Title:

Electromyographic Assessment of Forearm Muscle Function in Tennis Players With and Without Lateral Epicondylitis

Running Title:

Forearm Muscle Electromyography in Tennis Players with Implications for Lateral Epicondylitis

Authors:

Omid Alizadehkhaiyat (MD, PhD) [1], Simon P Frostick (DM, FRCS) [2]

1. School of Health Sciences (Sport and Exercise Science), Liverpool Hope University, Liverpool, UK

2. Musculoskeletal Science Research Group, Institute of Translational Medicine, University of Liverpool, Liverpool, UK

First Author and Corresponding Author:

Dr Omid Alizadehkhaiyat

School of Health Sciences, Liverpool Hope University

Hope Park, Liverpool L16 9JD, UK

Tel: 0044 151 291 3262

Fax: 0044 151 7065158

Email: alizado@hope.ac.uk

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ABSTRACT

There is no consensus about the main aetiology of Lateral Epicondylitis (LE) or Tennis Elbow. While electromyographic assessment of alterations in neuromuscular control and activation patterns of forearm muscles has received increasing interest as potential intrinsic factors in non-tennis players, there has been insufficient attention in tennis players. The purpose of present review was to search the literature for the electromyographic studies of forearm muscles in tennis players in order to 1) identify related implications for LE, 2) highlight key technical and methodological shortcomings, and 3) suggest potential pathways for future research.

An electronic search of PubMed, Scopus, Web of Science, and Google Scholars (1980 to October 2014) was conducted. Titles, abstracts, and full-text articles were screened to identify "peer-reviewed" studies specifically looking into "electromyographic assessment of forearm muscles" in "tennis players". After screening 104 articles, 13 original articles were considered in the main review involving a total of 216 participants (78% male, 22% female). There were indications of increased extensor activity in all tennis strokes and less experiences single-handed players, however with insufficient evidence to support their relationship with the development of LE. Studies varied widely in study population, sample size, gender, level of tennis skills, electrode type, forearm muscles studied, EMG recording protocol, EMG normalisation, and reported parameters. As a result, it was not possible to present combined results of existing studies and draw concrete conclusions in terms of clinical implications of findings. There is a need for establishment of specific guidelines and recommendations for EMG assessment of forearm musculature in terms of electrode and muscle selection. Further studies of both healthy controls and tennis players suffering from TE with adequate sample sizes and well-defined demographics are warranted.

1. INTRODUCTION

1.1 Lateral Epicondylitis

Lateral Epicondylitis (LE) also known as “tennis elbow” was first described in 1883 as a painful condition affecting the lateral aspect of the elbow (Major, 1883). The prevalence of LE is 1% - 3% in the general population with the men and women equally affected. The condition is most prevalent in the fifth decade of life (peak age incidence: 45–54 years) (Shiri et al., 2006). Even though less than 10% of patients are tennis players, around 50% of the players, particularly novice and single-handed backhand players, experience lateral elbow pain in their lifetimes with 75% of them representing true LE (Ollivierre and Nirschl, 1996). The condition affects functional capacity of the affected limb with subsequent impact on player’s professional and social life (De Smedt et al., 2007).

The diverse terminology such as row elbow pain, lateral epicondylitis, lateral tendinosis, lateral epicondylopathy, radial epicondylalgia, extensor tendinopathy, and extensor carpi radialis brevis tendinosis used for describing the condition reflects the confusion surrounding the underlying pathophysiology. The lateral elbow epicondyle serves as the common origin for wrist extensors including extensor carpi radialis longus (ECRL), extensor carpi radialis brevis (ECRB), extensor digitorum communis (EDC), and extensor carpi ulnaris (ECU) (Dines et al., 2015; Kraushaar and Nirschl, 1999; Nirschl and Ashman, 2003). Amongst these muscles, ECRB has multiple origins involving lateral collateral ligament, annular ligament, and intermuscular septum. Distally, ECRB inserts on the base of 3rd metacarpal underlining it as the principal wrist extensor (Verhaar, 1994). As originally described by Cyriax (Cyriax, 1936) ECRB is the most commonly affected muscle among wrist extensors. Histological studies have failed to identify inflammatory markers within the affected area and highlighted the ‘tendinosis’ or ‘angiofibroblastic degeneration’ of ECRB with or without EDC involvement as the dominant pathologic change (Kraushaar and Nirschl, 1999).

There is no general consensus on the aetiology of LE and existing knowledge is suggestive of a multifactorial aetiology. Based on anatomical studies, ECRB tendon has a distinct anatomic location that predisposes its under-surface to disproportionate contact and abrasion against the lateral edge of the capitellum during elbow movements (Bunata et al., 2007). Some other studies have theorised that repetitive contraction of the wrist extensor muscles involving wrist extension and supination leads to LE by causing microscopic tendon tears and consequent degenerative tendinosis mainly in ECRB (Nirschl and Ashman, 2003; Tosti et al., 2013). This overuse mechanism has been particularly related to the higher incidence of LE in the recreational and less experienced players due to the substantial eccentric contractions of the extensor carpi muscles reported by the kinematic studies in tennis players (Eygendaal et al., 2007). From another view, repetitive forceful and high speed tennis strokes place large amount of loads on the elbow joint at the ball impact. This high impact load resulted from combined valgus forces and rapid extension ('valgus extension overload') may lead to compression forces on the lateral aspect of elbow near the common origin of wrist extensors (Andrews and Whiteside, 1993; Eygendaal et al., 2007; Morrey et al., 1991). Finally, some reports have highlighted the role of altered muscle recruitment patterns and activation imbalances for predisposition to the LE as such predominant activity of the wrist extensors observed in the majority of tennis strokes (serve, forehand, one- and two-handed backhand) may predispose the wrist extensors and pronator teres muscles to the LE injury (De Smedt et al., 2007; Kelley et al., 1994). Other proposed factors that can potentially contribute to increased transmission of high impact loads to the extensor mass include training and technical errors, poor racket (inappropriate grip size and weight), strength deficits/muscle imbalances, and forceful gripping (Alizadehkhaiyat et al., 2007b; Bartlett, 2012; Bunata et al., 2007; De Smedt et al., 2007; Eygendaal et al., 2007; Herquelot et al., 2013; Pitzer et al., 2014).

