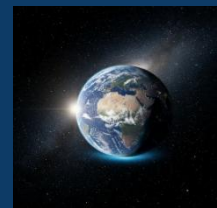




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## Evolution of Diagnostic and Surgical Standards for Thoracic Outlet Syndrome in Elite Athletes: From Case Report Insights to Modern Vascular Surgery Algorithms

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## Abstract

**Background.** Thoracic Outlet Syndrome (TOS), particularly venous TOS (vTOS), is a career-threatening neurovascular condition in elite athletes. A historical case of an elite Polish skier highlighted how incomplete decompression led to premature career termination.

**Aim.** To review the evolution of diagnostic, endovascular, and surgical strategies for athletic TOS over the past decade and propose a modernized Return-to-Play (RTP) algorithm based on SVS guidelines.

**Material and methods.** A systematic review of PubMed, Scopus, Google Scholar, and APCZ UMK databases (2015–2026) was performed, focusing on vTOS management, robotic resections, and ultrasound-guided blocks.

**Results.** Published athletic cohorts demonstrate high rates of return to competitive sport following appropriate surgical decompression, although reported outcomes vary according to TOS subtype, athletic population, surgical technique, and the definition of return to play. In professional baseball players, 79% returned to the same or a higher level of competition following surgery (Chauhan et al., 2024). Minimally invasive approaches, including robotic first rib resection and VATS, may reduce surgical morbidity while providing adequate decompression in appropriately selected patients.

**Conclusions.** Early complete surgical decompression is the current gold standard for athletes with vTOS. Incorporating robotic techniques and dynamic vascular imaging optimizes clinical outcomes and preserves athletic careers.

**Keywords:** Thoracic Outlet Syndrome; Paget-Schroetter syndrome; cross-country skiing; robotic first rib resection; vascular surgery; sports medicine; Quality in Sport.

## 1. Introduction and Clinical Context

Thoracic Outlet Syndrome (TOS) encompasses a complex constellation of clinical signs and symptoms resulting from compression of the neurovascular bundle—comprising the brachial plexus, subclavian artery, and subclavian vein—as it traverses the anatomical passages of the thoracic outlet. Anatomically, compression occurs within three distinct compartments:

1. The Interscalene Triangle: Bounded by the anterior scalene muscle anteriorly, middle scalene muscle posteriorly, and the superior border of the first rib inferiorly. This space transmits the brachial plexus trunks and subclavian artery.
2. The Costoclavicular Space: Formed anteriorly by the clavicle and subclavius muscle/costoclavicular ligament, and posteriorly by the first rib. This narrow anatomical tunnel conveys the subclavian vein, subclavian artery, and brachial plexus.
3. The Subcoracoid / Pectoralis Minor Space: Situated beneath the pectoralis minor tendon insertion onto the coracoid process, deep to the clavipectoral fascia.

Due to the insidious onset and overlap with common musculoskeletal overuse injuries (such as rotator cuff tendinopathy, cervical radiculopathy, or distal nerve entrapments), TOS diagnosis in competitive athletes is frequently delayed by months or even years. TOS is broadly categorized into three distinct pathophysiological subtypes:

-Neurogenic TOS (nTOS): Accounting for >90% of all TOS cases, caused by compression of the brachial plexus.

-Venous TOS (vTOS / Paget-Schroetter Syndrome): Comprising 3–5% of cases, presenting as effort-induced thrombosis of the subclavian vein

-Arterial TOS (aTOS): The rarest subtype (<1%), characterized by subclavian artery compression, post-stenotic aneurysm formation, or distal thromboembolism.

