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Advancements in minimally invasive treatment of deltoid ligament injuries combined with distal tibiofibular syndesmosis injuries

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Abstract
The deltoid ligament (medial collateral ligament) and the syndesmosis (a composite ligamentous structure at the distal tibiofibular junction) are critical for maintaining ankle stability. In cases of high-energy ankle fractures, these structures are often injured simultaneously, leading to instability and potential long-term complications such as post-traumatic arthritis. This review aims to explore advancements in minimally invasive techniques for the treatment of combined deltoid ligament and syndesmosis injuries, with a focus on optimizing surgical outcomes and reducing patient morbidity. Current treatment strategies primarily involve cortical screws for syndesmosis stabilization and anchor fixation for deltoid ligament repair. Recent innovations, such as bioabsorbable screws, suture-button devices with elastic micromotion, and syndesmotic plates, have demonstrated potential in improving biomechanical stability while minimizing complications. Furthermore, minimally invasive techniques, including arthroscopic repairs with suture anchors, as well as ligament reconstruction using autografts, allografts, or synthetic ligaments, are becoming increasingly popular. By incorporating these advancements, the field is moving toward more effective and patient-centered approaches to achieve anatomical and functional restoration under minimally invasive principles. Future research should focus on further validating these techniques and identifying the most effective strategies for complex injuries.

Keywords Ankle fractures, Deltoid ligament, Distal tibiofibular syndesmosis injuries, Ligament repair, Minimally invasive surgery

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Introduction

Deltoid ligament injuries combined with distal tibiofibular syndesmosis injuries are often accompanied by avulsion or complete fractures and ligamentous tears. These injuries frequently occur simultaneously in clinical settings and are often associated with severe complications, making them a focal point of research and debate in foot and ankle surgery. Preoperative diagnosis of these injuries should be comprehensive, incorporating the mechanism of injury, physical examination, and imaging studies to fully assess the patient's condition.

Studies have shown that the contact area of the talus bone decreases significantly as the talus shifts laterally. Specifically, a displacement of 1 mm can result in a 42% loss of contact area [1]. Therefore, promptly restoring the rotational and valgus stability of the talus within the ankle mortise is critical. The stability of the talus depends primarily on non-osseous structures, especially the deltoid ligament and the distal tibiofibular syndesmosis, underscoring the importance of accurate diagnosis and treatment of these injuries.

Conservative treatment is generally reserved for cases with intact osseous structures, where the ankle joint is immobilized using a cast or brace. However, this method relies on scar healing of the ligament ends, which significantly compromises ankle stability. Current surgical treatments often involve percutaneous screw fixation for syndesmosis injuries and anchor fixation for deltoid ligament repairs [2]. Nevertheless, studies have shown that patients treated with these traditional approaches often have poor outcomes, with low functional scores for the ankle joint [3]. Thus, simple fixation and natural ligament healing are insufficient to meet the demands of postoperative daily activities.

With the rise of minimally invasive techniques, the reconstruction or repair of ligaments to achieve both anatomical and functional restoration has emerged as a new therapeutic direction. Innovations such as elastic micromotion devices for syndesmosis injuries and arthroscopic repairs of deltoid ligaments are becoming mainstream approaches in foot and ankle surgery [4].

This review aims to summarize and evaluate the advantages and disadvantages of existing surgical treatment methods while exploring new materials and techniques under the concept of minimally invasive treatment. These include elastic devices, autograft or allograft ligament reconstruction, and arthroscopic techniques, providing clinicians with updated treatment principles and future directions for managing these complex injuries. The key points of the treatment of deltoid ligament injuries combined with distal tibiofibular syndesmosis injuries were shown in Table 1.

Pathogenesis

Injuries to the distal tibiofibular syndesmosis and the deltoid ligament are common in clinical practice, often occurring in conjunction with ankle fractures. The primary mechanism of these injuries is abduction and external rotation, frequently observed in Maisonneuve fractures or Dupuytren fractures [5]. The most common type is supination-external rotation ankle fractures, such as Danis-Weber type B, while pronation-external rotation ankle fractures, such as Weber type C, are also seen [6].

