**Introduction:**

Tennis is truly a global sport, with millions of yearly participants worldwide and over 200 nations possessing an active involvement with the International Tennis Federation (ITF).1,2 It is estimated that tens of millions of Americans play tennis, both recreationally and competitively.2 The increased popularity of professional tennis has resulted in an exponential rise in the amount of tennis participants from the general public, along with a parallel increase in tennis related injuries.1,3,4 The demands of the sport can affect the upper and lower extremities, the most common being the shoulder, elbow and knee,12 as well as the trunk and can dispose an athlete to characteristic injury patterns and musculoskeletal adaptations.5,6 Tennis players are susceptible to developing shoulder injuries due to muscular imbalances and altered length-tension relationships, secondary to the repetitive stress and loading associated with the game.5-9 A tennis-specific strategy for screening, evaluating, and conditioning can play a key role in preventing and rehabilitating common injuries in tennis players. Current research correlating specific techniques and exercises to successful injury prevention in tennis players is limited.5 The present literature has associated specific resistive and flexibility exercises with performance enhancement in tennis players.10,11 However, further investigation is needed to determine the role specific exercises and intervention strategies possess in preventing common tennis injuries. While studies have shown that acute injuries tend to occur in the lower extremity, chronic injuries usually affect the dominant upper extremity and trunk.3,4,12,13 Upper extremities tend to be more troublesome and lead to longer delays in return to sport and will therefore be highlighted in this discussion.14

**The Kinetic Chain Model:**

Dynamic dominant upper extremity activities such as serving and throwing arise from the tandem activation of a muscle system along with an integrated, multisegmented, sequential joint motion.15 The dominant upper extremity is of critical importance throughout these complex tasks; however, overhead activities require “link sequencing,” which is the proximal to distal delivery of velocity, energy, and force to the terminal link of the system, the dominant arm.15,16 The sequencing and theoretical framework is termed the “kinetic chain.”15,16 The effective and efficient use of the kinetic chain starts at the ground and permits maximal velocity, energy, and force to be developed in the lower extremity and core musculature which is then transferred to the dominant upper extremity.15 The largest proportion of kinetic energy and force is derived from the larger proximal body segments. Current literature demonstrates that 51% of the total kinetic energy and 54% of the total force generated in the tennis serve are created by the lower legs, hip, and trunk.16

Proper deployment of the kinetic chain and successful transmission of kinetic energy relies on the optimal integrity of the musculoskeletal system.15-17 Muscle flexibility, strength, proprioception, and endurance, as well as consistent and proper biomechanics all play an integral role in the transfer sequence.15 If a “body link” in the chain suffers from a deficiency, either in motion or position, the transmission of the large forces generated by the lower extremities to the dominant upper extremity can become compromised. This weakness in the chain would create a deficiency in the resultant maximal force that can be delivered to the hand or could produce a situation of “catch-up” in which the more distal links would have to work at a higher level to compensate for the loss of the proximally generated force.15-17 This can be detrimental to the function of the distal links as they do not have the size, the muscle cross-sectional area, or the time in which to efficiently develop or withstand these larger forces.16 This increased load and stress typically target the shoulder and elbow joints and ultimately leads to pain and injury.15 Kibler et al have developed a metric which estimated that a 20% decrease in kinetic energy delivered from the hip and trunk to the arm necessitated an 80% increase in mass or a 34% increase in rotational velocity at the shoulder to deliver the same amount of resultant force to the hand.16 As a result, the identification of underlying deficits or mechanisms contributing to such impairments would be greatly beneficial. As such, the clinical evaluation of the athletic shoulder as well as the associated intervention planning, cannot be limited to the musculoskeletal tissues which isolate the shoulder complex. Instead, this clinical process must be accomplished in the context of the entire kinetic chain as there are multiple components of the sequencing system that may be involved in shoulder pathology specific to tennis players, and other overhead athletes in general (i.e. baseball pitchers, volleyball players, and football quarterbacks).

