon transfer repair (score = 4.0), while preservation strategy had the lowest short-term pain relief effect (score = 2.0). Specifically, complete transection and relocation repair techniques demonstrate markedly superior pain relief compared to strategies that involve preservation or partial resection of the tendon. In a study examining these approaches, patients who underwent LHBT fixation with proximal amputation reported greater improvements in pain scores as measured by the visual analogue scale (VAS) at 3 and 6 months post-

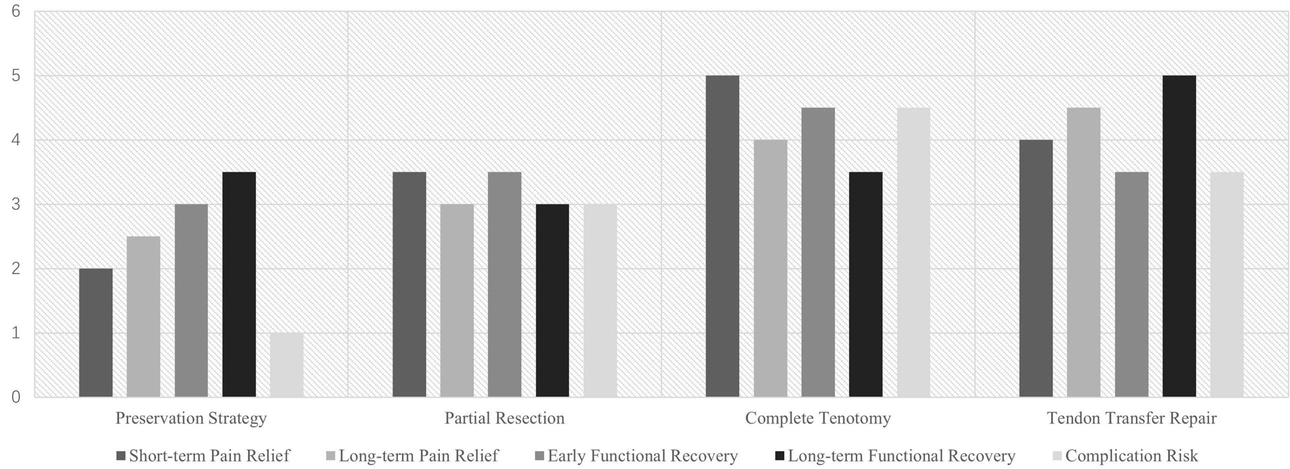

Figure 1 Grouped Bar Chart of Core Indicators for 4 Treatment Strategies of the Long Head of Biceps Tendon (LHBT).

operation, indicating a more effective alleviation of shoulder pain in the short term.[24] The rationale behind this finding may be attributed to the reduction of mechanical irritation and inflammation associated with the LHBT when it is completely transected and repositioned, thus allowing for a more stable and pain-free shoulder environment. For long-term pain relief, Figure 1 further shows that tendon transfer repair (score = 4.5) and complete tenotomy (score = 4.0) remained superior, whereas preservation strategy still showed limited efficacy (score = 2.5)—a result attributed to potential disease progression in retained LHBT with underlying pathology. Conversely, the preservation strategy, while potentially beneficial for maintaining some degree of tendon function, often results in limited pain relief, particularly in cases where the LHBT is significantly damaged or degenerated. This limitation necessitates a careful evaluation of the severity of the tendon injury when considering the preservation approach, as patients with more severe LHBT lesions may not experience the same level of pain relief as those with less severe injuries. Therefore, the choice of surgical strategy should be tailored to the individual patient's condition, with a focus on achieving optimal pain management outcomes.

Moreover, the findings suggest that while both surgical techniques can lead to improvements in shoulder function over time, the immediate postoperative period appears to favor the complete transection and relocation method in terms of pain relief. This is particularly relevant for clinicians when discussing surgical options with patients, as the expectation of pain relief can significantly influence patient satisfaction and overall outcomes.[1,41] It is essential to communicate that while preserving the LHBT may be less invasive and could potentially retain some of its functional capabilities, the trade-off may be inadequate pain management, especially in the early stages of recovery. As such, a comprehensive assessment of the patient's specific injury characteristics, including the degree of tendon degeneration and associated symptoms, is crucial in guiding the decision-making process regarding surgical intervention. Ultimately, the goal of any surgical strategy should be to maximize pain relief while promoting functional recovery, and the evidence suggests that complete transection and relocation may offer a more effective solution for patients with LHBT injuries in the context of rotator cuff repair.[24]