Currently, most syndesmosis injuries occur due to significant rotational forces experienced during ankle motion. When subjected to external rotational forces, the fibula externally rotates, and the anterior inferior tibiofibular ligament (AITFL) is subjected to excessive tension, exceeding its biomechanical limit, leading to injury or rupture [7]. Additionally, when external rotation is combined with foot abduction, exerting force on the interosseous membrane, it can result in a complete rupture of the deltoid ligament and separation of the tibiofibular syndesmosis [8].

The integrity of the syndesmosis and the deltoid ligament is crucial for ankle joint stability and directly impacts treatment strategies [9]. From an anatomical perspective, ankle stability is maintained by three key structures: the medial malleolus and deltoid ligament, the lateral malleolus and lateral collateral ligament, and the distal tibiofibular syndesmosis [10]. If one of these structures is compromised but the other two remain intact, ankle stability is typically preserved, and surgical intervention is not generally required. However, with advancements in foot and ankle surgery and sports medicine, the understanding of combined deltoid ligament and syndesmosis injuries has significantly evolved, laying a solid foundation for precise and effective treatment.

Anatomical and biomechanical characteristics

In the structure of the ankle joint, the distal tibiofibular syndesmosis plays a crucial role. It not only provides effective control over ankle joint stability but also supports its functional mobility. Additionally, the syndesmosis counters axial, anteroposterior, and rotational stresses, serving as a key mechanism to protect the ankle [5]. It is composed of the anterior inferior tibiofibular ligament (AITFL), posterior inferior tibiofibular ligament (PITFL), transverse ligament, interosseous ligament, and the distal portion of the interosseous membrane. The syndesmosis allows a micromotion range of 2° to 5° in three-dimensional space, which buffers excessive forces and reduces the risk of fractures [8].

The deltoid ligament, also known as the medial collateral ligament, connects the distal tibia to the talus in a fan-shaped structure. It consists of two layers: the superficial and deep layers [11]. The superficial layer comprises

Table 1 The key points of the Treatment of Deltoid Ligament Injuries Combined with distal tibiofibular syndesmosis injuries

Category	Key Points
Conservative Treatment	- Conservative treatment relies on fibrous scar healing, often leading to anatomical and functional impairments. - Casting for 6–12 weeks provides relative stability; early functional rehabilitation helps reduce joint stiffness and muscle atrophy. - Advanced imaging technologies, such as high-resolution MRI and ultrasound, allow dynamic monitoring of ligament healing to ensure proper recovery. - Reserved for stable injuries or patients with contraindications to surgery. Surgical repair becomes essential when the ruptured ligament hinders joint reduction.
Surgical Treatment	Syndesmosis Injuries - Percutaneous Screw Fixation: A minimally invasive method requiring precise screw placement. Risks include malreduction, over-compression, or malalignment if anatomical landmarks and imaging guidance are not meticulously utilized. - Elastic Fixation Devices: Suture-button systems, syndesmotic hooks, and hook plates allow for micromotion and early weight-bearing. Two-suture-button systems improve stability but may still fall short of native syndesmosis strength. Bioabsorbable suture-buttons show promise in optimizing functional recovery. Deltoid Ligament Injuries - Absorbable Anchors: Fully embedded anchors reduce surgical trauma, irritation, and the need for implant removal. They ensure robust fixation, even in cases of compromised healing, and effectively restore mechanical function. - Arthroscopic Repair: Minimally invasive arthroscopy enables direct visualization of ligament injuries, precise repairs, and improved postoperative outcomes. Advances like 4 K imaging, bioabsorbable anchors, and intraoperative imaging have enhanced the precision and durability of these repairs.
Treatment of Chronic Injuries	- Chronic injuries < 6 months: Aggressive ligament reconstruction using autologous gracilis tendons, combined with osteotomy to correct anatomical abnormalities. - Chronic injuries > 6 months: Distal tibiofibular fusion recommended to address chronic instability. - Advanced materials, such as nanoscale artificial ligaments and bioresorbable screws, reduce complications and improve functional recovery. - Allografts (e.g., semitendinosus tendon) minimize donor site morbidity while maintaining mechanical stability and promoting healing. - Combined limited-incision techniques and novel materials have enhanced surgical efficiency and long-term outcomes.
Future Trends	- Bioengineered Materials: Nanofiber-reinforced scaffolds mimic native ligament structure, enhancing biomechanical strength and tissue regeneration. - Advanced Imaging Guidance: Real-time imaging (e.g., intraoperative CT, ultrasound) improves precision during ligament reconstruction. - Minimally Invasive Techniques: Arthroscopic-assisted reconstruction reduces complications and recovery time while maintaining high patient satisfaction. - Allograft-Based Reconstruction: Superior outcomes with reduced donor site morbidity, enhanced functional scores, and fewer complications compared to autografts. - Novel Devices: Intraoperative tension-control devices replicate physiological forces, ensuring optimal joint stability. Future research will refine these protocols through large-scale clinical trials.