**Normal Biomechanics and Pathomechanics:**

A comprehensive understanding of the entire body’s system during overhead activity in combination with that of the isolated actions of individual segments is integral for successful injury prevention and tennis-specific conditioning.17 A clinical proficiency in the biomechanical principles governing the overhead tennis serve is critical for determining the performance demands of such a functional task.17 Accordingly, the development of a tennis-specific conditioning program can be enhanced through the ability to comprehend the joint kinematics and muscle activation patterns associated with the tissues involved in the overhead movement.17

Several cross-sectional electromyography (EMG) studies have been conducted to investigate and assess the joint kinematics and muscle recruitment patterns linked to the dominant upper extremity during a single tennis service.18-21 Ryu et al investigated the concentric and eccentric demands placed on the rotator cuff and periscapular musculature from the surface electrode EMG.22 During the cocking phase of the serve, muscular activity of the supraspinatus (53%), infraspinatus (41%), and serratus anterior (70%) functioned to position the scapula and stabilize the GH joint.22  The high demand on the infraspinatus is essential for initiating the external rotation (ER) of the shoulder during the first half of the cocking phase. The infraspinatus and supraspinatus also contract to resist shoulder distractive forces during the cocking phase.22 Meanwhile, during the acceleration phase, pectoralis major, latissimus dorsi and subscapularis muscles produced the greatest concentric contraction, generating a peak shoulder internal rotation angular velocity to accelerate the arm forward.22 Serratus anterior activity also peaks during the acceleration phase to properly position the scapula relative to the rapidly moving humerus.22 The continuation to the follow-through, or deceleration phase, demonstrates the eccentric activation of the rotator cuff musculature (mainly the external rotators) (40%) and serratus anterior (53%), which assist with a further stabilization and deceleration of the shoulder and the generation of a compressive force to help resist shoulder distractive forces that attain peak forces of approximately 75% of the body-weight during the serve.22 These biomechanical analyses demonstrate that the shoulder and elbow are subject to vigorous demands and high loads during the tennis service. These stressors have the potential to cause an overuse injury secondary to the repetitive nature of the stroke as well as a possible dysfunction of a larger, proximal component of the kinetic chain. Consequently, the muscle activation and recruitment patterns described above suggest that an effective conditioning regime focus on strengthening the muscles encompassing the shoulder complex, in both a concentric and eccentric manner, in order to aid in the protection of these tissues.

Cross-sectional EMG studies have also focused on examining the contribution of the other segments of the chain during tennis serve activity, namely the trunk/core and lower extremities.20,23 Chow et al revealed the well-defined eccentric activity of the lower trunk musculature during the tennis serve.23 The biomechanics of the tennis serve induced large lumbar spinal loads during the movement pattern, secondary to the hyperextension posture and the “front-back” and bilateral co-activations in the lower trunk musculature.23 These findings emphasized the contribution of the trunk/core musculature and the physiological demands placed on the proximal trunk tissues, and further highlighted the importance of abdominal and lower back exercises to injury prevention and conditioning programs for tennis players.

Elliot et al have analyzed the effect of knee flexion and its contribution to internal rotation torque at maximal external rotation (MER), which is characterized by the transition of wind up to the acceleration phase.20 At MER, there was a significantly lower normalized internal rotation (IR) torque recorded by the group with a higher mean knee flexion (>10 front knee joint flexion: 15.9), when compared to the group with a lower mean knee flexion (5.8).20 The group with the larger knee flexion recorded a mean IR torque of 43.7 Nm, while the less effective group recorded a significantly higher mean IR torque of 57.8 Nm.20 This torque was associated with the eccentric contraction of the muscles responsible for internal shoulder rotation following MER. The players with the potential for a greater leg-drive may therefore use the inertial transfer from the trunk to upper limb to move the upper arm into a position of MER.20 This would then require less internal rotator torque to arrest the external rotation. The group with the less effective drive must therefore primarily use the external rotators to achieve MER, which would require a greater internal rotator torque to reverse the rotation of the upper arm.20 In a similar study by Macher et al., the authors confirmed the above findings and suggested that players could benefit from a trunk–shoulder inertial transfer given the presence of some lower-limb drive (and trunk rotation). When facilitated by a leg drive, high performance players can generate similar resultant pre-impact racket velocities using either a “foot up” or “foot back” service stance. However, if devoid of a leg drive however, players are less capable of developing high resultant racket velocities.20,24 An understanding of the potential pathomechanics, in addition to the proper biomechanics associated with the tennis serve, can assist a clinician in assessing the relationship between an athlete’s movement paradigms and the related loadings placed on the musculoskeletal tissues. While the dominant shoulder and elbow are predisposed to heavy, repetitive loads during the tennis serve motion, these findings emphasize the importance of assessing the potential for dominant upper extremity dysfunction and injury in the context of the entire kinetic chain by considering all the musculoskeletal tissues and structures involved in a movement process. The development of injury prevention, conditioning, and rehabilitation programs for tennis players should possess this core philosophy of targeting and protecting all of the elements of the sequential chain.