Shoulder Joint Function Recovery

The recovery of shoulder joint function following surgical interventions for rotator cuff injuries, particularly in the context of LHBT management, is a critical aspect of postoperative outcomes. As visualized in Figure 1, the four strategies show distinct trends in functional recovery: complete tenotomy led in early functional recovery (score = 4.5), while tendon transfer repair achieved the highest score in long-term functional recovery (score = 5.0)—a contrast that highlights the need to balance short-term recovery speed and long-term functional sustainability. Studies have shown that patients who undergo arthroscopic rotator cuff repair with LHBT fixation without proximal amputation demonstrate favorable recovery in terms of shoulder range of motion and strength. Specifically, a comparative analysis of two patient groups—one undergoing LHBT fixation without cutting and the other with cutting—revealed that both groups exhibited significant improvements in shoulder function as measured by the Constant-Murley shoulder function scale and UCLA scores at multiple postoperative intervals.[24] Notably, while both groups achieved similar functional outcomes at the one-year follow-up, the group that underwent LHBT cutting showed superior recovery in the early postoperative phase (3 and 6 months), indicating a potential advantage of this approach in the short term. However, this early benefit must be weighed against the risk of complications, such as Popeye deformity, which was more prevalent in the tenotomy group.[33]

Moreover, the impact of complete LHBT transection on muscle strength and shoulder function cannot be overlooked. Evidence suggests that complete severance of the LHBT may lead to a decline in biceps strength, which can adversely affect overall shoulder function and stability.[42] The biceps brachii plays a crucial role in shoulder mechanics, contributing to both flexion and stabilization of the shoulder joint. Therefore, while the surgical strategy of cutting the LHBT may provide immediate functional benefits, it is essential to consider the long-term implications on muscle strength and joint integrity. This is consistent with Figure 1's long-term functional recovery data: complete tenotomy (score = 3.5) and preservation strategy (score = 3.5) showed similar moderate outcomes, while tendon transfer repair (score = 5.0) stood out—likely due to its ability to restore joint stability and maintain muscle-tendon unit function. The balance between achieving optimal shoulder function and minimizing the risk of postoperative complications is a key consideration in determining the best surgical approach for patients with rotator cuff injuries involving the LHBT.

In conclusion, the management of LHBT during rotator cuff repair is a nuanced decision that impacts shoulder joint recovery. The choice between preserving or cutting the LHBT should be individualized based on patient-specific factors, including the extent of injury and functional demands. Future studies are warranted to further elucidate the long-term outcomes of these surgical strategies, particularly in relation to muscle strength and overall shoulder joint stability, to guide clinicians in optimizing treatment protocols for enhanced recovery.

Complications and Recurrence Rates

The management of rotator cuff injuries, particularly in the context of biceps tendon involvement, presents a significant challenge due to the associated risks of complications and recurrence. Figure 1 quantifies the complication risk across strategies: preservation strategy had the lowest risk (score = 1.0), followed by partial resection (score = 3.0) and tendon transfer repair (score = 3.5), while complete tenotomy had the highest complication risk (score = 4.5)—primarily driven by "Popeye" deformity and muscle strength decline. When employing a preservation strategy for the long head of the biceps tendon (LHBT), studies indicate a heightened risk of disease progression and a relatively high recurrence rate. This is particularly evident in cases where the LHBT is retained during rotator cuff repair, as the underlying pathology may continue to affect shoulder function and lead to further deterioration of the tendon over time. The preservation approach, while beneficial in maintaining the anatomical structure, often does not address the intrinsic degenerative changes that can lead to re-tearing or persistent pain, ultimately resulting in a higher likelihood of subsequent surgical interventions.[43] In contrast, complete tenotomy or tenodesis of the LHBT, although effective in alleviating symptoms, can lead to specific complications such as the development of the "Popeye deformity," characterized by muscle bulging in the arm due to the retraction of the biceps muscle belly. This deformity, alongside muscle strength deficits, necessitates careful consideration when opting for surgical strategies involving the LHBT.[36]

Moreover, the complexity of biceps tendon transfer procedures, such as those involving suprapectoral or subpectoral tenodesis, introduces additional risks, including infection and nerve damage. The surgical technique employed can significantly influence the incidence of these complications. For instance, while suprapectoral tenodesis is associated with lower rates of transient nerve injuries, it has been linked to a higher prevalence of persistent bicipital pain and cosmetic deformities like the Popeye sign.[27] Conversely, subpectoral tenodesis may present a greater risk of wound complications and neurological injuries, emphasizing the need for a tailored approach based on individual patient factors and the specific surgical context.[44]