the tibionavicular ligament, tibiospring ligament, tibiocalcaneal ligament, and the superficial posterior tibiotalar ligament, which collectively prevent excessive talar eversion [12]. The most superficial structure, the tibiospring ligament, primarily supports the functions of the superficial layer [11]. The deep layer includes the deep anterior tibiotalar ligament and the deep posterior tibiotalar ligament, which restrict excessive talar pronation and maintain joint stability. Among these, the deep posterior tibiotalar ligament is the strongest component of the deltoid ligament complex. Overall, the deep layer of the deltoid ligament contributes significantly more to ankle stability than the superficial layer [12].

Diagnosis of the disease

Clinical presentation

Distal tibiofibular syndesmosis injuries often manifest as pain, swelling, and restricted mobility around the lateral malleolus. Common diagnostic methods include the Cotton test and external rotation test [13]. Mild syndesmosis injuries can often be diagnosed through physical examination. However, in cases of severe soft tissue contusion or fractures, pain may lead to false-positive results, necessitating further confirmation with imaging studies [8].

Patients with deltoid ligament injuries often have a history of ankle sprain, accompanied by medial malleolus tenderness and restricted motion. However, these symptoms are only indicative and cannot confirm a diagnosis. Definitive diagnosis requires combining eversion stress tests, the Cotton test, and imaging findings.

Physical examination

Medial malleolus tenderness can be a preliminary indicator of medial malleolus fractures or deltoid ligament injuries. Common tests include:

External rotation stress test With the patient seated and the hip and knee flexed at 90°, the examiner stabilizes the leg and externally rotates the foot to observe for pain.

Squeeze test Compression of the mid-calf to check for tenderness, though its sensitivity is relatively low [13].

Lateral malleolus examination may reveal tenderness over the syndesmosis. Additionally, external rotation tests, the Cotton test, and dorsiflexion tests are highly sensitive for diagnosing syndesmosis injuries [14].

Imaging studies

X-ray

X-rays are effective for screening musculoskeletal injuries in emergency settings. A distal tibiofibular gap > 6 mm suggests syndesmosis injury; a medial clear space > 4 mm or a talar tilt angle of 6°–10° indicates possible deltoid ligament injury. Injecting 3 ml of contrast medium into the ankle can assist in evaluating syndesmosis injuries through anatomical landmarks [15]. What is more, weight-bearing ankle plain X-rays are a critical diagnostic tool for evaluating the stability of ankle injuries, particularly in the context of suspected ligamentous injuries or fractures. They provide unique insights that non-weight-bearing X-rays or other imaging modalities may not reveal. They help identify subtle diastasis of the distal tibiofibular syndesmosis or medial clear space widening, which are hallmarks of unstable injuries [16].

CT

CT provides precise information on bony structures. A distal tibiofibular gap > 6 mm on the anterior tubercle of the distal tibia suggests injury. CT scans in coronal and sagittal planes can detect displacements of 2–3 mm, but sensitivity decreases for displacements < 1 mm [17]. While CT excels at assessing fracture displacement and classification, it is less effective for soft tissue evaluation. At the meantime., weight-bearing CT is a highly sensitive and specific tool for evaluating subtle ankle instability. Its ability to visualize the joint under load, combined with precise measurements and quantitative analysis, makes it a valuable addition to the diagnostic arsenal, especially in complex or ambiguous cases of ankle instability.