1.2 Implications for the assessment of forearm muscle function

Despite uncertainty regarding the main aetiology of LE, alterations in neuromuscular control and activation patterns of forearm muscles have received increasing attention as potential intrinsic factors. Biomechanical studies of three basic tennis strokes (overhead or serve, forehand and backhand) have projected a predominant activity of wrist extensors in all tennis strokes, backhand in particular, that would explain the predisposition of common extensor origin for injury (De Smedt et al., 2007; Elliott, 1988; Eygendaal et al., 2007). The high involvement of wrist extensors in performing all major tennis strokes throughout play may lead to excessive overloading of this muscular group as a result of repeated large impact forces. There has been a particular interest in the role of single-handed backhand that is used for both defensive and offensive functions in a tennis game (De Smedt et al., 2007; Elliott, 2006; Eygendaal et al., 2007). It is a fairly accepted concept that applying a one-handed backhand stroke increases the risk of LE as mainly sequential end-points of one upper extremity (i.e. elbow and wrist) are involved in generating the force and linear velocity required for swinging the racket. In two-handed backhand stroke, however, the hip and trunk rotation to facilitate the generation and transmission of force during the forward swinging phase of the stroke and increased force absorption through two upper extremities enhance the mechanics of the swing (Eygendaal et al., 2007; Roetert et al., 1995). Furthermore, the higher incidence of LE in recreational players has been attributed to the use of faulty stroke mechanics during one-handed backhand (flexed wrist of 13°) resulting in disadvantageous eccentric coactivation of extensor muscles (Elliott, 2006). This differs from that of experienced players who use a hyper-extended wrist (concentric contraction) to impact the ball (Blackwell and Cole, 1994). These interesting observations have led researchers to study EMG activity of wrist extensor muscles in relation to tennis strokes, specifically one- and two-handed backhand groundstrokes. With regard to the equipment, the common theories have been related to the possible contribution of over- or undersized racquet grip size (by altering grip tightness and wrist/forearm muscle firing patterns) and inappropriate racquet weight and stringing (by generating high loads on the lateral muscle tendon unit) (Hatze, 1976; Jobe and Ciccotti, 1994; King et al., 2012; Roetert et al., 1995). Consequently, EMG-induced information has been fundamental for understanding the impact of such technical elements on forearm muscle activity during tennis stroke production.

Furthermore, recent research in non-tennis populations has also theorised that impaired activation of forearm muscles may contribute to the development of LE by altering normal agonist-antagonist relationship (muscle imbalance) and subsequent joint misalignment (Alizadehkhaiyat et al., 2007a; Alizadehkhaiyat et al., 2007b; Blanchette and Normand, 2011; Rojas et al., 2007). Encouraging clinical outcome of wrist muscle strengthening programmes designed to restore the balance between wrist extensor and flexor groups has supported this theory (Cullinane et al., 2014; Raman et al., 2012; Tyler et al., 2014).

Despite growing evidence to support the efficacy of wrist muscle strengthening indicating that individuals with LE possess impaired strength, whether this muscle weakness develops due to the presence of LE rather than being an aetiological factor is not clear. Regardless of the true relationship, assessing muscle strength in isolation does not provide an adequate understanding of the impact of forearm muscle dysfunction on LE. As a matter of fact, isometric strength tests only partially relate to functional muscle activity, kinematics, and joint forces during (Wilson and Murphy, 1996). A substantial body of research has emerged to address this issue using EMG examination of the forearm muscles particularly in non-tennis populations (Alizadehkhaiyat et al., 2007a; Alizadehkhaiyat et al., 2007b; Blanchette and Normand, 2011; Rojas et al., 2007; Wilson and Murphy, 1996). The first reports describing the use of surface and fine-wire EMG were published in the (Tönnis, 1965) and since then research in the field has continued to offer sports professionals and clinicians with in depth knowledge of relevant muscle activity primarily focusing on the function of wrist extensors and flexors. While numerous studies have investigated the relationship between behaviour of the forearm muscles and TE during a broad range of functional and work-related tasks in both symptomatic and control participants, tennis-specific studies have been limited.

This review aims to evaluate existing literature regarding EMG assessment of forearm muscles in tennis. The outcome of this review will provide researchers and clinicians with a better understanding of the impact of tennis related factors such as type of stroke and racket specifications on forearm muscle activity with implications for LE, underline methodological considerations and limitations associated with forearm EMG, underline clinical relevance by means of injury prevention and rehabilitation, and highlight priorities for future research.

2. METHODS

2.1 Search Strategy

An electronic literature search was performed in PubMed, Web of Knowledge, and Google Scholars for relevant articles published from 1980 to October 2014. The search included following keywords in different combinations: Tennis Elbow; Lateral Epicondylitis; Lateral Elbow Pain; Electromyography; Forearm Muscles; Wrist Extensors; Muscle Fatigue; and Muscle Activity. The retrieved literature was further examined and supplemented with studies cited within them. As principal inclusion criteria studies included "electromyographic assessment of forearm muscles" (i.e. wrist extensors and flexors), involved "tennis players", and published in the "English language in peer-reviewed journals". In the next step, the title and abstract of identified studies were screened for potential relevance. The full text of potentially relevant studies was reviewed to determine if they describe a sound theoretical or practical application of the EMG for the assessment of forearm muscle function applicable to LE. Articles with insufficient discussions, poor data presentation, and unclear or vague descriptions of the applied protocols were not included. A single reviewer performed title and abstract screening, full text assessment, and data extraction from studies that met the inclusion criteria. An independent reviewer was involved to verify the studies to be excluded.

