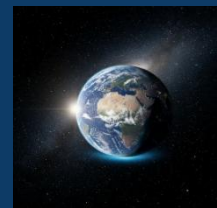




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Shoulder Overuse Injuries in Tennis Players: Biomechanics, Risk Factors, Prevention and Return to Sport - A Narrative Review

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Abstract

Background. Repetitive overhead loading places substantial demands on the shoulder in tennis, particularly when players are exposed to high volumes of serving.

Aim. To review current evidence concerning tennis-related shoulder biomechanics, risk factors, prevention, rehabilitation, and return to sport (RTS).

Materials and methods. A targeted narrative review of PubMed-indexed literature was conducted and supplemented by reference chaining from relevant reviews and consensus statements. Priority was given to systematic reviews, prospective cohorts, biomechanical studies, intervention trials, and clinical guidance.

Results. The tennis serve requires extreme glenohumeral rotation and exposes the shoulder to substantial mechanical loading. Dominant-arm internal-rotation loss and structural abnormalities are common, although they may reflect sport-specific adaptation rather than pathology. In adolescent competitive players, repeated workload spikes have been prospectively associated with higher rates of shoulder complaints and injury. Isolated ROM and strength measures, however, remain insufficient as stand-alone predictors of individual injury risk. Prevention and rehabilitation should combine progressive exposure, development of shoulder and kinetic-chain capacity, and gradual reintroduction of tennis-specific loading.

Conclusions. Tennis-related shoulder overuse injury is best considered a multifactorial problem in which mechanical demand interacts with exposure, physical capacity, and recovery.

Keywords: tennis; shoulder; overuse injury; biomechanics; rotator cuff; workload; prevention; rehabilitation; return to sport

1. Introduction

Tennis imposes a broad range of mechanical demands on the musculoskeletal system. Players accelerate, decelerate, change direction repeatedly, and perform high-velocity unilateral upper-extremity actions during both training and competition. Although acute lower-limb injuries account for a substantial proportion of the overall injury burden, chronic and overuse problems are particularly relevant in the upper extremity. The shoulder is repeatedly taken through large ranges of glenohumeral motion, especially during serving and other overhead actions. (1-3) The serve deserves particular attention. Unlike most groundstrokes, it is initiated entirely by the player and is commonly performed at high or near-maximal intensity. Generating serve velocity requires a coordinated transfer of mechanical energy beginning in the lower extremities and progressing through the pelvis, trunk, scapula, arm, forearm, and racket. (4-6) The shoulder therefore contributes to a larger proximal-to-distal kinetic sequence rather than acting as an isolated source of power. How changes within this kinetic chain affect shoulder loading is less straightforward than might initially be assumed. Some biomechanical studies indicate that altered coordination changes upper-extremity demands, but the direction and magnitude of these effects are not consistent across all experiments. Reduced front-knee flexion, for example, has been associated with greater upper-limb kinetics, while experimentally reducing leg drive has not consistently produced higher shoulder joint loading. Altered segment timing and less efficient energy transfer have likewise been linked with greater upper-limb kinetics or energy absorption. (7-13) Several of these studies followed athletes prospectively after the biomechanical assessment, which provides useful temporal information. Even so, sample sizes were generally modest. The findings therefore support biomechanical plausibility rather than a simple causal sequence in which one technical characteristic inevitably leads to future injury. The clinical picture is no less complex. Shoulder symptoms in tennis may involve the rotator cuff, long head of the biceps, labrum, capsular structures, internal impingement mechanisms, scapular dysfunction, or several of these structures at the same time. (4,14,15) At the same time, abnormal findings on physical examination or imaging do not automatically indicate clinically relevant pathology. Reductions in dominant-arm internal rotation, rotational strength asymmetries, scapular differences, and structural changes may all occur in players who remain asymptomatic. (16-21) Some of these findings are likely to represent adaptation to repeated unilateral overhead loading. This distinction has practical consequences. Prospective studies have challenged the assumption that a single screening measurement can reliably identify athletes who will later develop shoulder problems. Baseline ROM and strength measures have not consistently distinguished injured from uninjured players. Repeated spikes in external workload, on the other hand, have shown a clearer temporal association with shoulder complaints and injury in adolescent competitive players. (22,23) The purpose of this narrative review is to examine shoulder overuse injuries in tennis using a load-capacity framework. Particular attention is paid to serving biomechanics, physical and training-related risk factors, fatigue, prevention, rehabilitation, and RTS. A further objective is to separate biomechanical plausibility from prospective clinical evidence, since these two levels of evidence are often conflated.