The intricacies of these surgical interventions underscore the importance of a multidisciplinary approach to patient management, where orthopedic surgeons collaborate with rehabilitation specialists to optimize outcomes and minimize the risk of complications. Postoperative monitoring for signs of infection, nerve impairment, and functional recovery is crucial in the early detection and management of these potential complications. Furthermore, patient education regarding the risks associated with different surgical options, including the likelihood of recurrence and the implications of cosmetic deformities, is essential in the informed consent process. Ultimately, the choice of surgical strategy must balance the potential benefits of pain relief and functional restoration against the risks of complications and the possibility of recurrence, ensuring that patients receive the most appropriate and effective care for their specific conditions.[45,46]

The Impact of New Imaging and Anatomical Findings on Treatment Strategies

Association Between Acromiohumeral Interval (AHI) Reduction and Long Head of Biceps Tendon (LHBT) Pathology

The assessment of rotator cuff pathology and associated LHBT lesions has evolved beyond static radiographic measurements to encompass a holistic evaluation of the functional anatomy of the shoulder. While a narrowed acromiohumeral interval (AHI) can be a secondary sign of advanced cuff disease, contemporary practice prioritizes the assessment of tendon retraction and fatty infiltration (FI), which are powerful prognostic factors for reparability and clinical outcomes.[47,48] A 2023 meta-analysis confirmed that preoperative FI significantly increases the risk of post-operative re-tear and leads to worse functional scores.[47]

The fundamental pathology often lies in the disruption of the force couples stabilizing the glenohumeral joint. Failure of the posterior-superior cuff leads to superior migration of the humeral head and an unbalanced rotator cable, which in turn alters joint kinematics and contributes to specific pain patterns and functional deficits. In this biomechanically compromised environment, the LHBT frequently undergoes secondary overload as it attempts to act as a compensatory stabilizer. Modern surgical approaches now leverage the LHBT not merely as a structure to be treated, but as a valuable local autograft for complex reconstructions, such as in superior capsule reconstruction or dynamic anterior stabilization, to restore biomechanical balance.[1]

Therefore, a modern diagnostic approach integrates MRI-based assessment of muscle quality (FI) and tendon mobility (retraction) with a thorough clinical evaluation of the patient's functional deficits and pain patterns. This comprehensive strategy, moving beyond the AHI, allows for accurate prognostication and guides patient-specific management plans aimed at restoring the disrupted force couples, which is the cornerstone of modern shoulder instability treatment.[1,48,49]

Anatomical Controversies of the Transverse Humeral Ligament and Its Clinical Significance

The transverse humeral ligament (THL) has long been a subject of anatomical debate, particularly regarding its role as a continuation of the subscapularis tendon and its implications for the stability of the LHBT. Recent evidence supports the notion that the THL is not merely a passive structure but plays a crucial role in maintaining the integrity of the bicipital groove, which is the anatomical pathway for the LHBT. The bicipital groove is characterized by a bottleneck narrowing, which can predispose the LHBT to impingement and subsequent pathology, contributing to anterior shoulder pain.[50] Understanding the anatomical relationship between the THL and the subscapularis tendon is essential for clinicians in evaluating the stability of the LHBT during surgical interventions. The THL's anatomical variations can influence surgical outcomes, particularly in procedures involving biceps tenodesis or tenotomy. For instance, the release of the THL during these procedures has been shown to significantly affect the elongation of the biceps muscle tendon unit, thereby impacting postoperative rehabilitation and patient outcomes.[51]

This evolving understanding of the THL's anatomy prompts a need for more precise intraoperative handling of related structures. Surgeons must consider the potential implications of THL release on the stability of the LHBT, particularly in the context of rotator cuff repair. Studies indicate that routine release of the THL can alleviate postoperative anterior shoulder pain, which is a common complication following biceps tendon procedures.[50] Furthermore, the anatomical variations of the bicipital groove, such as its depth and width, can influence the choice of surgical technique. For example, a more distal tenodesis site may be preferable to avoid the bottleneck effect, potentially leading to improved surgical outcomes and reduced complications.[50]

The clinical significance of these anatomical considerations cannot be overstated. A thorough understanding of the THL and its relationship with the bicipital groove can guide surgeons in optimizing their surgical techniques, ultimately enhancing patient outcomes. This knowledge is particularly relevant in the context of concurrent rotator cuff repairs, where the stability of the LHBT is paramount. The findings from recent studies underscore the importance of individualized surgical strategies that take into account the unique anatomical features of each patient.[52] As our understanding of the THL and its clinical implications continues to evolve, it is imperative that orthopedic surgeons remain informed about these anatomical nuances to improve the efficacy of interventions involving the LHBT and to minimize postoperative complications.