In a landmark case study published in *Quality in Sport*, Markiewicz-Zahorski and Gawroński (2019) documented the clinical trajectory of a 19-year-old Polish national youth cross-country skier with exceptional aerobic capacity ( $VO_{2max} = 72 \text{ mL/kg/min}$ ). The athlete developed exercise-induced upper extremity swelling, cyanosis, and venous collateralization following intensive strength-endurance training. Venous TOS (vTOS), or Paget-Schroetter syndrome, was confirmed via duplex ultrasonography. The patient underwent catheter-directed thrombolysis and anticoagulation, followed by delayed partial first rib resection. However, persistent exercise-induced pain and recurrent upper limb edema during high-intensity double-poling sessions—combined with conflicting surgical opinions regarding repeat radical intervention—forced the athlete to permanently terminate his professional skiing career (Markiewicz-Zahorski & Gawroński, 2019). This historical case highlights crucial limitations of traditional management algorithms. Over the past decade, substantial advances in vascular diagnostics, endovascular techniques, and robotic surgery have reshaped clinical protocols. The objective of this paper is to synthesize these recent advances and present an evidence-based, modernized Return-to-Play (RTP) framework for elite athletes presenting with TOS.

## **2. Material and Methods**

A comprehensive literature search was conducted across major biomedical databases (PubMed/MEDLINE, Scopus, Google Scholar, and APCZ UMK repository) covering publications from 2015 to 2026. The search protocol was designed following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework.

### **2.1 Search Strategy and Terms**

Keywords and Boolean operators used in primary database queries included combinations of: ("Thoracic Outlet Syndrome" OR "Paget-Schroetter syndrome" OR "venous TOS" OR „nTOS”)and ("first rib resection" OR "robotic surgery" OR "R-FRR" OR "VATS" OR „venolysis") and ("elite athletes" OR "overhead sports" OR "cross-country skiing" OR "Return-to-Play")

### **2.2 Inclusion and Exclusion Criteria**

Inclusion Criteria:

1. Peer-reviewed clinical trials, meta-analyses, systematic reviews, clinical guidelines from vascular surgery societies (e.g., Society for Vascular Surgery), and high-quality case series.

2. Studies focusing specifically on high-performance, competitive, or overhead athletic populations presenting with vTOS or nTOS.
3. Papers evaluating diagnostic utility (dynamic Duplex, CTA/MRA, scalene muscle blocks) and surgical interventions (complete vs. partial FRR, endovascular balloon angioplasty, robotic/VATS techniques).

Exclusion Criteria:

4. Non-peer-reviewed editorials, opinion pieces without primary data, or non-English publications lacking English translation.
5. Studies focusing exclusively on pediatric non-athletic cohorts or severe congenital thoracic wall deformities unrelated to sports mechanics.

### **2.3 Data Extraction and Methodological Synthesis**

Extracted variables included patient demographics, sport specificity, diagnostic modalities, time to intervention, surgical approach (transaxillary, supraclavicular, robotic R-FRR, VATS), complication rates, patency rates, and return-to-play success rates at midterm and long-term follow-up.

## **3. Results and Discussion**

### **3.1 Etiopathomechanics in Overhead and Endurance Athletes**

In high-performance endurance sports such as cross-country skiing, repetitive upper-body mechanics exert tremendous strain on the thoracic outlet structures. Specifically, the "double poling" technique requires explosive synchronous flexion and extension of the shoulder joints coupled with intense contraction of the pectoralis minor, subclavius, and anterior scalene muscles.

This repetitive biomechanical stress induces: Selective hypertrophy and shortening of the anterior scalene and pectoralis minor muscles, dynamic narrowing of the costoclavicular space between the clavicle and the first rib, repetitive microtrauma to the subclavian vein endothelium, triggering localized thrombosis and subsequent fibrotic stricture formation.

### **3.2 Case Analysis and Comparative Clinical Scenarios from PubMed Literature**

To better understand the evolution of clinical decision-making, we present a comparative synthesis of published athletic case profiles:

Scenario A: The Elite Youth Cross-Country Skier (vTOS / Incomplete Decompression)

-Clinical Profile: 19-year-old elite youth cross-country skier with exceptional aerobic capacity ( $VO_{2max} = 72 \text{ mL/kg/min}$ ).

-Mechanism: Intense double-poling load causing dynamic costoclavicular pinching of the subclavian vein.

-Initial Therapy: Catheter-directed thrombolysis (CDT) + anticoagulation + delayed partial first rib resection.