2. Materials and Methods

A targeted narrative review was performed using PubMed-indexed literature together with citation chaining from key systematic reviews, consensus statements, and influential studies of tennis biomechanics. Search concepts included combinations of *tennis*, *shoulder*, *overuse injury*, *serve biomechanics*, *kinetic chain*, *glenohumeral rotation*, *rotator cuff strength*, *scapular dyskinesis*, *fatigue*, *training load*, *injury prevention*, *rehabilitation*, and *return to sport*. The literature search was updated through September 2026. Systematic reviews and meta-analyses were prioritized when summarizing the wider evidence base. Prospective cohort studies were given particular weight when evaluating potential risk factors, whereas primary biomechanical studies were used to describe the mechanical demands of serving. Intervention studies informed the sections on exercise and mobility, and consensus documents were used when discussing rehabilitation and RTS. Tennis-specific evidence was preferred whenever available. Findings from other overhead sports were incorporated when direct tennis evidence was limited. As the review was intended as a narrative synthesis, no formal PRISMA-based screening procedure was undertaken.

3. Results

3.1. Epidemiology and Clinical Characteristics of Shoulder Problems in Tennis

Reported injury rates in tennis vary considerably between studies. Differences in injury definitions, age groups, playing level, exposure measures, and follow-up periods make direct comparisons difficult. Despite this heterogeneity, epidemiological reviews consistently identify chronic upper-extremity disorders as an important part of tennis-related morbidity. (1-3) Time-loss definitions may also underestimate shoulder problems. Symptoms often develop gradually, and many players continue training or competing despite discomfort, sometimes by reducing serving intensity or modifying their playing routine. A shoulder problem can therefore be clinically relevant even when it does not immediately result in absence from sport. Professional players frequently demonstrate abnormal shoulder findings on clinical examination. López-Vidriero Tejedor et al. evaluated 135 athletes during ATP and WTA tournaments and reported a high prevalence of dominant-side alterations. Long-head biceps tenderness was present in 35% of dominant shoulders, while glenohumeral internal rotation deficit (GIRD) and scapular dyskinesis were also common. Ultrasound examination was additionally used to assess long-head biceps synovitis. (20) These findings do not imply that structural or clinical alterations inevitably produce symptoms. Johansson et al. reported MRI evidence of mild infraspinatus tendinosis in asymptomatic elite adolescent tennis players, accompanied by greater dominant-side infraspinatus and teres minor muscle size. (21) Repeated tennis exposure can therefore produce detectable structural and muscular changes without clear clinical dysfunction. For this reason, examination and imaging findings are best interpreted in context. Their relevance depends on symptoms, functional limitation, change from the athlete's usual status, and tolerance of tennis-specific loading rather than on the presence of an isolated asymmetry or structural abnormality.

3.2. Biomechanics of the Tennis Serve

3.2.1. Kinetic-Chain Contribution

The tennis serve is a whole-body movement. Mechanical energy is generated and transferred through a sequence of proximal-to-distal segments, and disruption at one level may alter the demands placed elsewhere. A commonly used framework divides the serve into eight stages: start, release, loading, cocking, acceleration,

contact, deceleration, and finish. (5) During loading, lower-limb flexion followed by extension contributes to force generation. Pelvic and trunk rotation then precede rapid upper-extremity movement. Scapular and glenohumeral motion position the arm for maximal external rotation, after which rapid internal rotation contributes to racket acceleration toward ball contact. (5,6,13) Reduced lower-limb contribution might be expected to increase shoulder loading, but the available evidence does not support such a simple relationship. Elliott et al. observed greater shoulder and elbow loading in players with reduced front-knee flexion despite similar ball velocities. (7) Reid et al., by contrast, reported broadly comparable shoulder kinetics across different leg-drive conditions, minimizing leg drive primarily reduced racket velocity. (8) Lower-limb contribution clearly influences serving performance and coordination, but reduced leg drive does not invariably translate into greater shoulder stress. Competitive level may also influence how mechanical load is distributed. Martin et al. identified differences in shoulder forces and torques between advanced and professional players, suggesting that similar performance outcomes may be achieved through somewhat different mechanical strategies. (9)