MRI

MRI is considered a good option for imaging diagnosis of syndesmosis injuries. It allows detailed visualization of ligament morphology and helps identify ischemia, soft tissue edema, and acute ligament injuries [18]. Studies have shown that superficial deltoid ligament tears often occur distally, while deep tears are commonly proximal, which can be confirmed using coronal MRI [19]. Sagittal MRI is required to detect distal deltoid or spring ligament tears. But MRI is typically performed in a non-weight-bearing position, making it less effective at detecting functional or load-induced instability. Considering the above point, weight-bearing X-rays or CT scans may be more helpful in order to identify instability.

Ultrasound

Ultrasound, with its non-radiation and low cost, is increasingly used to detect syndesmosis separation [13]. High-frequency ultrasound offers precise clinical diagnosis by assessing ligament thickness, course, and tension, especially for chronic ligament injuries [13].

Dynamic imaging

Although less reliable than weight bearing X-rays as they frequently overestimate the injury, dynamic imaging techniques, such as dynamic X-rays or dynamic MRI, are increasingly used to assess ankle injuries. These techniques capture joint movements in different positions, improving sensitivity for detecting subtle syndesmosis and deltoid ligament injuries.

Conservative treatment

Fractures involving deltoid ligament and distal tibiofibular syndesmosis injuries are often classified as highly unstable ankle injuries [13]. Conservative treatment primarily relies on fibrous scar healing of the ligaments, which can lead to significant anatomical and functional impairments. This instability may result in severe complications such as post-traumatic arthritis, chronic pain, and functional disability. Therefore, non-surgical treatment should be cautiously considered and is typically reserved for patients with specific contraindications to surgery or stable injuries, or in rare cases of mild injuries.

In non-surgical management, long-leg or short-leg casting for 6–12 weeks is commonly used to ensure relative stability of the ankle joint [20]. Recent studies suggest that early functional rehabilitation after cast removal may help minimize joint stiffness and muscle atrophy, promoting better functional recovery in patients with mild deltoid ligament and syndesmosis injuries [21].

Additionally, advancements in imaging technologies, such as high-resolution MRI and ultrasound, allow for dynamic monitoring of ligament healing during conservative treatment, ensuring that the recovery meets functional requirements.

For isolated ligament injuries with proper joint alignment, conservative treatment can achieve satisfactory short-term outcomes in selected cases with stable joints [22]. However, when the ruptured ligament precludes the reduction of the ankle joint, surgical repair of the ligament is essential. In case an anatomical reduction of the syndesmosis and the ankle joint has been achieved, the surgery repair of the ligament is optional.

Operation treatment

Treatment of syndesmosis injuries

Percutaneous screw fixation

Percutaneous screw fixation with a limited incision is a well-established method for treating syndesmosis injuries [23]. According to Bekerom et al. [24], the following points should be considered during screw placement: (1) The screw should be positioned 2–4 cm proximal to the tibiotalar joint surface and aligned parallel to the joint line. (2) In the transverse plane, the screw should be inserted at a 30° angle from posterolateral to anteromedial to prevent syndesmosis constriction that could restrict ankle dorsiflexion. Percutaneous syndesmosis fixation, while minimally invasive, may carry an increased risk of malreduction compared to open techniques, particularly when imaging guidance or proper anatomical landmarks are not meticulously utilized. The use of clamping during percutaneous syndesmosis fixation has been debated [25]. While clamping can facilitate joint reduction, improper use may inadvertently lead to overcompression or malalignment [26].

Biomechanical studies indicate that placing screws 30–40 mm above the tibiotalar joint minimizes Mises equivalent stress and provides optimal fixation [27, 28]. Fibula fracture should be fixed at any level except the fibular head, in order to gain the proper length [29].