2.2 Flow of reviewed studies

The search strategy initially returned a total of 104 articles. Duplicated articles were removed using reference manager software (EndNote version X6, Thomson Reuters, USA) leaving 79 articles. Further title/abstract and full-text screening resulted in eliminating 66 articles, either due to 'not being related to tennis' or 'lack of relevance to the main criteria', leaving a total of 13 articles for further analysis (Figure1). Some studies had methodological weaknesses (to be discussed in "Methodological Considerations" section) but still considered in the review because of their proposed theory, and relevance.

The data were individually abstracted using a data extraction pro-forma created for the purpose of this review. Extracted data from each article included: 1) study population/s (Control/LE), 2) sample size, 3) gender/age/body demographics, 4) level of tennis skills, 5) electrode type (surface/fine-wire), 6) studied forearm muscles, 7) use of forearm or wrist Band/Brace/Splint, 8) EMG recording protocol, 9) EMG signal normalisation, 10) reported EMG parameters, and 11) main results.

3. RESULTS

3.1 Participants

Table1 summarises sample size, studied population (Control/LE), gender, age, and body demographics in reviewed studies. A total of 216 participants were recruited and tested in these studies including 198 healthy controls and 18 LE patients. Only two studies involved both patient and control groups (Bauer and Murray, 1999; Kelley et al., 1994) and remaining eleven studies recruited only healthy participants (Adelsberg, 1986; Blackwell and Cole, 1994; Chow et al., 1999; Chow et al., 2007; Giangarra et al., 1993; Groppel and Nirschl, 1986; Hatch et al., 2006; Morris et al., 1989; Rogowski et al., 2009; Rogowski et al., 2011; Wei et al., 2006). The gender, age (rang or mean), and body demographics (height and weight) were reported in eleven (Adelsberg, 1986; Bauer and Murray, 1999; Blackwell and Cole, 1994; Chow et al., 1999; Chow et al., 2007; Groppel and Nirschl, 1986; Hatch et al., 2006; Kelley et al., 1994; Rogowski et al., 2009; Rogowski et al., 2011; Wei et al., 2006), eight (Bauer and Murray, 1999; Blackwell and Cole, 1994; Chow et al., 1999; Chow et al., 2007; Kelley et al., 1994; Rogowski et al., 2009; Rogowski et al., 2011; Wei et al., 2006), and five studies (Chow et al., 1999; Chow et al., 2007; Rogowski et al., 2009; Rogowski et al., 2011; Wei et al., 2006), respectively.

According to studies reporting gender characteristics, around 78% of participants were male and 22% females (136 vs. 39). The majority of studies (except two) described skill level of tennis players (Blackwell and Cole, 1994; Chow et al., 1999; Chow et al., 2007; Giangarra et al., 1993; Groppel and Nirschl, 1986; Hatch et al., 2006; Kelley et al., 1994; Morris et al., 1989; Rogowski et al., 2009; Rogowski et al., 2011; Wei et al., 2006). The largest and smallest sample sizes were twenty nine (Rogowski et al., 2011) and four (Adelsberg, 1986), respectively.

3.2 EMG Measurement Methods and Protocols

Tables 2 and 3 summarise main features of EMG methods and tennis strokes applied in the studies. Studies used different strokes (backhand, forehand, volley, and serve) and techniques (single- or double-handed, different grip sizes). Seven studies looked at different phases of single-handed backhand stroke during EMG (Adelsberg, 1986; Giangarra et al., 1993; Groppel and Nirschl, 1986;

Hatch et al., 2006; Kelley et al., 1994; Morris et al., 1989; Wei et al., 2006) with two of them also involving forehand strokes (Adelsberg, 1986; Morris et al., 1989). Tennis volley was used in three (Bauer and Murray, 1999; Chow et al., 1999; Chow et al., 2007) and serve in one study (Morris et al., 1989). One study measured EMG with and without various joint counterforce braces (Groppel and Nirschl, 1986) while another study assessed the impact of three different grip sizes (Hatch et al., 2006), both during single-handed backhand stroke. Double-handed backhand stroke was used in one study (Giangarra et al., 1993).

With regard to EMG technique, fine-wire (FWEMG) and surface electrodes (SEMG) were used in four (Giangarra et al., 1993; Hatch et al., 2006; Kelley et al., 1994; Morris et al., 1989) and nine studies (Adelsberg, 1986; Bauer and Murray, 1999; Blackwell and Cole, 1994; Chow et al., 1999; Chow et al., 2007; Groppel and Nirschl, 1986; Rogowski et al., 2009; Rogowski et al., 2011; Wei et al., 2006), respectively. Except one study, all others included muscles from both wrist extensor and flexor groups (Bauer and Murray, 1999; Blackwell and Cole, 1994; Chow et al., 1999; Chow et al., 2007; Giangarra et al., 1993; Groppel and Nirschl, 1986; Hatch et al., 2006; Kelley et al., 1994; Morris et al., 1989; Rogowski et al., 2009; Rogowski et al., 2011; Wei et al., 2006). Six studies envisioned to study ECRB and ECRL individually (Bauer and Murray, 1999; Blackwell and Cole, 1994; Giangarra et al., 1993; Hatch et al., 2006; Kelley et al., 1994; Morris et al., 1989) while seven others collected collective signals from wrist extensors (i.e. ECR or wrist extensor group) (Adelsberg, 1986; Chow et al., 1999; Chow et al., 2007; Groppel and Nirschl, 1986; Rogowski et al., 2009; Rogowski et al., 2011; Wei et al., 2006). All of studies reporting muscle activation levels used EMG during maximal voluntary contraction (MVC) or maximal voluntary effort (MVE) referred to as EMG_{max} for normalisation purpose (Adelsberg, 1986; Bauer and Murray, 1999; Blackwell and Cole, 1994; Chow et al., 1999; Chow et al., 2007; Giangarra et al., 1993; Hatch et al., 2006; Kelley et al., 1994; Morris et al., 1989; Rogowski et al., 2009; Rogowski et al., 2011; Wei et al., 2006). Two studies which measured muscle activation durations (Groppel and Nirschl, 1986) and muscle activation onset/offset (Rogowski et al., 2009) as indicators of muscle activity did not apply normalisation.