3.2.2. Glenohumeral Motion and Joint Loading

Elite serving requires exceptionally large shoulder motion. Fleisig et al. studied world-class players competing at the Sydney Olympic Games and reported a mean maximal shoulder external rotation of approximately 172°. Peak internal-rotation angular velocity reached approximately 2420°/s in men and 1370°/s in women. (24) These values illustrate the magnitude of the mechanical demand but should not be interpreted as thresholds beyond which injury occurs. Overuse injury is unlikely to be explained by a single high-velocity movement. Repeated exposure, the rate at which workload changes, recovery, and the player's current capacity to tolerate load are likely to be equally important. Technique nevertheless influences the distribution of joint loading. Elliott et al. found greater shoulder and elbow loading in players with less front-knee flexion, even though ball velocity remained comparable. (7) Certain technical characteristics may therefore increase the relative mechanical demand on the upper limb, although this relationship should not be generalized to all forms of reduced lower-limb contribution. Serve type also fails to provide a straightforward indicator of shoulder loading. In a comparison of high-performance flat and kick serves, Reid et al. found clear kinematic differences but broadly comparable shoulder joint loads. (25) Simply categorizing a serve as flat or kick therefore offers limited information about individual injury risk.

3.2.3. Energy Transfer and Potentially Unfavorable Mechanics

Joint angles and torques provide only part of the mechanical picture. Energy-flow analyses attempt to describe how mechanical energy is generated, transferred, and absorbed between segments during the serve. Martin et al. assessed serve mechanics in expert players and subsequently monitored them over two competitive seasons. Players who later sustained overuse injuries demonstrated less favorable energy-transfer patterns, greater energy absorption at selected upper-extremity joints, and lower serve velocity than players who remained uninjured. (10) A related investigation focused on the timing of pelvic, trunk, and upper-extremity actions. Certain temporal patterns were associated with greater upper-limb joint kinetics, and players who subsequently developed overuse injuries showed less favorable sequencing than their uninjured counterparts. (11) The fact that biomechanical testing preceded injury surveillance strengthens the temporal interpretation of these findings compared with cross-sectional studies. It does not, however, establish causality. The cohorts were relatively small, and residual confounding cannot be excluded. The waiter's serve provides a useful counterexample. Touzard et al. reported greater shoulder internal-rotation torque and other upper-limb loads in junior players using this technique,

despite similar serve velocity. Prospective follow-up did not show a statistically significant difference in injury occurrence. (12) Greater biomechanical loading, therefore, does not necessarily translate directly into a higher observed injury rate. A 2025 systematic review and meta-analysis identified rotational strength, internal-rotation ROM, weekly tennis volume, age, body mass, and height among variables associated with tennis-serve-related injury outcomes. (26) Many of the reported associations were based on relatively few studies and heterogeneous designs. No individual biomechanical or anthropometric variable emerged as a validated stand-alone predictor of injury.

3.3. Fatigue and Accumulated Exposure

Laboratory protocols generally examine a limited number of serves under relatively fresh conditions. Match play is different. A player may perform repeated high-intensity serves over several hours and then compete again the following day, sometimes without full recovery. Rota et al. found reductions in serve velocity and accuracy following strenuous exercise, alongside changes in maximal voluntary force and muscle activation. (27) Injury was not assessed, but the results show that fatigue alters both performance and neuromuscular function. Experimental work involving the lower trapezius points in a similar direction. Reduced lower-trapezius capacity changed scapular motion and muscle activation even though racket speed could still be maintained. (28) In other words, short-term performance may remain relatively stable despite altered neuromuscular organization. Whether these fatigue-related changes translate into higher clinical injury risk is uncertain. Most studies report biomechanical or performance outcomes rather than injuries, and no specific fatigue threshold has been linked reliably with subsequent shoulder pathology.

3.4. Glenohumeral Range of Motion

Rotational asymmetry of the dominant shoulder is one of the most consistent physical findings in competitive tennis. Ellenbecker et al. reported lower internal rotation in the dominant shoulder of elite junior players. (16) In a separate cohort of male junior athletes, total rotational motion was approximately 9° lower on the dominant side. (17)