During surgery, screws can be fixed through either 3 or 4 cortices. Fixation through 3 cortices is associated with a lower risk of joint space narrowing, while 4-cortex fixation provides greater holding strength but carries a higher risk of screw breakage. Liu et al. [6] suggested that the diameter of the fibula determines the appropriate screw size. Once the syndesmosis ligament has healed, screw removal is optional to prevent adverse effects on ankle function or risks of loosening and breakage [30].

CT imaging has shown that the rate of malreduction of the syndesmosis can reach up to 36% after screw fixation, but this rate significantly decreases after screw removal [31]. Therefore, it is recommended to remove screws within 8–12 weeks postoperatively to allow for ligament healing and restoration of normal joint function.

In recent years, the use of bioabsorbable screws has emerged as a solution to the potential complications of permanent metal implants. Bioabsorbable screws provide sufficient fixation strength and gradually degrade after tissue healing, eliminating the need for secondary screw removal surgery [32]. While bioabsorbable screws are designed to provide sufficient strength during the healing period, their mechanical properties may be inferior to those of metallic screws, particularly in high-stress applications or in patients with poor bone quality. In addition, during the degradation process, bioabsorbable screws can release acidic byproducts, potentially causing local inflammation, sterile effusion, or osteolysis in some patients [33].

Minimally invasive elastic fixation devices for distal tibiofibular syndesmosis

Minimally invasive elastic fixation devices for the distal tibiofibular syndesmosis are designed based on the biomechanical characteristics of the ankle joint and are effective in achieving syndesmosis reduction. These devices offer several advantages, including reduced surgical trauma through limited incisions, allowing micromotion of the syndesmosis to align with its physiological function, relatively simple operation without the need for secondary implant removal, and enabling early weight-bearing and functional training.

Common elastic fixation devices include the suture-button system, syndesmotic hooks, and hook plates. Studies have shown that single suture-button fixation achieves results comparable to traditional screw fixation. However, using two suture-buttons (2-Suture-button) provides better outcomes in anatomical reduction and rotational stability, though it may still fall short of the stability seen in a healthy syndesmosis [34]. The suture-button system offers specific advantages, such as avoiding common complications of screw fixation like loosening or breakage, and eliminating the need for secondary implant removal. However, appropriate tension must be maintained during application to prevent over-compression of the syndesmosis, which could impair joint function [35].

The Tightrope system is an innovative minimally invasive method for treating syndesmosis injuries. Research reports an overall repair satisfaction rate exceeding 95%, with no need for secondary implant removal [36]. Furthermore, the Bolt Tightrope system, which combines bolt compression with a suture-loop titanium plate, has demonstrated favorable clinical outcomes. However, intraoperative care is essential to avoid irritation of distal tibial soft tissues or excessive pressure on the cortical bone.

Recent studies suggest that elastic fixation devices maintain biomechanical stability of the syndesmosis more effectively than traditional screws during long-term weight-bearing activities [37]. Additionally, the development of novel materials such as bioresorbable suture-button devices has shown promise in optimizing functional recovery. These advancements have made minimally invasive treatment of syndesmosis injuries safer and more effective, providing new possibilities for restoring ankle joint function.

Treatment of deltoid ligament injuries

Minimally invasive repair with absorbable anchors

Traditional methods for repairing deltoid ligament injuries, such as transosseous wire or non-absorbable suture repair, are associated with significant surgical trauma and suboptimal outcomes [38]. With advancements in medical biomaterials, minimally invasive suture anchor techniques have become the mainstream approach for deltoid ligament repair [39]. These anchors, which are fully embedded within the bone, minimize irritation to surrounding soft tissues and eliminate the need for secondary implant removal surgery. This technique simplifies the procedure while ensuring robust fixation of the bone cortex, avoiding unnecessary interference with the ligament. Even in cases of compromised blood supply or delayed healing at the ligament ends, at least two tension-bearing suture strands can adequately replace the deep layer of the deltoid ligament, restoring its mechanical function.