The Impact of LHBT Treatment Strategies from a Biomechanical Perspective

The Role of the Long Head of Biceps Tendon (LHBT) in Shoulder Joint Stability

The LHBT plays a crucial role as a stabilizing structure in the shoulder joint, particularly in maintaining anterior stability and facilitating proper joint mechanics during various arm movements. As a dynamic stabilizer, the LHBT contributes to the shoulder's ability to resist dislocation and enhances the overall stability of the glenohumeral joint. Research indicates that the LHBT aids in counteracting posterior translation of the humeral head during forward flexion, which is a common position during overhead activities. In a study involving cadaveric shoulders, it was demonstrated that unloading the LHBT resulted in significant posterior translation of the humeral head, underscoring its stabilizing function during functional motions.[53] Furthermore, the LHBT's engagement during shoulder flexion not only stabilizes the joint but also helps in tensioning the posterior capsuloligamentous complex, thereby preventing dislocation during dynamic activities.[20]

Different surgical strategies involving the LHBT, such as tenodesis or transfer, have been explored to enhance shoulder stability in cases of anterior instability, particularly when there is associated glenoid bone loss. The biomechanical implications of these strategies reveal that the LHBT can effectively augment traditional repair techniques, such as Bankart repairs, by providing additional support to the anterior glenohumeral structures. For instance, a biomechanical study comparing the effects of LHBT transfer versus Bankart repair indicated that LHBT transfer significantly improved resistance to dislocation forces, thereby restoring glenohumeral positioning closer to that of an intact state.[54]

Moreover, the LHBT's role extends beyond stabilization; it also influences the mechanical environment of the shoulder joint. Different treatment strategies for shoulder injuries, including the use of the LHBT as an autograft for labral reconstruction, have shown promising results in restoring joint stability. In cadaveric studies, the LHBT was found to enhance the biomechanical stability of the shoulder when used to reconstruct the labrum, leading to improved resistance against dislocation and better functional outcomes.[55] This suggests that the LHBT not only serves as a passive stabilizer but also actively participates in the shoulder's dynamic stabilization mechanisms.

The effectiveness of various treatment modalities involving the LHBT highlights the need for a nuanced understanding of its biomechanical properties and the impact of surgical interventions on shoulder stability. The LHBT's unique anatomical and functional characteristics make it a valuable resource for surgeons aiming to restore stability in patients with shoulder instability. As research continues to evolve, the integration of LHBT strategies into surgical practice may offer enhanced outcomes for patients suffering from chronic shoulder instability, particularly in the context of complex injuries involving the rotator cuff and labrum. Overall, the LHBT's contribution to shoulder joint stability is multifaceted, emphasizing its importance in both the anatomical structure and functional performance of the shoulder.

The Role of LHBT Management in Shoulder Load Regulation During Rotator Cuff Repair

The management of the LHBT during rotator cuff repair is a critical factor in maintaining shoulder joint load balance. Preserving the LHBT has been shown to contribute positively to the stability and functionality of the shoulder joint. The LHBT plays a significant role in shoulder biomechanics, particularly in load distribution across the glenohumeral joint. When the LHBT is retained during surgical interventions, it can help maintain the natural tension and alignment of the shoulder structures, thereby facilitating a more balanced load distribution. Studies have demonstrated that the preservation of the LHBT can enhance the glenohumeral compression force, which is essential for joint stability and function.[56] Moreover, retaining the LHBT may help to mitigate the risk of postoperative complications such as shoulder instability and pain, which can arise from altered joint mechanics following rotator cuff repairs.

On the other hand, the decision to cut or transpose the LHBT must be carefully considered based on the individual patient's condition. In certain cases, detaching or repositioning the LHBT may be necessary to address specific pathologies, such as significant labral injuries or severe rotator cuff tears. However, such interventions can lead to changes in shoulder mechanics, potentially increasing the load on other structures within the shoulder joint. For instance, transferring the LHBT or performing a tenotomy can lead to alterations in the force transmission pathways, which may inadvertently increase the risk of joint instability or exacerbate existing conditions.[35] Therefore, it is crucial for orthopedic surgeons to weigh the benefits of LHBT preservation against the potential risks associated with its alteration. This decision should be guided by a thorough assessment of the patient's specific shoulder pathology, functional demands, and overall health status.