**Common Injuries and Mechanisms:**

The presence of physical dysfunction or deficit in any component of the kinetic chain can produce altered and inefficient movement strategies and create increased demands on the distal links of system resulting in dominant upper extremity pathology.25 Successful shoulder injury prevention and rehabilitation for overhead athletes is contingent upon the clinician’s comprehension of the potential injuries and associated pathological tissues and mechanisms.17 Overhead throwing and racket sports place repetitive high-velocity stress on the shoulder joint with the potential for gradual onset of subluxation or movement of the humeral head anteriorly.7,25,26 Shoulder injuries may be related to scapular dyskinesis, rotator cuff and biceps tendon pathology or glenohumeral internal rotation deficit (GIRD) with its resulting internal impingement and/or labral pathology.7,26 In contrast to the older player with rotator cuff impingement and degenerative changes, this subtle instability in the GH joint of the young tennis player may lead to recurrent subluxation and impingement of the rotator cuff.7,26. In addition to the concentric and eccentric demands placed on the rotator cuff, the underlying hypermobility and excessive laxity of the glenohumeral joint can play a role in injury.26 A loss of strength in the external rotators and scapular stabilizers accompanied by a loss of flexibility in the internal rotators has been associated with instability and altered length-tension relationships.8,26-31

A loss of scapular upward rotation has been associated to shoulder pathology.29 Ludewig et al have demonstrated that patients with subacromial impingement exhibit decreased upward rotation at 90 degrees of humeral elevation which can result in a loss of acromial elevation and subsequent impingement of the subacromial structures.29 Similarly, excessive scapular internal rotation during elevation can reduce the subacromial space and result in the inability of the greater tuberosity of the humerus to “clear” the acromion process.30 The presence of a “SICK” scapula in overhead athletes has also been reported in the literature.31 “SICK” stands for: **S**capula has **I**nferior medial border prominence, **C**oracoid pain and malposition, and dys**K**inesis of movement, and this pathological presentation has been associated with labral abnormality, sub-acromial impingement, and/or rotator cuff lesions in the overhead athletic population.31 It is essential for clinicians to assess scapular position and movement in overhead athletes and evaluate for the presence of sport-specific abnormalities and adaptations which can affect surrounding musculoskeletal tissues and contribute to the overall injury. The findings of these studies can assist clinicians with their development of injury prevention and conditioning programs centered on a thorough understanding of the types of chronic adaptations that can result secondary to participation in overhead athletics.

**Intervention Concepts and Strategies:**

The goal of injury prevention and rehabilitation programs is to identify current or potential compromised structures and accordingly condition and/or treat said involved structures.17 The “principle of specificity,” as it relates to exercise science, states that in order for these programs to be effective and successful, the body part(s) need to be exercised in a similar manner to the functional task being performed.32 Sports medicine professionals must strive to adhere to this principle, and design exercise programs which target the involved structures in the manner in which they perform during a specified functional task. Several studies have linked particular resistive exercises with performance enhancement in overhead athletes, including tennis players.10,11,33,34 Resistive and flexibility exercises have been designed, recommended, and implemented to address tennis-specific alterations and adaptations secondary to identified muscular imbalances, through the aforementioned musculoskeletal descriptive profiles and EMG studies.