A 2024 systematic review and meta-analysis including 25 studies reported a similar pattern. Pooled dominant-arm internal rotation was approximately 53°, compared with roughly 63° on the non-dominant side. (18) Asymmetry, however, should not be equated automatically with pathology. Years of unilateral overhead loading may influence capsular and muscular properties, movement strategy, and humeral torsion. Complete bilateral symmetry may therefore be neither realistic nor clinically desirable in every competitive player. Cross-sectional evidence further complicates interpretation. Moreno-Pérez et al. reported lower external-rotation strength and a lower external-to-internal rotation strength ratio in players with a history of shoulder pain. (19) Since the study was not prospective, it cannot establish whether these differences preceded symptoms or arose after them. Prospective evidence provides even less support for using ROM in isolation as a risk marker. In the SMASH cohort, baseline rotational ROM did not clearly distinguish players who subsequently developed shoulder injury from those who remained uninjured. (23) ROM assessment remains useful in clinical practice, particularly when previous measurements are available, but a single GIRD threshold should not be treated as an independent predictor of future injury.

3.5. Shoulder Strength and Scapular Function

The rotator cuff contributes to glenohumeral stability, rapid rotational movement, and eccentric deceleration during serving. Measuring shoulder strength is therefore relevant during assessment and rehabilitation. Its value

as a prospective injury predictor is less certain. In the SMASH cohort of 301 adolescent competitive players, higher eccentric external-rotation strength normalized to body mass was associated with subsequent shoulder injury. Higher isometric internal-rotation strength in the 90°/90° position was also associated with later injury. (23) These findings do not support a simple model in which greater strength is protective and weakness is inherently harmful. Competitive level, serve velocity, training exposure, and maturation may all influence the observed associations. Scapular dyskinesis has also attracted substantial attention. The scapula contributes to glenoid positioning and force transfer within the kinetic chain, making altered motion a plausible contributor to shoulder symptoms. Dyskinesis is common in overhead athletes and may coexist with shoulder pain. (14,20,29) Interpretation remains difficult because scapular motion varies considerably between individuals, and asymmetry may also be observed in pain-free athletes. Visual identification of dyskinesis alone should not therefore be treated as evidence of pathology. It may carry greater clinical relevance when altering scapular position or control also changes symptoms or functional performance.

3.6. Training Load and Shoulder Injury Risk

Among tennis-specific studies, workload provides some of the more convincing prospective evidence regarding shoulder outcomes. The SMASH cohort followed adolescent competitive players for 52 weeks and recorded spikes in tennis training, match play, and fitness training. (22) Each additional accumulated spike in tennis training/match-play workload was associated with an approximately 26% higher rate of shoulder complaints and a similar increase in the rate of shoulder injury. (22) Spikes in fitness training were also associated with shoulder outcomes, although the relationships were weaker. Because workload exposure was recorded before shoulder outcomes occurred, these findings provide useful temporal evidence. They do not establish a universal causal rule, nor do they validate one acute-to-chronic workload ratio or define a fixed number of serves that can be considered safe. Training duration by itself is also an imperfect measure of shoulder exposure. Two sessions of equal length can differ substantially in serve number, serve intensity, match density, groundstroke volume, strength training, technical demands, fatigue, recovery status, and recent training history. Bradley et al. similarly identified weekly tennis volume among variables associated with injury-related outcomes. (26) Broader overhead-sport research suggests that some factors, including rotational strength and scapular dyskinesis, may be associated with shoulder injury, whereas the evidence for ROM and several other isolated screening measures remains limited or inconsistent. (29,30) Together, these findings provide a rationale for prevention strategies that consider both the progression of exposure and the athlete's capacity to tolerate it.

3.7. Prevention

There is little evidence that shoulder injury prevention in tennis can be reduced to one exercise, one screening threshold, or one technical correction. A more realistic approach is to develop the athlete's capacity while avoiding unnecessarily abrupt increases in shoulder demand.

3.7.1. Load Management

Prospective workload data provide direct tennis-specific support for avoiding repeated sudden increases in external workload, although the strongest evidence comes from adolescent competitive players. (22) This may be particularly relevant after injury, illness, an off-season period, or another interruption in regular training. Keeping workload chronically low is not the objective. Competitive tennis requires substantial sport-specific exposure, and players need sufficient serving and match practice to develop tolerance. Progression is better considered in relation to recent training history, symptoms, and recovery than against a single universal

workload threshold. Monitoring does not necessarily require sophisticated technology. Weekly training duration, match density, major changes in serving volume, perceived exertion, and shoulder symptoms can already provide useful information when recorded consistently.