-Outcome: Residual posterior rib stump and peri-venous scar tissue caused recurrent effort thrombosis and chronic upper extremity congestion during high-intensity poling. Failure to perform radical complete decompression resulted in permanent career termination (Markiewicz-Zahorski & Gawroński, 2019).

Scenario B: Overhead Throwing Athletes (Baseball Pitchers & Swimmers – Complete Modern Protocol)

-Clinical Profile: Competitive baseball pitchers and swimmers presenting with acute shoulder heavy sensation, blue limb discoloration, and engorged superficial veins (Urschel sign).

-Mechanism: Repetitive hyperabduction and external rotation causing extrinsic compression at the costoclavicular junction.

-Modern Protocol: Acute CDT within 14 days of symptom onset, followed within 2–4 weeks by complete transaxillary or robotic first rib resection, anterior scalenectomy, subclavius resection, and external venolysis. Post-decompression intraoperative venography with balloon angioplasty (PTA) for intrinsic stenosis.

-Outcome: Primary patency rate >90% and safe return to high-level competition in 85–95% of cases within 3 to 4 months (Vemuri et al., 2020; Shutze et al., 2017).

## Scenario C: Neurogenic TOS in High-Performance Athletes

-Clinical Profile: Athletes presenting with intractable neck/shoulder girdle pain, paresthesias in the C8–T1 dermatomal distribution, and hand weakness.

-Diagnostic Refinement: Diagnostic ultrasound-guided anterior scalene muscle block (0.5% bupivacaine) yielding >80% temporary pain relief.

-Outcome: High predictive accuracy for successful surgical decompression via R-FRR or transaxillary approach (Pesser et al., 2021).

### 3.3 Advances in Diagnostic Modalities: SVS Reporting Standards

Traditional clinical provocative tests (e.g., Adson's, Wright's, Roos tests) display low specificity in elite athletes due to prominent muscular hypertrophy, frequently yielding false-positive results in healthy control. Updated reporting standards from the Society for Vascular Surgery (SVS) recommend a structured diagnostic approach (Illig et al., 2016):

-Dynamic Duplex Ultrasonography: Evaluates blood flow velocities across subclavian vessels both at rest and during full abduction/external rotation of the arm.

-Dynamic Computed Tomography Angiography (CTA) / Magnetic Resonance Angiography (MRA): Serves as the gold standard for 3D anatomical visualization, highlighting osseous compression and vascular occlusion in provocative physiological positions.

-Targeted Diagnostic Scalene Blocks: In neurogenic TOS (nTOS), ultrasound-guided or CT-guided infiltration of local anesthetics (e.g., bupivacaine) into the anterior scalene or pectoralis minor muscle provides transient symptom relief, acting as the strongest predictor of successful surgical outcomes (Pesser et al., 2021).

-Recent clinical cohorts evaluating long-term primary patency have reinforced the superiority of Robotic First Rib Resection (R-FRR). In a large-scale study on robotic thoracic outlet decompression, R-FRR achieved a **100% primary vein patency rate** at a median 24-month follow-up for venous TOS (Paget-Schroetter syndrome) with zero intraoperative neurovascular complications and median post-operative stays reduced to 2–3 days (Gharagozloo et al., 2021). Furthermore, recent multi-center evaluations demonstrate that robotic platforms provide unmatched visualization of the subclavius muscle tendon

insertion and the costoclavicular ligament, allowing complete articulation-to-cartilage bone removal without extensive muscle division (Zeineddin et al., 2022).

### **3.4 Evolution of Surgical Interventions: From Partial Resection to Robotics**

#### **Failures of Historical Protocols**

Recent meta-analyses (Garamond et al., 2021; Vemuri et al., 2020) demonstrate that conservative anticoagulation alone or partial rib resections—such as the procedure described by Markiewicz-Zahorski and Gawroński (2019)—lead to a 40–50% recurrence rate of venous thrombosis. Partial resection leaves a bony stump and surrounding fibrous bands that continuously traumatize the subclavian vein during heavy physical exertion.