Furthermore, biomechanical studies suggest that surgical techniques involving the LHBT can significantly influence the shoulder's response to load during rehabilitation. Research indicates that techniques preserving the LHBT, such as dynamic LHBT sling procedures, can provide superior biomechanical support compared to those that do not.[41] These findings underscore the importance of individualized surgical planning that takes into account the unique anatomical and functional characteristics of each patient's shoulder. The implications of LHBT management extend beyond the immediate surgical outcome, as they can impact long-term joint health and patient satisfaction. In conclusion, the handling of the LHBT during rotator cuff repair is a pivotal aspect that requires careful consideration and a tailored approach, ensuring that the chosen strategy aligns with the patient's specific needs and anatomical considerations to optimize shoulder function and stability postoperatively.

Selection of Individualized Treatment Strategies in Clinical Practice

Strategy Development Based on Severity of Lesion

In the context of managing LHBT injuries during rotator cuff repair, the severity of the lesion plays a critical role in determining the appropriate surgical strategy. For mild LHBT lesions, conservative approaches such as preservation or partial resection of the tendon can be considered. This strategy is particularly relevant when the tendon is structurally intact or only exhibits minor degenerative changes. Studies suggest that maintaining the LHBT can lead to favorable outcomes, as it contributes to shoulder stability and function. For instance, patients with mild lesions often report satisfactory pain relief and functional recovery when treated conservatively, which may include physical therapy and activity modification.[57] Conversely, in cases of severe tears or when the rotator cuff is irreparable, a more aggressive approach is warranted. The surgical options typically involve tenotomy or tenodesis of the LHBT, which can alleviate pain and restore shoulder function by eliminating the source of irritation. Research indicates that patients undergoing tenodesis often experience significant improvements in pain and shoulder function, particularly when combined with rotator cuff repair.[43] The decision to proceed with tenotomy or tenodesis should also consider the patient's age, activity level, and the presence of concomitant shoulder pathologies. For instance, younger and more active patients may benefit more from tenodesis, as it preserves the biceps muscle's function and prevents cosmetic deformities associated with tenotomy, such as the "Popeye" deformity.[58] In severe cases where the rotator cuff cannot be repaired, prioritizing LHBT tenodesis can help stabilize the shoulder joint and improve overall outcomes.[59] Ultimately, the surgical strategy should be tailored to the individual patient's condition, taking into account the severity of the LHBT lesion, the integrity of the rotator cuff, and the patient's functional demands. This nuanced approach can lead to better clinical outcomes and enhanced patient satisfaction post-surgery.

Patient Age, Functional Demands, and Expected Recovery

In the context of rotator cuff repair, particularly focusing on the long head of the biceps tendon, the age and functional demands of the patient play a crucial role in determining the most appropriate surgical strategy. For younger patients with high functional demands, the choice of a tendon transfer repair, which is associated with better functional recovery, is often favored. These individuals typically engage in activities that require a greater range of motion and strength, making it imperative that surgical interventions restore as much functionality as possible. Research suggests that younger patients tend to have better healing capacities and a higher tolerance for more invasive procedures, which can lead to improved long-term outcomes when opting for tendon transfer techniques.[14] Furthermore, the anatomical intricacies of the shoulder, including the relationships between the biceps tendon and other rotator cuff structures, highlight the importance of preserving and optimizing the function of these interconnected elements during repair.[14]

Conversely, older patients or those with lower functional demands may benefit from a more conservative approach, such as tenotomy, which can provide rapid symptom relief. This demographic often presents with degenerative changes and may not require the same level of functional restoration as their younger counterparts. The primary goal in these cases is to alleviate pain and improve quality of life rather than to restore full athletic function. Studies indicate that tenotomy can be effective in reducing pain and improving shoulder function in older patients, allowing them to return to daily activities without the need for extensive rehabilitation that more complex repairs would necessitate.[14] Moreover, the decision to perform a tenotomy rather than a more invasive repair can be influenced by the patient's overall health status, comorbidities, and personal preferences regarding recovery time and expected outcomes.

In summary, the decision-making process surrounding the treatment of rotator cuff injuries, particularly concerning the management of the long head of the biceps tendon, must take into account the patient's age and functional demands. Younger, high-demand patients are generally better served by tendon transfer repairs that aim for optimal functional recovery, while older or low-demand patients may find greater benefit from tenotomy, which offers quicker symptom relief. This tailored approach not only aligns the surgical strategy with the patient's lifestyle and expectations but also enhances the likelihood of satisfactory outcomes post-surgery.