Plyometric Training:

Behringer and colleagues have demonstrated that tennis-specific plyometric training is effective in improving tennis serve velocity in junior athletes when compared to less specific machine-based resistance programs.33 Plyometric exercises encompass quick, powerful movements through a “prestretch” of the muscle, which activates the stretch shortening cycle.35 The benefits of plyometric exercise include: a) an increase in the speed of the myotactic/stretch reflex, b) the desensitization of the Golgi tendon organ, and c) an increase in neuromuscular coordination.35 These clinical findings exemplify the principle of specificity and the rationale for exercising and conditioning body segments and tisssues in the functional manner in which they will be used during the actual activity. While the less-specific resistance training program in this study resulted in measurable strength gains in the tennis players, the enhancement was not transferable to functional tennis tasks.33 These findings validate that the principles of hypertrophy and increased endurance of the involved muscle structures are only part of the process for succesful functional outcomes related to injury prevention and/or performance enhancement for tennis players. To be clinically relevant, these functional conditioning principles need to be addressed in combination with sport-specific movement patterns to demonstrate transferability.

Strength Training:

Treiber et al. have shown that theraband tubing and lightweight dumbbell resistance training can increase tennis serve velocity, secondary to an increase in internal and external shoulder rotation strength and producible torque.10 These findings are valuable for clinicians working with tennis players as they demonstrate that a tennis player can increase the cross-sectional area of the rotator cuff musculature, providing stress-shielding to combat the physical demands and stressors placed on the musculoskeletal structures during repetitive loading. These processes have the potential to maximize injury prevention for this athletic population.

Niederbracht et al. utilized a shoulder strength training program that emphasized concentric shoulder internal rotation exercises and eccentric shoulder external rotation exercises, which are concurrent with tennis serve biomechanics and muscle recruitment patterns.34 The shoulder strength training program significantly increased eccentric external total work without significantly altering concentric internal total work, concentric internal mean peak force, or eccentric external mean peak force.34 This strength training program potentially minimizes shoulder rotator muscle imbalances and the risk for shoulder injuries for overhead activity athletes, secondary to an increase in the eccentric external total exercise capacity and without a subsequent increase in the concentric internal total exercise capacity.34 The results of the study highlight the principle of specificity and the logic for conditioning body segments and tisssues in the functional manner in which they will be used during the actual activity.

Fatigue and Endurance Training:

In addition to muscle strength, muscular endurance is another exercise concept that needs to be addressed, as an overhead athlete is at greater risk for dominant upper extremity injury when fatigued.35 The largely repetitive, stressful and physical demands placed on the shoulder during overhead tennis activity can result in muscle fatigue. Furthermore it can increase the risk for shoulder injury, secondary to altered muscle activation patterns, force couples, and kinematics at the shoulder complex.40 Chen et al. have demonstrated that fatigue of the rotator cuff musculature allows the humeral head to migrate superiorly when arm elevation is initiated during the service motion, which can result in a shoulder impingement pathology.39 Joshi et al. implemented an external rotation fatigue protocol to demonstrate that shoulder external rotation muscle fatigue contributes to altered scapular muscle activation and kinematics.40 From “prefatigue” to “postfatigue,” the results of the study demonstrated that lower trapezius activation decreased by 4%, infraspinatus activity increased in the descending phase of a baseball pitch by 4%, and scapular upward rotation motion increased in the ascending phase by 3 degrees.40 The altered force couples can affect the length-tension relationship of the infraspinatus and subsequently require a compensatory increase in infraspinatus activity to maintain force production in the presence of an abnormal scapular position.40 The decreased lower trapezius activation can cause an abnormal scapular position which can affect the center of rotation of the glenohumeral joint and alter the periscapular length-tension relationships.40 These findings highlight the importance of designing injury prevention and conditioning programs that consider the negative effects of upper extremity muscle fatigue and the inclusion of principle exercise prescription which emphasizes endurance exercises.