A critical aspect of this surgical technique is to secure the ligament repair only after fracture reduction and fixation, to prevent excessive tension on the repaired ligament that might compromise its integrity [40]. Shen et al. [38] conducted a retrospective study involving 34 patients with ankle fractures and deltoid ligament ruptures. All patients underwent primary suture anchor repair, with an average follow-up of 28.4 months. The mean final AOFAS score was 92.6, and the medial clear space on stress X-rays was (3.74 ± 0.32) mm, comparable to the contralateral uninjured side at (3.65 ± 0.17) mm. The study concluded that suture anchor repair achieved satisfactory surgical outcomes and effectively restored the deep posterior tibiotalar ligament.

Further follow-up studies have confirmed that the suture anchor technique offers superior results compared to traditional methods, particularly in addressing deep deltoid ligament injuries [41]. However, potential complications, such as rare occurrences of implant rejection or irritation of the surrounding skin, highlight the need for further research. Future directions may focus on evaluating various implant materials in terms of biomechanics and clinical outcomes, aiming to optimize both performance and patient comfort. Recent advancements, such as bioresorbable anchors with enhanced biocompatibility and reduced inflammatory responses, show promising potential in minimizing these complications and improving long-term outcomes.

Arthroscopic surgery for the ankle joint

Vega et al. [42] conducted a retrospective study on 13 patients with medial and lateral ligament injuries caused by ankle fractures. Using an anteromedial approach via ankle arthroscopy, ruptured deltoid ligaments were repaired under direct visualization with automated suture clamps. After an average follow-up of 35 months, the median AOFAS score improved significantly from 70 preoperatively to 100 at the final follow-up. All 13 patients reported substantial improvements in ankle function. Researchers emphasized that arthroscopy allows for direct visualization and assessment of deltoid ligament injuries and monitored repair to evaluate ankle stability after reconstruction [43].

Acevedo et al. [44] performed arthroscopic repair on 87 patients with deltoid ligament injuries. Using suture anchors and sutures during arthroscopic procedures, the patient satisfaction rate exceeded 90%. The minimally invasive nature of arthroscopic surgery, coupled with favorable postoperative outcomes, has provided a new solution for deltoid ligament repair. Arthroscopic minimally invasive surgery has become a significant trend in foot and ankle surgery.

Recent advances in arthroscopic techniques have significantly improved the precision and outcomes of deltoid ligament repairs. Enhanced instrumentation, including high-definition 4 K imaging systems and advanced suture management devices, has greatly increased the accuracy of visualizing ligament injuries and the efficiency of suture placement. The use of bioabsorbable suture anchors has also gained popularity due to their biocompatibility and the elimination of the need for hardware removal, with studies demonstrating outcomes comparable or superior to those of traditional metallic anchors. Additionally, combining arthroscopy with real-time imaging modalities such as ultrasound and intraoperative CT has enhanced the assessment of joint stability and ligament tension during repairs, improving surgical precision and reducing the risk of residual instability.

Biomechanical studies, although currently limited, have started to validate the stability and functional outcomes of arthroscopic deltoid ligament repairs, particularly under weight-bearing conditions. Another promising advancement is the incorporation of bioengineered ligament substitutes in arthroscopic procedures. These synthetic grafts, used alongside traditional suture anchors, offer superior mechanical strength and promote healing in cases of extensive ligament damage. Furthermore, recent long-term follow-up studies indicate that patients undergoing arthroscopic deltoid ligament repair maintain stable functional outcomes over a period of 5–10 years, reinforcing the efficacy and durability of arthroscopic approaches compared to open surgery [45]. These advancements collectively highlight the growing potential of arthroscopic techniques in foot and ankle surgery.

Treatment of chronic injuries

Ligament reconstruction for distal tibiofibular syndesmosis injuries commonly uses autologous fibular longus or brevis tendons [46]. This approach avoids issues such as implant rejection and screw loosening while meeting anatomical and functional restoration requirements. Additionally, artificial ligament materials, such as polyethylene terephthalate (PET), have been utilized due to their high tensile strength and biocompatibility, effectively accelerating functional recovery [47]. Combining absorbable screws, compression screws, and single-side suspension techniques further enhances surgical efficiency and reduces operative time.