3.7.2. Strength and Kinetic-Chain Preparation

Physical preparation commonly targets the rotator cuff and scapular musculature, but serving cannot be reduced to the shoulder alone. Trunk and lower-limb function contribute to both force generation and its transfer through the kinetic chain. (5,7,8) Treiber et al. reported improvements in shoulder rotational torque and serve-related performance after a short program using elastic resistance and lightweight dumbbells. (31) These results demonstrate improvements in physical capacity, they do not show that the same intervention prevents shoulder injury. Evidence from other overhead sports remains heterogeneous. An earlier systematic review reported limited or conflicting evidence for many proposed risk factors and relatively little evidence concerning preventive interventions. (29) A later review was somewhat more favorable, reporting moderate evidence involving shoulder rotational strength, scapular dyskinesis, and prevention programs. (30) Wright et al. identified only seven eligible studies in a systematic review of shoulder injury prevention programs and concluded that the available evidence remained insufficient to establish overall effectiveness across overhead athletes. (32) Differences in sport, population, injury definition, intervention design, and study quality make direct translation to tennis difficult. Exercise is therefore better viewed as a way of developing physical capacity and addressing clinically relevant deficits than as a guarantee of injury prevention.

3.7.3. Mobility

Mobility interventions may be appropriate when a player has meaningful posterior-shoulder restriction or symptomatic loss of internal rotation. Rehabilitation guidance for tennis-related internal impingement includes restoration of clinically relevant glenohumeral mobility. (15) Anjupriya et al. randomized male tennis players with substantial dominant-side internal-rotation deficiency to modified sleeper or modified cross-body stretching. Both approaches improved internal-rotation ROM and upper-extremity functional scores over four weeks. (33) This supports stretching when a meaningful mobility deficit is present, but it does not establish that routine prophylactic stretching lowers future injury risk. Trying to eliminate every dominant-to-nondominant difference is therefore difficult to justify.

3.7.4. Technique

Technical assessment can be useful when a player appears to rely disproportionately on the upper extremity, demonstrates inefficient sequencing, or presents another movement pattern that plausibly increases local mechanical demand. Several biomechanical studies have shown that changes in serving technique can influence shoulder kinetics and energy transfer. (7-13,25) These effects are not uniform. More importantly, convincing trials demonstrating fewer shoulder injuries after correction of a particular serve pattern are lacking. The goal should therefore not be to force players toward a single idealized technique. A movement pattern that is efficient and appropriate for the individual athlete is a more defensible objective. Once symptoms have developed, however, the same interaction between exposure and physical capacity becomes relevant to rehabilitation.

3.8. Rehabilitation

Rehabilitation should begin with an attempt to identify the likely clinical source of symptoms rather than treating every presentation as a generic “tennis shoulder.” Rotator-cuff-related pain, biceps-labral pathology, instability, internal impingement, and other disorders may overlap clinically, yet the early rehabilitation priorities are not

necessarily identical. Imaging can be useful when it addresses a specific clinical question. Structural or ultrasound findings should not, however, be interpreted in isolation, since similar abnormalities may be observed in asymptomatic or minimally symptomatic tennis players. (20,21) The Bern consensus favors principle-based rehabilitation and progressive restoration of load rather than one protocol applied to every shoulder problem. (34) Early management often involves reducing the most provocative exposure while maintaining activities that remain tolerable. Complete withdrawal from tennis or conditioning is not necessarily required in every overuse presentation. As symptoms improve, the loading stimulus can gradually become more demanding. Controlled rotator-cuff and scapular exercises may progress toward heavier resistance, eccentric loading, faster contractions, and integrated kinetic-chain movements. (15,34) The trunk and lower extremities should also be incorporated. Keeping rehabilitation focused solely on isolated shoulder exercise does not reflect the demands of tennis. Later stages may therefore include rotational movements, overhead loading, medicine-ball work, racket-based drills, and ultimately serving. Progression is better guided by symptoms, function, and the response to previous loading than by a rigid timetable. Loading should not lead to progressive loss of function or substantial deterioration during the subsequent recovery period. Restoring shoulder function is only one part of the process. The final challenge is translating that recovery into tolerance of unrestricted tennis participation.