3.3 Muscle activity assessment

3.3.1 Non-LE (Stroke Type, Single- vs double-handed, Skill Level, Equipment)

Using FWEMG, Giangarra et al, (Giangarra et al., 1993) compared the activation level of ECRB, ECRL, EDC, FCR during different phases of single- and double-handed backhand stroke in uninjured competitive tennis players. In general, a common pattern was observed for all muscles using both techniques with a low level of activity during preparation, an increase during acceleration through ball impact (peak activity), and then a gradual decline during follow-through phase. The peak activity during both single- and double-handed backhand strokes reached by the ECRB (58% MMT and 80% MMT), ECRL (71% MMT and 68% MMT), and EDC (68% MMT and 54% MMT) at the acceleration (ball contact) phase. Activity level of FCR was generally lower during both single- (26% MMT) and double-handed (41% MMT) backhand strokes. FCR had significantly higher activity in preparation phase of double-handed backhand compared to single-handed technique due to differences in stroke mechanics. Study found no significant differences in EMG activity of wrist extensors between single- and double-handed backhand ground strokes and suggested that lower incidence of LE in players using a double-handed backhand technique may not be related to decreased extensor activity.

Blackwell and Cole (Blackwell and Cole, 1994) used SEMG to compare activity of ECRB and FCR muscles in novice and expert players performing single-handed backhand stroke. Results revealed no difference in overall activation of ECRB and FCR between novice and expert players at the ball-racket impact. During post-impact interval, activity of ECRB increased in both groups (significantly larger in expert group) but remained unchanged for FCR. In contrast to novice players who continued the initial wrist flexion motion until ball-racket impact, expert players consistently produced the stroke by extended wrist and with an angular velocity in extension direction. Authors concluded that wrist flexion during backhand stroke should be considered as a facilitating factor for LE as imposed position requires lengthening of wrist extensor tendons and subsequent increased force in extensor muscles. The results implicated that using proper joint position and techniques for the backhand stroke may reduce risk of injury.

Wei et al., (Wei et al., 2006) used SEMG to compare activity of wrist extensors and flexors at different phases of single-handed backhand stroke (acceleration, impact, and follow-through) between experienced (>10yrs experience) and recreational (<6months experience and <3h exercise/week) tennis players. Study did not specify any individual muscle and measured activity of wrist and flexor muscles as groups. Results showed that while experienced players maintained both extensor and flexor activity near maximal level, recreational players significantly increased flexor activity from submaximal (0.84 MVC) to maximal (1.07 MVC) and extensor activity from maximal (1.11 MVC) to supra-maximal level (1.44 MVC). At the impact phase, extensor activity was significantly higher in recreational players (1.45 MVC) compared to experienced players (0.91 MVC). Both experienced and recreational players maintained activity of wrist flexors (1.01MVC) during the impact. The largest EMG difference was found in follow-through phase where wrist extensor and flexor activity reduced up to 50% of MVC in experienced players but remained at maximal level in recreational players. Wrist extensors of recreational players' showed supra-maximal level activity at both impact and follow-through phases. It was suggested that high contraction of wrist extensors and associated stiffness during and after ball-to-racket impact may be related to a higher incidence of LE among recreational tennis players.

Morris et al., (Morris et al., 1989)studied activity of ECRL, ECRB, EDC and FCR along with elbow muscles (biceps, triceps, and brachioradialis) by means of FWEMG during forehand, backhand, and serve strokes in professional and collegiate level tennis players. The groundstrokes were divided into four phases (preparation, acceleration, early follow-through, late follow-through) and serve into six phases (wind-up, early-cocking, late-cocking, acceleration, early follow-through, and late follow-through). During forehand there was an increased activity of all wrist extensors from preparation to acceleration phase with the highest level observed for ECR, ECRB, and EDC (>40%MMT). Activity of ECRB remained >40%MMT during early follow-through. During backhand, acceleration phase was associated with increased activity (>25%MMT) in all muscles (except for FCR) with the highest activity observed in ECRB and EDC (>60%MMT). The increase in muscle activity from preparation to acceleration was significant for all wrist extensors. During early-cocking the ECRB and EDC showed a significant increase in activity (>25% MMT) over the wind-up phase. Activity of these muscles continued to increase during late-cocking (>40%MMT). FCR activation showed a significant increase during acceleration phase (>40% MMT). Authors concluded that marked activity of wrist extensors in several phases of the three strokes may predispose these muscles to injury.

Groppel et al., (Groppel and Nirschl, 1986)compared the muscle activity by means of SEMG durations for ECR, ECU, FCR, and FCU during serve and backhand strokes in unbraced and braced (lateral elbow, medial elbow, and radial/ulnar wrist) tennis players of different skill levels (skilled competitors, intermediate recreational players, inexperienced novice players). The data were analysed only for pre-impact phase due to significant artefact associated with the impact and post-impact recordings. With regards to ‘wrist brace’, EMG durations were increased for all muscles during both strokes at all skill levels. The ‘medial elbow brace’ resulted in decreased EMG durations for all muscles in low skilled players, FCR in intermediate group, and ECU, FCR, and FCU in skilled players during serve stroke. Within backhand stroke, there was less activity of all muscles in advanced players; ECU, FCR, and FCU in low skilled players; and FCR and FCU in intermediate group. The ‘lateral elbow counterforce brace’ caused lower EMG activity of ECR, ECU, and FCR across all skill levels during serve stroke. During one-handed backhand, both ECR and ECU showed marked less activity in all skill levels while FCR and FCU had only slightly lower or unchanged activity. Authors suggested that lateral elbow counterforce brace might have a positive preventative effect in tennis players owing to lower muscular activity in two extensor muscles during both serve and one-handed backhand strokes across all skill levels.