Biomechanical studies suggest that oblique fixation through a limited incision between the anterior inferior tibiofibular ligament and the interosseous ligament provides optimal outcomes [48]. This technique effectively incorporates the micromotion mechanism of the syndesmosis, significantly improving ankle joint functionality while reducing the incidence of complications.

Connors et al. [49] reported a case of a female patient with an ankle fracture and syndesmosis rupture who underwent allograft semitendinosus tendon transplantation. After two syndesmosis screws were removed at 6 months postoperatively, the patient exhibited no signs of ankle instability or syndesmosis separation. At over two years of follow-up, the patient showed no notable functional loss.

Li et al. [50] conducted a biomechanical study comparing suture-button systems and autologous semitendinosus tendon reconstruction in 8 cadaveric specimens. They measured three-dimensional syndesmosis diastasis, ultimate torque, and rotation angles, finding no statistically significant difference between the two techniques in restoring syndesmosis function. However, the biomechanical results for autologous ligament reconstruction were more promising, warranting further clinical exploration.

Recent advancements in limited-incision techniques and novel materials, such as nanoscale artificial ligaments combined with absorbable screws, have expanded the possibilities for syndesmosis reconstruction. Limited-incision approaches not only minimize surgical trauma but also significantly enhance postoperative functional recovery. As more cases are accumulated and long-term follow-up data become available, refined surgical protocols will gradually emerge, offering superior treatment options for complex ankle injuries.

Traditional reconstruction techniques for the deltoid ligament involve anchoring less functional ligaments to the medial malleolus. Common approaches include Kitaoka, Wihberger, and Hintermann techniques, which use autologous tendons to reconstruct the tibionavicular ligament, aiming to restrict talar external rotation. Similarly, Deland's technique involves reconstructing the tibiocalcaneal ligament using autologous tendons to prevent talar eversion. Yoo et al. [51] investigated the use of autologous semitendinosus tendons as substitutes for the deltoid ligament, while Persaud [52] reported successful deltoid ligament reconstruction using autologous posterior tibial tendon transplantation. Immediate postoperative imaging revealed restoration of normal anatomical alignment, and 14-month follow-ups demonstrated satisfactory imaging and clinical outcomes.

These techniques, however, are performed at the expense of autologous tendons such as the flexor hallucis longus and fibularis longus. This approach not only involves significant surgical trauma but also impacts the muscle strength at the donor site, potentially leading to long-term adverse effects on ankle joint function and arch stability. To address these limitations, superficial deltoid ligament repair can employ allogeneic semitendinosus tendons. This technique involves weaving the distal end of the tendon with suture anchor threads, offering advantages such as minimal invasiveness, shorter operative time, and reduced functional impact compared to traditional methods.

Brodell et al. [53] conducted a retrospective study on deltoid ligament reconstruction, involving 14 patients. Among these, 6 underwent allogeneic semitendinosus tendon transplantation, and 8 received allogeneic fibularis longus tendon grafts. Postoperative weight-bearing X-rays showed that the reconstructed feet achieved normal anatomical alignment. After an average follow-up of 24 months, the mean Foot and Ankle Ability Measure (FAAM) score improved from 69.3 preoperatively to 90.1 postoperatively. Oburu et al. [54] utilized Y-shaped allograft popliteus tendons to reconstruct both the deep and superficial layers of the deltoid ligament. They further reinforced the allograft tendons with fiber bundles or non-absorbable fiber sutures to ensure robust fixation.

Recent studies have explored advanced materials and minimally invasive approaches to enhance deltoid ligament reconstruction. Bioengineered ligaments, such as nanofiber-reinforced scaffolds, have shown promise in improving biomechanical strength and reducing immune responses [55]. These materials mimic the native ligament structure and provide an ideal environment for cell proliferation and tissue regeneration. Additionally, 3D-printed scaffolds tailored to patient anatomy have demonstrated the potential to ensure optimal fit and mechanical stability while promoting host tissue integration.