3.9. Return to Sport

RTS is better viewed as a progression than as a single clearance decision. An athlete may first return to selected training tasks, then to broader participation, and only later to unrestricted competitive performance. The Bern consensus recommends considering clinical status, physical capacity, sport-specific demands, psychological readiness, and tolerance of load. (34) A 2026 systematic review reported good reliability and validity for several upper-extremity functional tests, particularly the Single Arm Shot Put Test and Closed Kinetic Chain Upper Extremity Stability Test. Tennis-specific thresholds capable of independently determining RTS readiness, however, have not been established. (35) Clinically relevant domains may include acceptable pain, sport-relevant ROM, rotational strength and endurance, confidence during overhead movement, and tolerance of progressively faster activity. None has a universal tennis-specific cut-off that can determine readiness on its own. This matters because long-term tennis adaptation may make perfect bilateral symmetry an unrealistic target. Where available, preseason or preinjury measurements may be more informative than comparison with the non-dominant shoulder alone. The Single Arm Shot Put Test and Closed Kinetic Chain Upper Extremity Stability Test can provide additional information and have reasonable psychometric support in athletic populations. (35) Still, neither reproduces the repeated high-velocity demands of serving. They should therefore be considered components of assessment rather than stand-alone tennis RTS tests. The final stages of rehabilitation should include progressively increasing tennis exposure. Interval return-to-play programs generally increase groundstroke volume first, followed by gradual reintroduction of serving intensity, serve number, session duration, point play, sets, and unrestricted match participation. (36) A limited number of pain-free serves performed while fresh is not equivalent to readiness for tournament play. The athlete should demonstrate tolerance of repeated high-intensity serving without a clinically meaningful increase in symptoms during the session or subsequent recovery.

4. Discussion

Shoulder overuse injury in tennis is unlikely to have a single explanation. The serve requires extreme glenohumeral motion together with rapid generation, transfer, and absorption of mechanical energy, yet many players tolerate these demands for years without developing clinically relevant symptoms. What seems to matter

is the interaction between mechanical demand, exposure, physical capacity, recovery, and movement coordination. Biomechanical research describes the mechanical demands of serving in considerable detail. Elite players generate very high internal-rotation velocities and substantial shoulder kinetics, and alterations in lower-limb contribution, temporal sequencing, or energy transfer can modify upper-extremity mechanics. (7-11,13,24) The results are not always consistent. Reduced front-knee flexion has been linked with greater upper-limb loading, whereas experimentally minimized leg drive did not produce a parallel increase in shoulder kinetics in another study. (7,8) A simple statement such as “poor leg drive causes shoulder overload” is therefore not supported by the available evidence. Some biomechanical investigations offer stronger temporal evidence because athletes were assessed before subsequent injury surveillance. (10,11) This is an important methodological advantage, but it does not remove the limitations of small observational cohorts. Such studies can identify patterns that deserve attention, they cannot show that correcting one characteristic will prevent injury or reliably identify which individual athlete will later become symptomatic. The waiter’s serve illustrates this distinction particularly well. Despite producing greater shoulder loading, it was not associated with a statistically significant increase in injury occurrence during follow-up. (12) A movement pattern can therefore look mechanically unfavorable without being established as an independent clinical risk factor. ROM presents a similar interpretive problem. Reduced dominant-side internal rotation is repeatedly observed in tennis players. (16-18) Prospective evidence, however, does not support a simple relationship in which greater GIRD necessarily leads to greater injury risk. (23,30) In some players, what appears abnormal relative to the non-dominant arm may represent a long-term adaptation to unilateral overhead sport. This has obvious implications for screening. Physical examination remains useful when it identifies pain, marked functional restriction, or a meaningful change from the athlete’s usual state. An isolated asymmetry is less informative. It should not automatically become either a diagnosis or an estimate of future injury risk. Imaging raises much the same problem. Tendinotic, structural, and ultrasound-detected abnormalities can occur without substantial clinical dysfunction. (20,21) Imaging is most useful when it addresses a specific clinical question. Incidental abnormalities, particularly in athletes exposed to years of repetitive loading, need to be interpreted cautiously. Strength findings are similarly difficult to fit into a simple model. Players with a history of shoulder pain may show lower external-rotation strength, while prospective data have also linked higher values of selected strength measures with subsequent injury. (19,23) These observations are not necessarily contradictory. Stronger athletes may serve faster, play at a higher level, or accumulate more exposure. Maturation, training history, and other unmeasured variables may contribute as well. For that reason, the relationship between demand and capacity may be more informative than strength considered by itself. Capacity matters, but so does how rapidly and how often that capacity is challenged. The workload data fit this interpretation. Repeated spikes in tennis training/match-play exposure were associated with higher rates of shoulder complaints and injury in adolescent competitive players. (22) Compared with most isolated ROM measures, these findings provide a clearer temporal association with subsequent shoulder outcomes. Selected strength variables have also shown prospective associations, however, so workload should not be treated as the only relevant factor. (23) The age of the SMASH population is another important limitation: these findings should not simply be extrapolated to adult recreational players or professional athletes. Fatigue may further influence the balance between demand and capacity. Experimental studies show that strenuous activity reduces serve performance and alters neuromuscular organization. (27,28) Although they do not measure injury directly, they demonstrate that movement