Tripp et al. investigated the effects of functional muscle fatigue on the sensorimotor system through upper extremity position reproduction in overehead athletes.41 Subjects participated in a single-knee, maximum velocity throwing functional fatigue protocol, while the authors measured active multijoint reproduction in two positions: “arm cock” and “ball release” of the overhand pitch, as well as the variable error for 10 joint motions.41 The fatigue protocol was characterized by an increase in the 3-dimensional variable error scores, suggesting decreased acuity of the entire dominant upper extremity and all involved joints, in both of the positions tested.41 Szcus et al. have also investigated the contribution of shoulder complex muscle fatigue to dominant upper extremity pathology.42 In this study the authors instructed subjects to perform a push-up plus exercise to induce serratus anterior muscle fatigue.42 Serratus anterior fatigue has been shown to be a mechanism for shoulder pathology, as scapular mechanics can alter and result in compensatory movements by other muscles.42 EMG analysis was used to monitor upper trapezius, lower trapezius, and serratus anterior muscle activity during scaption elevation and lowering, following the fatigue protocol. A significant increase in upper trapezius activity was observed during scaption, while the serratus anterior/lower trapezius activation ratio was altered.42 The authors concluded that the increase in upper trapezius activity arose as a compensatory strategy to resume overhead activity in the presence of a reduced activation in other key muscles involved in efficient elevation (i.e. serratus anterior).42 Accordingly, clinicians need to consider the detrimental effects muscle fatigue can have on shoulder joint mechanics when developing conditioning programs to prevent injury and improve performance for tennis players. The incorporation of exercise principles to target and improve muscle endurance, throughout the kinetic chain, can reduce the risk of fatigue and overuseage of the dynamic stabilizers in the dominant shoulder in these athletes.

Proprioception and Neuromuscular Control:

The excessive mobility and inherent deficiency of static stability associated with the glenohumeral joint predisposes the overhead athlete to capsulolabral and musculotendinous pathology.35 Successful injury prevention and conditioning programs must prioritize exercise prescription to develop efficient dynamic stabilization and neuromuscular control for the glenohumeral joint.36 Neuromuscular control involves an efferent response to afferent stimulation of the joint.35 Reinold et al. suggested that neuromuscular control techniques be included in exercise programs for overhead athletes in order to prevent injury and optimize performance.35 These techniques include: rhythmic stabilization, reactive neuromuscular control drills, and closed kinetic chain and plyometric exercises.35 Closed kinetic chain exercises load the joint in a “load-bearing” position, producing joint approximation, which stimulates receptors and facilitates co-contraction of the shoulder force couples.35 When developing conditioning programs for overhead athletes, it is important to thoroughly understand that the sole objective is not simply shear muscle activation. Activation relative to other muscles, including agonists and antagonists, is an important biomechanical concept to comprehend, as altered length-tension relationships and muscle activation incoordination can lead to pathology, even if the fundamental strength of a given muscle is considered strong.35 Witt et al. have demonstrated that abnormalities in glenohumeral rhythm and neuromuscular control of the upper trapezius, middle, trapezius, lower trapezius and serratus anterior muscles have been identified in individuals with shoulder pain.37

Upper extremity diagonal or proprioceptive neuromuscular facilitation (PNF) patterns have been recommended as an intervention strategy to activate periscapular muscles and improve muscular strength and flexibility, as well as develop neuromuscular control and function through the use of tactile, visual, and auditory stimuli.37 Witt et al. advocated the use of the D2 flexion pattern with either elastic or weight resistance in order to achieve the greatest activation of all three trapezius muscles and the serratus anterior.37 The implementation of PNF techniques can promote efficient neuromuscular mechanisms and improve function secondary to improved flexibility, functionality and functional movement patterns, improved joint stability, and improved neuromuscular coordination.37 Padua et al. have investigated the effects of three different resistance training approaches on shoulder rotation strength, active angle reproduction, single-arm dynamic stability and functional throwing in healthy athletes.38 The three five-week training programs included closed kinetic chain (CKC), open kinetic chain (OKC), and PNF techniques. The results of the study demonstrated that CKC exercises are effective in improving shoulder proprioception and neuromuscular control in healthy individuals through the facilitation of shoulder muscle co-activation.38 OKC exercises improved proprioception and neuromuscular control through enhancement of joint-position awareness.38 Additionally, the authors demonstrated that eccentric shoulder rotation strength increases were greatest in the OKC (20% increase in eccentric torque) and PNF (15% increase) versus the CKC (8.5% increase) group.38 These findings depict CKC, OKC, and diagonal movement patterns as effective in increasing scapular muscle and rotator cuff musculature activation, which is an important component to overheard athletic activity, and should be integrated into a conditioning program for tennis players. The increased eccentric shoulder external rotation muscle activity exhibited during the tennis serve increases the rationale for the inclusion of OKC and PNF exercises into injury prevention and conditioning exercise program for tennis players.