Using SEMG, Chow et al., (Chow et al., 2007) examined the pre- and post-impact activation of ECR, FCR, deltoids, and triceps muscles during tennis volley across 18 conditions of ball speed (slow, medium and fast), ball type (two oversize and one regular size) and side of the body (forehand and backhand). Results indicated a significant muscle-side (FCR and ECR had greater activation in the forehand and backhand volley, respectively) and muscle-speed (activity increased 12% from slow to fast speed condition). For post-impact phase, main effects were observed for muscle-speed (activity increased by 10% from slow to fast speed condition) and muscle-side. There was no indication that oversize tennis balls increase muscle activation compared to regular size balls. While FCR activation reported to be fairly constant across different ball conditions during pre- and post-impact phases, ECR showed the greatest post-impact activation in both forehand and backhand strokes. This increased level of activity was linked to the wrist-stabilising role of ECR to reduce post-impact hand vibration. Authors suggested that tennis players suffering from LE should avoid forehand and backhand volleys due to marked increased ECR activation and subsequent negative impact on the recovery.

In a SEMG study, Chow et al., (Chow et al., 1999) examined ECR and FCR activity in skilled players during tennis volley under 18 experimental conditions of contact location (forehand and backhand), ball placement (high, middle, and low), and speed (fast, medium, and slow) produced by a ball machine. Study used force platforms and high-speed video cameras to identify critical instants of a tennis volley. Based on results, muscle activity increased with increasing ball speed. ECR showed higher activity than FCR during both forehand and backhand volleys indicating employment of wrist extension/abduction (cocking the wrist). The highest EMG levels found during the forward swing phase were attributed to the tightening of the grips shortly before ball impact until after ball impact.

Rogowski et al., (Rogowski et al., 2009) investigated Onset and offset of the muscle activation (EMG bursts) and temporal sequence of upper extremity (including ECR and FCR) and trunk muscles in relation to the mass of tennis racket (regular and six rackets with increased mass) during crosscourt forehand drives. SEMG results indicated a strong relationship between racket mass increase and activation pattern of some shoulder/trunk muscles but not FCR and ECR. In terms of temporal sequence, no relationship was observed between increases in racket mass and offset of EMG burst for any of muscles. It was concluded that using heavier rackets might increase risk of shoulder injury but not elbow. Authors suggested that EMG, particularly, when combined with other sensorial techniques could provide a better understanding of muscle activity alterations in relation to racket properties.

Hatch et al., (Hatch et al., 2006) compared firing patterns of ECRB, ECRL, EDC, FCR, and PT during single-handed backhand ground stroke using different racket grip sizes (¼ inch above and below Nirschl’s recommended size). While activity of ECRB, ECRL, EDC, and FCR was progressively increased from early acceleration phase through ball impact, alteration in grip size (bigger and smaller) did not result in significant differences in muscles' activity at any phase of the backhand stroke. The highest and lowest increase in activity for recommended grip size was related to ECRL (105% MMT ± 58%) and PT (38% MMT ± 39% SD), respectively. Activity of all muscles then decreased in early follow-through with two exceptions: FCR activity increased using big grip size and remained unchanged using regular grip size. Authors concluded that racket grip size is unlikely to be a significant contributing factor to LE pathology in tennis players. Study used only grip size alterations within a ¼ inch of recommended size.

Adelsberg (Adelsberg, 1986) used SEMG to examine the effect of different racket grip sizes ($4^{1}/^{4}$, $4^{1}/^{2}$, and $4^{3}/^{4}$ inches) on wrist extensor (extensor mass) muscle activity during forehand and backhand strokes. It was found that while activity of extensor group decreased with the middle ($4^{1}/^{2}$) and increased with the large ($4^{3}/^{4}$) size grip racket during forehand stroke; it remained unchanged during backhand. From authors' perspective, results did not provide sufficient support for the efficacy of changing the grip size in the management of LE.

3.3.2 LE vs. Non-LE

Kelly et al., (Kelley et al., 1994) applied FWEMG to compare activity of ECRB, ECRL, EDC, FCR, and pronator teres muscles during single-handed backhand stroke in tennis players with and without LE. ECRB had lower activity (28% vs. 62% MMT) during early acceleration and higher activity (94% vs. 40% MMT) during ball impact and early follow-through (67% vs. 43% MMT) in the injured group compared to the uninjured group. The activity of ECRL was higher in injured payers during preparation (28% vs. 13% MMT) and ball impact phases (89% vs. 43% MMT) than uninjured group. No difference in EDC activity was noted between two groups. FCR showed slightly higher activation in injured group compared to uninjured group during early acceleration (19% vs. 14% MMT) and late follow-through (23% vs. 11% MMT). PT activated in higher levels in injured subjects compared to uninjured players during ball impact (60% vs. 26% MMT) and early follow-through (61% vs. 32% MMT). Authors attributed aberrant activation of wrist extensors in injured group to abnormal stroke mechanics in terms of leading elbow, wrist extension, exaggerated wrist pronation, and ball contact in the lower portion of string area. They suggested that faulty mechanics particularly in sub-acute phase of injury might lead to increased activity and recurrent injury.

Bauer and Murray (Bauer and Murray, 1999) investigated the applicability of SEMG for distinguishing between LE patients and healthy controls by looking at differences in temporal muscle activation patterns and integrated EMG of ECRB, and FCU during nine different conditions of a tennis volley: three velocities (low, medium, high) x three racket-head impact locations (centre, long-axis, torsional). Results demonstrated that patients activated ECRB earlier, longer, and greater than controls as an attempt to reduce pain experience of forced wrist flexion during backhand volley. The combined ECRB muscle activation duration for all impact conditions was 0.47s in LE patients compared to 0.33s in controls ($p<0.05$). Integrated-EMG was also significantly higher for ECRB in LE group for all racket impact conditions compared to the controls. However, based on kinematic video analysis this increased activation strategy failed as both patients and controls employed similar forced flexion. This increased activation would intensify strain on injured tissue, promote muscle fatigue, and delay healing process. Authors concluded that SEMG is a helpful tool for the differentiation of muscle activation strategies between LE patients and healthy controls.