organization changes as fatigue develops. The biomechanics of a small number of fresh laboratory serves may therefore differ from those used late in a prolonged match. A multidimensional approach to prevention follows naturally from these observations. Progressive exposure has direct prospective support from adolescent tennis data, while shoulder and kinetic-chain conditioning offer a reasonable means of developing physical capacity. (22,29-32) Evidence from other overhead sports suggests that some modifiable factors and prevention programs may influence injury outcomes, but considerable heterogeneity limits direct translation to tennis. (29,30) Mobility work is reasonable when a clinically relevant restriction exists, whereas attempts to eliminate all sport-specific asymmetry are difficult to support. (15,33) Technical modification may also be appropriate in selected athletes. If assessment reveals a movement strategy that plausibly increases upper-limb demand, changing that strategy may be biomechanically sensible. At the same time, not every technical alteration produces the same shoulder response, and most studies report joint mechanics rather than prospective injury outcomes. (7-13,25) Technique is therefore better considered alongside workload, symptoms, strength, recovery, and overall physical capacity.

The same principles apply during rehabilitation. Absence of pain during everyday activity is only an intermediate step. A competitive tennis player eventually needs to tolerate repeated high-speed generation and absorption of force, often under fatigue and sometimes over consecutive days. RTS remains one of the least well-validated parts of tennis-specific shoulder management. Strength, ROM, and functional tests can contribute useful information, and several upper-extremity tests have acceptable psychometric properties. (34,35) None reproduces repeated maximal serving, and no tennis-specific threshold has been validated as an independent predictor of successful return. Progressive exposure to serving and match play therefore remains an important element of final decision-making. (36) The evidence base has several limitations. Many biomechanical studies include relatively small samples and disproportionately represent high-level male players. Definitions of injury vary, and systematic reviews of prevention and risk factors often combine different overhead sports. Even prospective tennis cohorts generally include modest numbers of injury events. These limitations restrict causal interpretation and reduce confidence when findings are generalized to female athletes, recreational players, younger children, or older competitors. Future research should combine prospective symptom surveillance with repeated assessment of training exposure, serve number and velocity, shoulder strength, ROM, recovery, and biomechanics. Prevention trials need to measure clinical injury outcomes rather than assuming that improvements in strength or mobility will translate into fewer injuries. The same gap is evident in RTS research. Tennis-specific criteria that can predict successful return, and ideally recurrence, remain an important target for future work.

5. Conclusions

Shoulder overuse injuries in tennis appear to develop through an interaction between high-velocity serving mechanics, repeated exposure, individual physical capacity, and recovery. Altered kinetic-chain coordination and less efficient energy transfer may increase upper-extremity mechanical demand, although the effect of individual biomechanical characteristics varies across studies. Some mechanical features have shown temporal associations with later overuse injury in small observational cohorts, but no isolated biomechanical variable can currently be considered a definitive predictor of injury in an individual player. Reduced internal rotation of the dominant shoulder, strength asymmetries, scapular differences, and structural or ultrasound-detected abnormalities are common in tennis players. Depending on the athlete and clinical context, these findings may reflect adaptation

rather than pathology. Their significance is therefore better judged alongside symptoms, functional capacity, previous measurements, and current exposure. Among the available tennis-specific prospective data, repeated abrupt increases in training and match-play workload show a clearer temporal association with shoulder complaints and injury than most isolated ROM measures, although selected strength variables have also been prospectively associated with injury outcomes. (22,23) The strongest workload evidence comes from adolescent competitive players and should not be generalized automatically to all tennis populations. A pragmatic prevention approach should combine progressive exposure, development of shoulder and whole-body capacity, and individualized management of clinically meaningful deficits. Rehabilitation and RTS should progress from restoration of tolerable shoulder function toward repeated high-speed, tennis-specific loading and ultimately competitive match exposure. At present, no single ROM value, strength threshold, functional test, or fixed time interval can independently establish readiness for unrestricted competitive tennis.

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Disclosure

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