Postoperative Rehabilitation and Follow-Up Management

The postoperative rehabilitation and follow-up management of patients undergoing rotator cuff repair, particularly in the context of varying strategies for managing the long head of the biceps tendon, necessitate a tailored and individualized approach. Different surgical techniques and treatment modalities, such as tenodesis versus tenotomy, can influence the rehabilitation protocols employed. For instance, patients undergoing tenodesis may require a more gradual reintroduction of shoulder mobility and strength exercises to accommodate the altered biomechanics resulting from the surgical intervention.[60] Conversely, those who have undergone tenotomy may benefit from a more aggressive rehabilitation strategy aimed at restoring function and strength more rapidly, given the absence of the biceps tendon's stabilizing effects on the shoulder joint. This individualized rehabilitation design is critical, as it ensures that the specific needs of each patient are met, thereby optimizing recovery outcomes. Moreover, the rehabilitation process should incorporate regular assessments of shoulder function, strength, and range of motion to monitor progress and adjust the rehabilitation plan accordingly.[61]

In addition to individualized rehabilitation plans, imaging follow-up plays a crucial role in assessing the efficacy of the surgical intervention and in the early detection of potential complications. Advanced imaging modalities, such as ultrasound and MRI, can provide valuable insights into the healing status of the rotator cuff and the long head of the biceps tendon, allowing clinicians to evaluate tendon integrity, muscle atrophy, and any signs of re-tear.[62] For example, musculoskeletal ultrasound has been shown to be effective in monitoring postoperative changes in shoulder structures, including the long head of the biceps tendon and surrounding soft tissues, thereby facilitating timely interventions if complications arise.[62] Furthermore, imaging follow-up can help guide rehabilitation strategies by providing objective data on the patient's recovery trajectory, allowing for adjustments to be made to the rehabilitation protocol based on the patient's healing progress and functional status. This comprehensive approach to postoperative rehabilitation and follow-up management is essential for maximizing functional recovery and minimizing the risk of complications, ultimately leading to improved patient outcomes following rotator cuff repair.

Conclusion

In conclusion, the management of LHBT lesions holds significant anatomical and functional implications in the context of rotator cuff repair. The strategies employed in addressing these lesions directly influence postoperative pain relief and functional recovery, underscoring the need for a nuanced understanding of the various treatment modalities available. Recent advancements in anatomy and imaging techniques have provided a more precise basis for diagnosing and treating LHBT pathologies, allowing clinicians to tailor their approaches based on individual patient needs.

As we have discussed, the spectrum of treatment strategies for LHBT lesions each presents unique advantages and limitations. For instance, the transfer repair technique has demonstrated superior outcomes in functional recovery; however, it is accompanied by increased surgical complexity. This complexity necessitates careful consideration of the patient's overall health, activity level, and personal goals when determining the most appropriate intervention. Conversely, tenotomy may be more suitable for patients with clearly defined symptomatic relief needs, offering a less invasive option that can effectively alleviate pain. Meanwhile, preservation and partial resection techniques serve as viable alternatives for patients presenting with mild lesions, allowing for a balance between preserving tendon function and addressing symptomatic concerns.

The challenge for clinicians lies in striking a balance between the varying research perspectives and findings surrounding these treatment modalities. It is essential to integrate evidence-based practices with the individual patient's clinical presentation and preferences. This individualized approach not only enhances patient satisfaction but also optimizes functional outcomes. The ongoing dialogue within the medical community regarding the best practices for LHBT lesion management is crucial, as it fosters an environment of continuous learning and adaptation to new evidence.

Looking ahead, future research endeavors must focus on elucidating the long-term efficacy of the different treatment strategies available for LHBT lesions. This includes not only comparing the functional outcomes of various surgical techniques but also refining postoperative rehabilitation protocols to maximize recovery potential. By establishing a clearer understanding of the long-term impacts of each intervention, we can better inform clinical decision-making and improve the overall treatment landscape for patients suffering from rotator cuff injuries.

In summary, the management of LHBT lesions in the context of rotator cuff repair is a complex interplay of anatomical understanding, surgical technique, and patient-centered care. As we advance our knowledge and refine our approaches, the ultimate goal remains clear: to enhance the quality of life for our patients through effective, personalized treatment strategies that address both their immediate symptoms and long-term functional aspirations.

Author Contributions

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

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