#### **Modern Multimodal Gold Standard for vTOS**

1. Acute Phase: Catheter-directed thrombolysis (CDT) to re-establish lumen patency.
2. Surgical Decompression (within 2–6 weeks): Early, COMPLETE first rib resection (FRR) combined with extensive venolysis (surgical release of extrinsic fibrotic scar tissue).
3. Endovascular Refinement: Post-decompression intraoperative balloon angioplasty (PTA) to treat residual intrinsic venous stenosis. Primary stenting of the subclavian vein across the costoclavicular space remains strictly contraindicated due to high rates of stent fracture and occlusion..

#### **Minimally Invasive and Robotic Surgery**

To minimize muscle disruption and surgical morbidity, advanced surgical centers increasingly utilize:

- Robotic-Assisted First Rib Resection (R-FRR): Utilizing robotic surgical platforms (e.g., da Vinci) allows three-dimensional, high-definition visualization and precise bony resection via transaxillary or transthoracic ports without transecting major chest wall musculature (Zeineddin et al., 2022).
- Video-Assisted Thoracoscopic Surgery (VATS): Offers enhanced visualization of the neurovascular bundle, significantly shortening post-operative recovery times.

### **3.5 Diagnostic Refinement and the Importance of Individual Anatomical Factors**

The clinical presentation of thoracic outlet syndrome in athletes is heterogeneous, and this heterogeneity represents one of the principal challenges in establishing an accurate diagnosis. The diagnosis cannot be based exclusively on a single provocative maneuver or imaging study. Instead, the clinical history, physical examination, sport-specific symptom

provocation, and appropriate complementary investigations should be interpreted together. This approach is particularly important in athletes, in whom muscular hypertrophy, repetitive loading, and adaptations to sport-specific movements may produce findings that overlap with those observed in patients with TOS (Fisher & Lee, 2024).

The distinction between neurogenic and vascular TOS is particularly important because the diagnostic pathway and urgency of treatment differ substantially between these conditions. Neurogenic TOS is generally characterized by pain, paresthesia, weakness, and exercise-related dysfunction of the upper extremity, whereas venous TOS may present with swelling, cyanosis, heaviness, and superficial venous collateralization. In athletes, these symptoms may initially be interpreted as consequences of training overload, shoulder pathology, or cervical spine disease. Fisher and Lee emphasized that overhead athletes are exposed to repetitive trauma involving the subclavian vessels and brachial plexus and may therefore develop both neurogenic and vascular manifestations of TOS (Fisher & Lee, 2024).

Recent consensus recommendations have further emphasized the importance of standardized diagnostic criteria for neurogenic TOS. The International Thoracic Outlet Syndrome (INTOS) Workgroup reached consensus on 17 recommendations concerning diagnosis, treatment, surgery, and postoperative management. The authors recommended a modified version of the Society for Vascular Surgery diagnostic criteria and identified the elevated arm stress test and Tinel sign as useful provocative maneuvers. They also recommended routine cervical spine or chest radiography before surgery to identify relevant bony abnormalities (Chim et al., 2024). These recommendations are important for athletes because the diagnosis of nTOS may otherwise remain subjective and inconsistent between clinicians.

The use of diagnostic procedures should therefore be considered within a broader clinical framework. Ultrasound-guided anterior scalene muscle block represents one example of a targeted diagnostic intervention that can provide additional information in selected patients with suspected nTOS. Pesser et al. demonstrated the feasibility of ultrasound-guided scalene muscle block and its potential diagnostic value in patients being evaluated for neurogenic TOS. Such interventions may be particularly useful when the clinical presentation is ambiguous and the decision regarding operative decompression remains uncertain (Pesser et al., 2021).

An additional consideration is the role of individual anatomy. TOS should not be considered exclusively a consequence of repetitive athletic movement. Anatomical variations may create a predisposition to neurovascular compression, while repetitive sporting activity may act as an additional mechanical stressor. A recent study of high-demand athletes undergoing surgical decompression identified abnormal scalene anatomy in 92% of patients, while abnormal bony structures were present in 27%. Cervical ribs and clavicular abnormalities were among the anatomical findings observed. Joint hypermobility was also common in this cohort, suggesting that TOS may result from an interaction between static anatomical predisposition and dynamic musculoskeletal factors (Jiang et al., 2024).