Combined techniques, such as arthroscopic-assisted reconstruction with advanced imaging guidance (e.g., intraoperative CT or ultrasound), have improved surgical precision and outcomes [56]. These approaches reduce intraoperative complications and enhance postoperative recovery. Furthermore, recent meta-analyses suggest that allograft-based techniques outperform autografts in terms of reducing donor site morbidity, improving functional scores, and lowering complication rates [57]. Allografts combined with bioresorbable anchors are gaining popularity among surgeons.

The development of intraoperative tension-control devices has also significantly advanced deltoid ligament reconstruction. These devices ensure precise replication of physiological forces, which is critical for restoring normal joint mechanics. Future research should focus on optimizing graft selection, evaluating the long-term performance of novel materials, and standardizing reconstruction protocols. Prospective controlled trials and large-scale biomechanical studies will be essential in driving further progress.

This integration of innovative materials, advanced technologies, and minimally invasive approaches is transforming deltoid ligament reconstruction into a safer, more effective, and patient-centered procedure.

Patients with combined distal tibiofibular and deltoid ligament injuries require timely surgical intervention. Delayed treatment can lead to joint instability, degenerative changes, cartilage damage, and, in severe cases, traumatic arthritis. For patients with high expectations for functional recovery, simultaneous repair of both ligaments may be considered. However, the final surgical approach should be based on clinical presentation, imaging findings, and arthroscopic evaluation.

For chronic injuries with a duration of less than six months, aggressive repair or reconstruction of the ligaments is recommended [58]. This often involves reconstruction using autologous gracilis tendons, combined with osteotomy to correct abnormal bony structures and restore stability. For injuries lasting more than six months, distal tibiofibular fusion is generally advised to address chronic instability [59].

When addressing chronic deltoid ligament injuries, the surgical approach should take into account the ligament's shorter and deeper anatomical characteristics and the presence of scar tissue. The preferred method involves fixing the original ligament using suture anchors. If the original ligament is insufficient, tendon grafts (e.g., semitendinosus tendon, flexor hallucis longus tendon, or plantaris tendon) can be used to stabilize the ankle joint.

Future perspectives

The future of minimally invasive treatment for combined deltoid ligament and distal tibiofibular syndesmosis injuries is promising, with advancements in surgical techniques and materials shaping new directions. The integration of advanced imaging technologies, such as augmented reality (AR), intraoperative 3D CT, and ultrasound, will enhance surgical precision by providing detailed visualization of ligament and joint structures during minimally invasive procedures. These tools will enable more accurate diagnosis, precise repairs, and reduced intraoperative complications.

Next-generation implants, including biocompatible and bioabsorbable suture anchors and fixation devices, are expected to provide optimal strength and stability while minimizing the need for hardware removal. Innovations such as bioengineered nanomaterials and 3D-printed patient-specific implants will further refine treatment options. Additionally, advancements in arthroscopic techniques, incorporating robotic assistance and improved instrumentation, are anticipated to make arthroscopy the gold standard for addressing combined injuries, offering greater precision and faster recovery times.

A growing emphasis on biomechanics and functional restoration will guide minimally invasive procedures, focusing on preserving natural joint motion and reducing the risk of post-traumatic arthritis. Biological augmentation, using growth factors, platelet-rich plasma (PRP), and mesenchymal stem cells, will play an increasing role in enhancing ligament healing and tissue integration, accelerating recovery and improving tissue quality.

Customized rehabilitation protocols will be tailored to individual patient needs, with early functional rehabilitation and real-time monitoring tools aiming to maximize recovery and minimize complications. The use of large-scale clinical data and artificial intelligence (AI) will support the development of evidence-based surgical protocols, assisting in predicting outcomes and optimizing treatment plans.

Finally, comprehensive long-term outcome studies will validate the efficacy and safety of minimally invasive approaches, helping to establish standard practices and improve long-term joint stability and patient satisfaction. The future of minimally invasive treatment for these injuries lies in integrating advanced technology, personalized medicine, and biological innovation to enhance surgical precision, patient outcomes, and overall recovery experiences.

Supplementary Information

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Supplementary Material 1

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