4. DISCUSSION

4.1 Muscle Activity

Different EMG techniques and parameters have been applied for investigating alterations in the muscle behaviour that may contribute to the development of different musculoskeletal disorders including LE. This review summarised the key components of EMG studies of forearm muscles with potential implications for tennis-induced LE in tennis players with and without LE. While a large number of forearm EMG studies have been published on non-tennis populations, this review was able to identify only 13 tennis-related studies of which only two (Bauer and Murray, 1999; Kelley et al., 1994) involved tennis players with a history of LE. While studying tennis players with LE injury may potentially explore only post-injury muscle activation patterns rather than causative factors, it has strong implications for the development of effective rehabilitation interventions and assessment of functional recovery (Alizadehkhaiyat et al., 2009; Gibson, 2012; Regan, 2009).

The use of appropriate movement biomechanics is fundamental for producing safe and effective stroke techniques and achieving optimal tennis stroke performance. In contrast, applying suboptimal and faulty biomechanics may affect the fundamental mechanical structure involved in tennis strokes and lead to sport injuries (Elliott, 2006). In LE, repetitive concentric contraction of wrist extensors during forceful impact between racket and ball and resulting micro-trauma leads to the injury (Frostick et al., 1999). Hence, considering the principal involvement of wrist extensor muscles in the pathomechanics of LE, it has become imperative to define and analyse the EMG behaviour of key muscles in relation to techniques and equipment design in order to effective interventions to enhance performance, minimise risk of injury and develop rehabilitation programmes (Morrison, 2002).

Literature indicates a particular interest in EMG examination of the forearm muscles as biomechanical knowledge support a predominant involvement of wrist extensors in common tennis strokes (De Smedt et al., 2007). These studies refer to the theory according to which repetitive large impact forces generated by the strokes, backhand in particular, result in disproportionate overloading of the wrist extensor group. EMG studies by Morris et al., (Morris et al., 1989) and Giangarra et al. (Giangarra et al., 1993) supported such a concept as both reported a marked increase in the activity of wrist extensors including ECRB and ECRL in multiple phases of forehand, serve, and backhand strokes with the activity of wrist flexors remaining fairly constant. Furthermore, a considerably higher EMG activity of ECR during repetitive pre- and post-impact in both forehand and backhand volley in the presence of unchanged FCR activity has been suggested to predispose players to injury or delay recovery process in tennis players already suffering from LE (Chow et al., 1999; Chow et al., 2007). Finally, an earlier, longer, and greater activation of ECRB during backhand volley at combined conditions of velocity and racket-head impact locations has been reported in LE patients compared to non-injured players (Bauer and Murray, 1999).

Considering the lower incidence of LE in players with double-handed backhand stroke, several studies attempted to investigate the impact of single-handed backhand technique, which is commonly performed during both defensive and offensive strokes on forearm muscle activity (Elliott, 2006). Biomechanical principles advocate a greater risk of LE injury associated with such technique as players largely use distal joints of the one upper extremity (elbow and wrist) to generate the force and linear velocity required during the ball impact. This differs from that of players with two-handed backhand stroke where both upper extremities are involved in energy/force absorption and large body segments such as hip and trunk rotations are used for force production and transmission during the stroke (Roetert et al., 1995; Groppel, 1992). Despite the biomechanical indications, existing EMG studies failed to provide supporting evidence on the advantage of double-handed backhand over single-handed technique as ECRB activity did not differ between two techniques (Giangarra et al., 1993; Morris et al., 1989).

There are also suggestions that sub-optimal joint biomechanics during one-handed backhand stroke contribute to a higher incidence of LE observed in recreational and novice players. This refers to the difference in wrist joint angle between unskilled and skilled players. Kinematic studies have shown that while skilled players use a hyper-extended wrist (i.e. concentric contraction) to impact the ball (Blackwell and Cole, 1994), recreational players hit the ball with a flexed wrist causing repetitive eccentric contraction and lengthening of the wrist extensors (Leach and Miller, 1987). Current knowledge from EMG studies examining differences of activation patterns across different skill levels suggests that: 1) Contrary to novice players, expert players perform the backhand with extended wrist and with an angular velocity in the extension direction. This reflects that wrist flexion used by the novice players during stroke may facilitate LE injury due to overactivation of the wrist extensors to counterbalance flexor activity (Blackwell and Cole, 1994), 2) Radial deviation applied by inexperienced players to produce vertical velocity from the flat to topspin forehand drives requires further recruitment and higher activity of wrist extensor muscles (Rogowski et al., 2011), and 3) While experienced players are able to maintain muscle activity approximately at maximal level throughout single-handed backhand, less experienced players increase extensor activity to a supra-maximal level at the impact. This high contraction of wrist extensors and associated stiffness during ball impact may result in a higher incidence of LE in inexperienced players (Wei et al., 2006).

Biomechanical observations have also encouraged researchers to investigate the impact of grip size and resultant grip tightness on forearm muscle activation during tennis stroke production (Eygendaal et al., 2007; Roetert et al., 1995). Considering that producing a great amount of stroke power with minimal vibration transmission to the hand is the ideal condition for the tennis player, biomechanical studies have suggested tight and moderate-light and tight grip as the most advantageous grip tightness for elite and unskilled players, respectively (Hatze, 1976). Accordingly, it has been suggested that high frequency vibrations associated and high wrist extension torques associated with the use of a tight grip may generate large loads on the lateral muscle tendon unit and facilitate the development of LE (Hatze, 1976; King et al., 2012). Despite these observations, EMG studies of various racket grip sizes above and below Nirschl's recommended size have failed to provide any significant evidence on altered wrist extensor activity despite a trend toward higher extensor activity with increasing grip size from early acceleration phase through ball impact during backhand (Adelsberg, 1986; Hatch et al., 2006).