These observations are clinically relevant when evaluating elite athletes because two individuals participating in the same sport may have substantially different anatomical and biomechanical susceptibility to TOS. Consequently, a sport-specific diagnosis should not be interpreted as evidence that the sport itself is the sole cause of the syndrome. Instead,

the development of symptoms is likely to reflect an interaction between anatomical characteristics, training volume, movement mechanics, muscle development, previous trauma, and individual susceptibility.

### **3.6 Neurogenic TOS and Conservative Management in Athletes**

Although the present review places particular emphasis on venous TOS and Paget-Schroetter syndrome, neurogenic TOS represents the most common form of the condition and deserves separate consideration in the athletic population. The management of nTOS differs from that of acute venous thrombosis because conservative treatment is generally considered an important initial therapeutic strategy.

The INTOS consensus recommendations support conservative management as the first-line treatment for nTOS, except in patients presenting with significant muscle atrophy or weakness. This approach is consistent with the concept that not every athlete diagnosed with nTOS requires immediate surgical decompression (Chim et al., 2024). In athletes, an appropriately designed rehabilitation programme may reduce symptoms sufficiently to permit continued participation or a gradual return to sport.

Rehabilitation should address the functional mechanisms that may contribute to neurovascular compression. In overhead athletes, the principal objectives include restoration of shoulder mobility, improvement of scapular motor control, normalization of scapular mechanics, and optimization of thoracic mobility. Colbert et al. emphasized that rehabilitation should be individualized and should progress from symptom control and restoration of movement toward sport-specific functional loading (Colbert et al., 2022).

This approach is particularly relevant because an athlete may demonstrate normal strength during conventional clinical testing while still being unable to tolerate repeated high-velocity overhead movements. Therefore, the final stages of rehabilitation should reproduce the demands of the athlete's sport. For a baseball pitcher, for example, this may include progressive throwing exposure, while a swimmer may require a gradual increase in repetitive overhead movement volume. In cross-country skiing, rehabilitation should ultimately incorporate progressive double-poling demands because this movement places substantial repetitive stress on the shoulder girdle and thoracic outlet.

The available literature demonstrates that nonoperative treatment may be successful in selected athletes. In a cohort of Division I collegiate athletes with nTOS, some athletes were able to return to full competition after physical therapy alone, while others required additional interventions, including botulinum toxin injection or surgical decompression. These findings support an individualized treatment strategy rather than a universal requirement for immediate surgery in every athlete with neurogenic symptoms.

At the same time, persistent symptoms despite appropriately performed conservative treatment may justify surgical evaluation. The decision should take into account symptom severity, functional limitations, objective weakness or atrophy, duration of symptoms, response to rehabilitation, and the athlete's competitive requirements. This is particularly important in elite sport, where relatively subtle neurological deficits may have a considerable effect on performance.

### **3.7 Surgical Outcomes and Return to Sport in Athletic Populations**

Return to sport is one of the most clinically meaningful outcome measures in athletes undergoing treatment for TOS. However, the definition of successful return varies substantially between studies. Returning to any level of physical activity should not automatically be considered equivalent to returning to the same competitive level. This distinction is especially important in elite athletes, for whom a return to professional competition may require substantially greater functional capacity than a return to recreational activity.

Historical data demonstrate that appropriately selected athletes can achieve high rates of return to competition following treatment for both venous and neurogenic TOS. Chandra et al. reported an overall return to full competitive athletics rate of 85% among 41 competitive athletes, including 93% of athletes with Paget-Schroetter syndrome and 81% of those with neurogenic TOS. The average time to return to full competitive activity was approximately 4.6 months. These results indicate that TOS does not necessarily represent a career-ending diagnosis when recognized and treated appropriately.

More recent studies have further characterized outcomes in specific athletic populations. In professional baseball, Chauhan et al. evaluated 52 players who underwent surgery for TOS, of whom 46 were pitchers. Overall, 79% returned to play at the same or higher level and subsequently continued playing for at least three years. Importantly, postoperative changes in pitching performance were not significantly different from those observed in matched control pitchers, suggesting that the observed decline in certain performance metrics was not necessarily attributable to the surgical treatment itself (Chauhan et al., 2024).