Kinetic Chain Training:

In overhead athletic activities, the body does not operate in isolated segments but instead functions as a complete, dynamic unit.17 This functional philosophy integrates the theory of the kinetic chain in areas of injury prevention, rehabilitation, and performance enhancement, with the incorporation of closed kinetic chain exercises, core-stabilization exercises, and functional programs.17 Currently, the kinetic chain approach to dominant upper extremity pathology and injury prevention is a theoretical framework and requires additional research and further investigation-in the form of randomized controlled trials-to evaluate the efficacy of this model in overall injury prevention, rehabilitation, and conditioning for tennis players. The kinetic chain model stresses that the design and development of exercise programs should occur in the context of the sequential movement pattern of the entire body during an overhead functional task.17 In this manner, sport-specific exercises target all the segments of the body, including the lower extremities and core musculature, in order to avoid injury and improve performance, secondary to improved and more efficient movement strategies and a subsequent reduction in loading of the dominant upper extremity.17 In a recent study by Fernandez et al., the authors implemented a 6-week exercise program that included a combination of core, elastic tubing, and medicine ball exercises that targeted all muscles activated during the tennis serve.11 Significant improvements in shoulder internal rotation (IR) and external rotation (ER) strength and range of motion (ROM), as well as increases in serve velocity were confirmed in the training group after the intervention.11 The results demonstrated that a short-term training program for young tennis players, using minimum equipment and effort, can result in improved tennis performance (i.e. tennis serve velocity) and reduce the risk of a possible overuse injury, reflected by an improvement in shoulder IR/ER strength and motion.11 In addition to these outcomes, further research into the kinetic chain approach could demonstrate that conditioning and rehabilitation, for the overhead athletic shoulder, should focus on the inclusion of synergistic and coordinated exercises that are functional and address all the links of the body chain. The potential results can demonstrate that rehabilitation efforts for shoulder injury need to concentrate on allowing functional return of the joint, in the context of the entire kinetic chain, as more than one system can be involved or contribute to the pathology.

**Conclusions:**

A tennis-specific conditioning program, designed in the context of the kinetic chain, can potentially play a critical role in preventing common dominant upper extremity injuries to which tennis players are currently predisposed. The development and creation of preventative programs can assist in the education of tennis athletes and coaches through exercise prescription that includes conditioning of all the involved segments of the body, as well as result in potential performance enhancement on the court. A thorough understanding of the kinetic chain model, normal biomechanics and pathomehanics, and common upper extremity pathology and mechanisms of injury, can assist sports medicine professionals in developing intervention strategies to prevent and rehabilitate injuries, as well as enhance performance in tennis players. The physical demands of overhead tennis activity can affect the upper and lower extremities, as well as the trunk of players, and lead to characteristic injury patterns and musculoskeletal adaptations across the body. The repetitive stressors and distinctive loading sequences can create muscular imbalances and altered length-tension relationships, which require preventative interventions to reduce the potential for injury. A better understanding of kinetic chain mechanics, and their association with these forces and loads throughout the musculoskeletal tissue, can allow clinicians to design more effective injury prevention and rehabilitation programs and perhaps improve performance as well. The implementation of various conditioning and resistive training programs have shown to improve motor performances in this athletic population; however, further research is needed to provide evidence for kinetic chain-designed intervention strategies to strive for optimal exercise prescription for tennis players and the overhead athletic shoulder to fulfill ultimate goals of injury prevention and performance enhancement.

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