In terms of racket characteristics, inappropriate weight has been associated with the generation of high loads in the wrist extensor muscle-tendon unit at the lateral epicondyle (De Smedt et al., 2007; Jobe and Ciccotti, 1994). Furthermore, it is suggested that a heavier racket may prevent injury by reducing the movement velocity and vibration during forehand (forward swing) and increasing muscle coactivation (Rogowski et al., 2009). This however appears to be the case regarding shoulder/trunk muscles where a strong correlation has been reported between racket mass and muscle activation level during crosscourt forehands but not for the forearm muscles (Rogowski et al., 2009). Hence, existing evidence is insufficient to support the contribution of racket mass to the development of LE.

Finally, there are biomechanical suggestions that braces may help to prevent/manage LE by reducing the load and repetitive stress to the common extensor origin (Walther et al., 2002). The outcome would however be much dependent on the characteristics of the product and placement. The only EMG study examining the impact of three different braces on activation duration of forearm muscles during serve and backhand strokes (only pre-impact phase) suggested the use of lateral elbow counterforce brace to reduce risk of injury by means of lowering extensor muscular activity across all skill levels (Groppel and Nirschl, 1986).

4.2 Methodological Considerations

Sample size of studies varied significantly with the smallest and largest studies recruiting 4 (Adelsberg, 1986) and 29 (Rogowski et al., 2011) controls, respectively. These indicate the need for further studies of both healthy controls and tennis players suffering from LE with adequate sample sizes and well-defined demographics. Of eleven studies appropriately specifying participant skill level (Table3), only two involved novice and inexperienced players (Blackwell and Cole, 1994; Groppel and Nirschl, 1986). Most studies were performed on highly skilled players meaning that main body of the EMG research did not reflect neuromuscular patterns of average players. Novice and recreational players represent the majority of tennis-playing population who may have higher risk of injury because of inadequate conditioning and suboptimal techniques in performing tennis strokes. For example, both studies involving novice players (Blackwell and Cole, 1994; Groppel and Nirschl, 1986) demonstrated significant differences in forearm muscle activity patterns compared to skilled players that could be associated with increased risk of injury in high handicap tennis players. Additionally, it needs to be pointed out that the majority of studies recruited female players (136 vs. 39). There are fundamental gender-related differences in upper limb muscle profile and strength capacity (Alizadehkhaiyat et al., 2014; Miller et al., 1993) as such the results of these studies cannot be generalised.

There was a considerable diversity in the protocol design used for EMG recording. Studies varied widely in tennis shot selection (forehand, backhand, serve, and volley), phase classification, handiness (single- or double-handed), racket grip size, ball speed (slow, medium and fast), and ball type (oversize and regular size). Backhand stroke was the most commonly used movement amongst the EMG studies (eight studies) (Adelsberg, 1986; Blackwell and Cole, 1994; Giangarra et al., 1993; Hatch et al., 2006; Kelley et al., 1994; Morris et al., 1989; Wei et al., 2006). These methodological inconsistencies add additional difficulty to effective interpretation of findings and drawing any conclusive conclusions. None of the studies detailed racket specifications, and hence there was no report on the influence of using different rackets on EMG patterns. At the present time that comprehensive biomechanical knowledge and advanced technology are routinely utilised by the manufacturers, it is of great significance to provide racket-specific information.

EMG parameters have been widely used in musculoskeletal disorders to describe muscle activation patterns, activity level, and localised muscle fatigue. There is relatively strong evidence that aberrant activation of forearm muscle, particularly wrist extensors, contributes to the pathology of LE and that should be considered in terms of injury prevention and management (Alizadehkhaiyat et al., 2007a; Alizadehkhaiyat et al., 2007b; Finsen et al., 2005; Johansson et al., 2004; Landis et al., 2005; Roetert et al., 1995). However, the major body of knowledge comes from non-tennis studies and tennis-related data is sparse. Several studies have recommended using a gripping task for the EMG assessment of forearm muscles as it effectively activates both wrist extensor and flexor groups even at low forces (Alizadehkhaiyat et al., 2007a; Alizadehkhaiyat et al., 2007b; Hagg and Milerad, 1997; Mogk and Keir, 2003; Snijders et al., 1987). This reflects that the activity of these muscles may be appropriately investigated during tennis strokes, as they require active gripping effort throughout movement phases to meet flexing moments. Electromyographic assessment of forearm muscle activity has yielded paradoxical results as studies, however on populations of different backgrounds, have reported both decreased and increased activity of wrist extensors (Alizadehkhaiyat et al., 2007b; Bauer and Murray, 1999; Kelley et al., 1994; Morris et al., 1989). The following section condenses existing EMG knowledge of forearm muscle behaviour in tennis and highlights key implications for tennis-induced LE.

Some studies did not detail the electrode placement making direct comparison of the results from different studies a challenge. Studies applied both surface (Adelsberg, 1986; Bauer and Murray, 1999; Blackwell and Cole, 1994; Chow et al., 1999; Chow et al., 2007; Groppel and Nirschl, 1986; Rogowski et al., 2009; Rogowski et al., 2011; Wei et al., 2006) and fine-wire (Giangarra et al., 1993; Hatch et al., 2006; Kelley et al., 1994; Morris et al., 1989) electrodes to obtain EMG signals from forearm muscles. Each of these techniques has own advantages and disadvantages. While fine-wire electrodes eliminate crosstalk and assure more precise collection of the data from target muscle; in the forearm with such proximity of several small muscles the appropriate placement of the electrodes cannot be guaranteed without guide (e.g. ultrasound) (Kerver et al., 2013; Riek et al., 2000). Additionally, EMG signals collected with indwelling electrodes are largely limited to the action potentials from nearby muscle fibres (Nawab et al., 2008). Six studies attempted to study ECRB and ECRL in isolation, two of which used surface (Bauer and Murray, 1999; Blackwell and Cole, 1994) and four fine-wire electrodes (Giangarra et al., 1993; Hatch et al., 2006; Kelley et al., 1994; Morris et al., 1989). Signals intended to be collected by surface electrodes from individual forearm muscles; particularly those distinguishing between ECRB and ECRL can be potentially affected by crosstalk and result in inaccurate interpretation of the results. Considering the fact that EMG activity of ECRL and ECRB cannot be differentiated even with fine-wire electrodes (Perotto and Delagi, 1994), it may also be preferential to report EMG profile of the forearm muscles collectively (i.e. extensor group and flexor group). Some technical considerations such as applying double differential technique, and reducing electrode size and inter-electrode distance enhance the quality of signal and reduce the crosstalk (De Luca, 1997). Hence, there is need for the establishment of specific guidelines and recommendations for EMG assessment of forearm musculature in terms of electrode and muscle selection.