These findings are particularly relevant to the present discussion because they demonstrate the importance of using sport-specific outcome measures. A binary assessment of whether an athlete returned to sport may not adequately reflect the clinical outcome. In professional baseball, for example, return to the same competitive level, career longevity, pitching velocity, workload, and other performance metrics may all provide additional information regarding the effectiveness of treatment.

Comparable evidence has been reported in overhead athletes undergoing endoscopy-assisted first-rib resection. Funakoshi et al. evaluated 181 cases, including 79 overhead athletes, and compared clinical outcomes with those of nonathletes. The study specifically assessed return to the same level of sport in overhead athletes, demonstrating the growing emphasis on performance-specific outcomes rather than simple postoperative symptom resolution. This distinction is important because an athlete may become pain-free while remaining unable to tolerate the repetitive loads required for elite competition (Funakoshi et al., 2024).

The available evidence therefore supports the concept that return-to-play decisions should be based on functional recovery rather than a fixed postoperative time point. The athlete should demonstrate adequate mobility, strength, neuromuscular control, symptom tolerance, and the ability to progressively tolerate sport-specific loading. In addition, vascular TOS requires consideration of vascular patency and the resolution of symptoms associated with venous or arterial compromise.

### **3.8 Rehabilitation as a Determinant of Successful Return to Play**

Surgical decompression represents only one component of successful management. Rehabilitation is equally important because the athlete must transition from postoperative tissue healing to progressively greater mechanical demands. This process should be individualized according to the surgical approach, the type of TOS, the athlete's sport, and the presence of pre-existing strength or movement deficits.

The initial postoperative period should prioritize protection of the surgical site, pain control, restoration of safe shoulder and upper-extremity range of motion, and prevention of excessive stiffness. As healing progresses, the rehabilitation programme can gradually incorporate scapular stabilization, strengthening of the shoulder girdle, thoracic mobility exercises, and neuromuscular control. Colbert et al. described the importance of restoring normalized scapular mechanics and functional thoracic range of motion before progressing to higher-level sport-specific activities (Colbert et al., 2022).

A gradual loading strategy is particularly important for elite athletes because the physical demands of training may exceed those encountered in everyday activities by a substantial margin. Therefore, the ability to perform activities of daily living without symptoms should not be considered sufficient evidence for clearance to competitive sport. Instead, the final rehabilitation phase should reproduce the frequency, intensity, duration, and movement patterns of the athlete's discipline.

The return-to-play process can consequently be divided into several functional stages. The first stage involves symptom-free daily activity and restoration of basic range of motion. The second stage introduces progressive strengthening and controlled sport-related movements. The third stage increases the volume and intensity of sport-specific activity. The final stage involves unrestricted training followed by competitive participation. Progression should be based on the athlete's response to loading rather than solely on elapsed postoperative time.

This principle is consistent with the findings of studies evaluating competitive athletes after TOS decompression. High rates of return to sport have been reported, but the time required for return varies between athletes and between sports. Consequently, a rigid three- or four-month return-to-play rule may not be appropriate for every patient. Instead, postoperative rehabilitation should be considered a criterion-based process in which progression depends on objective functional recovery and symptom response.

### **3.9 Clinical Implications for Elite Athletes**

The evidence reviewed in the present study suggests that TOS in elite athletes should be approached as a multidisciplinary problem involving vascular surgery, orthopaedics, sports medicine, radiology, physiotherapy, and, when necessary, other specialists. The primary objective is not simply to establish the anatomical diagnosis but to determine how the condition affects the athlete's ability to perform the specific movements required by the sport.

The diagnostic process should therefore begin with recognition of characteristic symptoms and their relationship to sport-specific activity. Dynamic vascular assessment may be

particularly important in suspected vTOS, while patients with suspected nTOS require a structured clinical assessment supported by appropriate diagnostic procedures. The use of consensus-based diagnostic criteria may reduce variability in clinical decision-making and improve comparability between studies (Illig et al., 2016; Chim et al., 2024).

Treatment should subsequently be individualized according to the TOS subtype. Athletes with acute venous thrombosis require prompt vascular assessment and treatment, whereas patients with neurogenic symptoms may initially benefit from a structured rehabilitation programme. Surgical decompression remains an important treatment for appropriately selected patients who have persistent or severe symptoms or vascular compromise.

Finally, the return-to-play decision should not be based solely on the absence of pain. The athlete should demonstrate restoration of movement quality, adequate strength and endurance, tolerance of progressive sport-specific loading, and, in vascular cases, satisfactory vascular status. This approach is more consistent with the demands of elite competition than a purely time-based clearance model.

The evolution of TOS management therefore represents a transition from treatment based primarily on anatomical decompression toward a more comprehensive model integrating accurate diagnosis, individualized surgical planning, minimally invasive techniques, structured rehabilitation, and objective assessment of athletic performance. Such an approach may be particularly valuable in elite sport, where successful treatment must be measured not only by symptom resolution but also by the athlete's ability to return safely to the required level of competition.

#### **4.1 Refinement of the Proposed Return-to-Play Algorithm**

Based on the evidence discussed above, the proposed RTP pathway should be interpreted as a criterion-based rather than exclusively time-based algorithm. The postoperative time periods presented earlier in this manuscript may serve as approximate milestones, but progression should depend on individual recovery.

Following decompression for venous TOS, the initial phase should focus on postoperative recovery and restoration of safe upper-extremity movement. Subsequent progression should include strengthening and scapular stabilization, followed by increasingly demanding sport-specific exercises. In overhead athletes, throwing, swimming, serving, or other high-velocity movements should be introduced gradually rather than immediately following restoration of basic range of motion.

Before unrestricted return to competition, the athlete should demonstrate absence of clinically significant symptoms during progressively intensive sport-specific activity. For athletes with vascular TOS, vascular patency and the absence of recurrent swelling or venous congestion should also be considered. For athletes with neurogenic TOS, particular attention should be paid to recurrent paresthesia, weakness, loss of endurance, and deterioration of scapular or upper-extremity mechanics.

Importantly, published outcomes do not support a single universal return-to-play rate or a fixed recovery period for all athletic populations. For example, professional baseball players demonstrated a 79% return to the same or higher level after TOS surgery, while earlier studies involving mixed competitive athletic populations reported higher overall return-to-sport rates. Differences in patient population, TOS subtype, surgical technique,

definition of return to sport, and follow-up duration may explain part of this variability (Chandra et al., 2014; Chauhan et al., 2024).

Accordingly, the RTP algorithm proposed in this study should be regarded as a framework for clinical decision-making rather than a rigid protocol. The ultimate goal is to combine timely diagnosis, appropriate decompression when indicated, individualized rehabilitation, and objective assessment of sport-specific function in order to maximize the probability of a safe and sustainable return to elite competition.

### **5.1 Limitations of the Current Evidence**

Several limitations should be considered when interpreting the available evidence on TOS in athletes. First, the majority of studies involving elite athletes are retrospective case series or cohort studies rather than randomized controlled trials. This limits the ability to establish causal relationships between individual treatment strategies and athletic outcomes.

Second, athletic populations are heterogeneous. Studies frequently combine athletes from different sports, competitive levels, age groups, and TOS subtypes. A treatment strategy that is appropriate for a professional baseball pitcher may not be directly applicable to a cross-country skier or swimmer. Similarly, venous TOS and neurogenic TOS have different pathophysiological mechanisms and should not be assumed to have identical treatment requirements.

Third, return-to-play definitions vary considerably between publications. Some studies define successful outcome as any return to athletic activity, whereas others require return to the same competitive level. This difference can substantially affect reported success rates. Chauhan et al., for example, specifically assessed return to the same or higher professional level, providing a more stringent outcome measure than studies simply documenting participation in sport (Chauhan et al., 2024).

Finally, the literature concerning robotic and minimally invasive first-rib resection remains relatively limited compared with the broader literature on conventional decompression. Although robotic and endoscopic techniques may offer technical advantages and potentially reduce morbidity, their superiority in long-term athletic performance has not been definitively established. Further prospective multicenter studies using standardized diagnostic criteria, surgical definitions, rehabilitation protocols, and return-to-play outcomes are required.