Several studies proposing to use EMG of the MVC (EMG_{max}) for normalisation purpose did not clearly specify applied the mathematical process. Because of this unclarity, it is not possible to compare muscle activation results between studies and between different testing conditions (e.g. stroke type). It is important that studies from different laboratories apply well-established and widely accepted normalization guidelines such as 'European Recommendations for Surface ElectroMyoGraphy' (SENIAM) (Hermens et al., 2000) in order to enhance consistency of reports and facilitate direct comparisons. Only two papers studied timing parameters including muscle activation durations (Groppel and Nirschl, 1986) and muscle activation onset/offset (Rogowski et al., 2009). The small number of studies and variations in methods used for data analysis makes it difficult to draw any conclusion.

Limb motions and forceful impacts with external objects (e.g. racquet making contact with the ball or a foot making contact with the floor) can cause a movement at the electrode-skin interface and impair the consistency of the signal by generating motion artefact (De Luca et al., 2010; Roy et al., 2007; Whitting et al., 2009). While it is expected that excessive motion artefact in the EMG signal caused by mechanical perturbation at impact to have affected the consistency and reliability of data during some of the measurements, only one study reported the effect of impact from tennis strokes on EMG recordings (Groppel and Nirschl, 1986). The influence of such artefact on EMG recordings and analysis needs to be clearly addressed in future studies.

4.3 Clinical Implications and Directions for Future Research

It is not possible to present combined results of existing studies and draw concrete conclusions with regard to their clinical implications due to several reasons such as divergent methodology (fine-wire vs. surface, individual muscle vs. muscle mass/group), differing reported parameters, inadequate sample sizes, and incoherent participants (e.g. diverse sample populations, gender inequality). Although EMG has great usefulness in this area, attempts are needed to standardise the data. Hence, future studies of coherent techniques and protocols are required to effectively assess the relationship between aberrant forearm muscle activation in the development of LE. It is broadly accepted that normalisation process potentially controls for between subject differences by eliminating the influence of individual factors on EMG signal (Burden, 2010; Burden and Bartlett, 1999; Halaki and Ginn, 2012). While majority of reviewed studies normalised EMG relative to a maximal effort, some others used a different method or did not apply any normalisation. Considering difficulty of performing a maximal in painful conditions, further research is needed to determine an optimal normalisation method to enhance the reliability of EMG assessment.

EMG studies measuring timing parameters are required to examine the influence of level of expertise. While EMG studies have reported a link between forearm muscle fatigue and LE and in non-players (Alizadehkhaiyat et al., 2007a; Alizadehkhaiyat et al., 2007b; Hagg and Milerad, 1997; Hagg et al., 1997), the fatigability of muscles has not been studied in tennis-related performances. EMG has been suggested as a helpful tool to assess functional recovery from LE in non-tennis players (Alizadehkhaiyat et al., 2009), however, no study has looked at the pre- and post-intervention EMG profile of forearm muscle in tennis-induced LE. Future research examining forearm muscle activation patterns in tennis strokes performed by both male and female players is desirable.

5 CONCLUSIONS and FUTURE RESEARCH DIRECRTIONS

Despite indications of increased activity of wrist extensor muscles during all basic tennis strokes, insufficient evidence exists to support its aetiologic relationship with LE. While existing literature is suggestive of increased wrist extensor activity in less experienced single-handed backhand players due to suboptimal joint biomechanics, its association with the development of LE requires further evidence. There is no evidence to support an association between single- and double –handed technique, racket grip size, and racket mass with development of LE in tennis players. Current research evaluating the association of forearm muscle activity with LE is limited due to heterogeneity in methodological design including EMG recording protocols and analysis procedures, lack of sufficient information on the EMG methods used, low sample sizes, participant inclusion criteria, and lack of prospective research. Future research of adequate sample sizes should aim to: 1) establish an standardised protocol for electromyographic assessment of forearm muscles in terms of measuring protocol and muscle and electrode selection; 2) evaluate the value of forearm muscle activity and fatigue screening in identifying players most likely to develop LE; and 3) examine forearm muscle activation patterns during various tennis strokes in both male and female players.

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Figure Legends

Figure1. The flow diagram summarising the study selection process for study inclusion

Table1. Summary of participant (players with and without lateral epicondylitis) demographic data in the reviewed studies

LE: Lateral Epicondylitis; **CON:** Control; **NR:** Not Reported; **D:** Dominant; **ND:** Non-Dominant.

Table2. Summary of electromyographic methods (muscles, electrode type, reported EMG variable, and normalisation process) used in the reviewed studies

ECR: Extensor Carpi Radialis; **ECRB:** Extensor Carpi Radialis Brevis; **ECRL**: Extensor Carpi Radialis Longus; **FCU:** Flexor Carpi Radialis; **FCU:** Flexor Carpi Ulnaris; **EDC:** Extensor Digitorum Communis; **PT:** Pronator Teres; **NR:** Not Reported; **EMG_{MAX}:** EMG Maximum; **MVE:** Maximal Voluntary Effort; SEMG: Surface EMG; FWEMG: Fine Wire EMG.

Table3. Summary of participant specifications (skill level) and EMG measurement protocol (tennis stroke, experimental conditions, racket grip size, single- double-handed) applied in the reviewed studies

NR: Not Reported; **NTRP:** National Tennis Rating Program; **NCAA:** National Collegiate Athletic Association; **ITN:** International Tennis Number