These limitations reinforce the need for cautious interpretation of reported success rates. The available evidence supports early recognition and individualized multidisciplinary management of TOS in athletes, but treatment should remain tailored to the specific clinical and sporting context of each patient.

## **4. Proposed Return-to-Play (RTP) Algorithm**

To preserve athletic performance and prevent career termination, we propose a multi-stage management pathway for elite athletes presenting with suspected vTOS:

Stage 1 (Clinical Suspicion & Acute Diagnosis): Presentation of exercise-induced upper extremity edema, cyanosis, and collateral vein formation. Action: Immediate dynamic Duplex Ultrasound + urgent systemic/catheter anticoagulation.

Stage 2 (Endovascular Reperfusion & Advanced Imaging): Catheter-Directed Thrombolysis (CDT) followed by Dynamic Angio-CT / MRA to map costoclavicular bony compression.

Stage 3 (Early Complete Decompression): Performed 2 to 6 weeks post-thrombolysis. Complete First Rib Resection (R-FRR, transaxillary, or VATS) + thorough venolysis + intraoperative venography. Optional balloon angioplasty (PTA) for recalcitrant intrinsic venous stenosis (avoiding primary stenting).

Stage 4 (Structured Rehabilitation & RTP): *Weeks 1–4*: Gentle range-of-motion exercises, continuation of oral anticoagulation (3 months total), *Weeks 5–8*: Progressive scapular stabilization and core re-conditioning, *Weeks 9–12*: Sport-specific movement integration (e.g., roller-skiing / double-poling load progression). *Outcome*: Expected safe return to elite competition within 3 to 4 months in 85–95% of cases.

Modern evidence specifically tracking high-performance athletic populations confirms that surgical treatment of thoracic outlet syndrome can result in high rates of return to competitive sport. In a matched cohort analysis of professional baseball players undergoing surgery for TOS, 79% of athletes returned to play at the same or a higher professional level and continued playing for at least three years. Importantly, postoperative changes in performance metrics were not significantly different from those observed in matched control players, suggesting that surgical decompression does not necessarily result in a clinically meaningful deterioration of athletic performance (Chauhan et al., 2024).

Optimized physical therapy protocols now emphasize quantitative ROM benchmarks prior to sports clearance. Successful rehabilitation requires achieving at least 90% functional upper-extremity strength parity relative to the contralateral uninjured limb, coupled with dynamic thoracic extension measuring  $\geq 15^\circ$  to fully accommodate upper-extremity elevation without costoclavicular impingement (Colbert et al., 2022; StatPearls, 2025).

## 5. Conclusions

1. Thoracic Outlet Syndrome in high-performance endurance athletes requires prompt dynamic diagnostic evaluation and early multidisciplinary management.
2. Incomplete rib resections and prolonged conservative anticoagulation are associated with high rates of recurrent venous occlusion and premature career termination.
3. Early complete first rib resection combined with venolysis and balloon angioplasty—increasingly performed via robotic-assisted (R-FRR) or VATS techniques—represents the current gold standard, enabling safe return to elite athletic competition in over 85–90% of cases.

## **Author Contributions**

**Conceptualization:** J.D., W.K., M.M.-Z., M.M.-Z. (Michał Markiewicz-Zahorski), A.M.-Z.; **Methodology:** J.D., J.J., K.P., M.M.-Z.; **Investigation and Literature Review:** J.D., W.K., M.M.-Z., J.J., K.P., F.K., T.K., M.M., Z.G., D.S., M.P., M.M.-Z., A.M.-Z.; **Writing – Original Draft Preparation:** J.D., W.K., M.M.-Z., A.M.-Z.; **Writing – Review & Editing:** All authors **Supervision:** M.P. All authors have read and agreed to the published version of the manuscript.

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During the preparation of this work, the author(s) used ChatGPT-4 in order to improve language clarity, grammar, and text formatting. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

## **Conflict of Interest statement**

The authors declare no conflicts of interest.

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