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BIOMECHANICAL COMPARISON OF BACKHAND TECHNIQUES
USED BY NOVICE AND ADVANCED TENNIS PLAYERS:
IMPLICATIONS FOR LATERAL EPICONDYLITIS

by

John Patrik Ingelman
B.Sc., Dalhousie University, 1988

THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

in the School of Kinesiology
(Faculty of Applied Sciences)

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December 1991

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Abstract

It has been predicted that the majority of novice tennis players will show symptoms of lateral epicondylitis at some time during their playing careers. The reasons behind their predisposition for the injury are unclear. Various hypotheses regarding lateral epicondylitis etiology have been suggested, but quantitative support for these hypotheses is negligible.

This study was designed to test quantitatively one of the suggested hypotheses. A biomechanical analysis, using techniques of electromyography and electrogoniometry, was carried out to compare the backhand stroke techniques of novice and advanced tennis players.

It was hypothesized that novice players generate greater forces with their wrist extensor musculature than do advanced players due to poor backhand techniques. Parameters associated with muscle force were measured and subsequently compared between the players with different skill levels.

Results indicate significant ECRB muscle force parameter differences between novice and advanced players. Parameter differences observed for the greater part of the stroke were believed to cancel each other out in terms of muscle force estimations. Specifically, the force-elevating effects of higher levels of muscle activation of the advanced players
were balanced by the force-elevating effects of longer muscle lengths of the novice players. Just after impact, however, when forces were considered maximal, the results suggest that the novice players had greater ECRB impulses than did the advanced players. This was due to highly significant differences between their eccentric muscle velocities in the wrist flexion/extension plane. The leading elbow backhand technique, as used by many novice tennis players, is implicated as a significant contributor to lateral epicondylitis etiology.
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I. INTRODUCTION

Tennis is a popular sport, yet along with its popularity there exists a high incidence of tennis elbow. Epidemiological studies have observed that over fifty percent of all tennis players acquire tennis elbow at least once during their playing careers (Nirschl, 1975; Gruchow & Pelletier, 1979; Priest, Braden & Gerberich, 1980; Carroll, 1981; and Kamien, 1988). Although there are numerous treatments available for the injury, including surgery for severe cases, prevention is obviously preferred.

Prevention of tennis elbow is a problem because its etiology is poorly understood. Numerous hypotheses have been made with regards to the etiology, but support for them is minimal. One such hypothesis is that poor backhand technique may induce overloading of wrist extensor muscles, which may result in tennis elbow (Bernhang, Dehner & Fogarty, 1974; Cohen, 1980; McLaughlin & Miller, 1980; Nirschl & Sobel, 1981; Legwold, 1984; Levisohn & Simon, 1984; Allman, Torg & Welsh, 1987; and Stites, 1988).

Purpose

The main purpose of this study was to test the hypothesis that poor backhand technique is a significant contributor to tennis elbow in novice tennis players. Comparison of parameters associated with wrist extensor
muscle force, namely activation, length and velocity, between novice and advanced backhand techniques, provided the means for testing this hypothesis.
II. LITERATURE REVIEW

A. Lateral Epicondylitis - General Information

1. Definition

The medical term for classic tennis elbow, the variety that involves pain near the lateral humeral epicondyle, is lateral epicondylitis (LE) (Peterson & Renström, 1986). This is contrasted with a similar ailment involving the medial epicondyle, namely medial epicondylitis. LE is at least five times as prevalent as medial epicondylitis (Priest et al., 1980 and Legwold, 1984).

It is interesting to note that LE does not only affect tennis players. Other athletes, including squash, badminton, table tennis, baseball and football players, golfers, and javelin throwers have all been documented with the ailment (Root & Kiernan, 1974 and Peterson & Renström, 1986). Also, workers, such as carpenters, plumbers, painters, electricians, butchers, dentists and surgeons, have encountered the injury (Goldie, 1964; McLaughlin, 1978; Gruchow & Pelletier, 1979; and Dimberg, 1987). Even people who simply perform activities like knitting, long-hand writing and playing the violin can acquire LE (Root & Kiernan, 1974 and McLaughlin, 1978). Repetitive wrist motion, while gripping an object in the hand, seems to be the important link between tennis playing and these other
activities, in terms of potential mechanisms of the injury (Snijders, Volkers, Mechelse & Vleeming, 1987).

Victims of LE experience pain in the region of the lateral epicondyle. The pain often shoots down the posterolateral aspect of the forearm, and can be unbearable even with the slightest movement of the hand. The pain can last for several months, making the numerous hand movements of everyday life difficult (Peterson & Renström, 1986).

The most common finding during surgical investigation of patients with severe cases of LE has been tearing of the extensor carpi radialis brevis (ECRB) tendon where it is part of the common extensor tendon near the lateral epicondyle (see Figure 1). Granular tissue, produced in response to soft-tissue tearing, has also been observed in the damaged area (Goldie, 1964; Coonrad & Hooper, 1973; Ryan, 1977; Nirschl & Pettrone, 1979; and Shields, 1987).
Figure 1a. Wrist extensor muscles (ECRB is shaded). (Copied with permission from Anderson, 1983: fig. 6-91A.)
Figure 1b. Origins and insertions of the wrist extensor muscles (ECRB’s shaded). (Copied with permission from Anderson, 1983: fig. 6-90.)
Studies have provided evidence to support the surgical finding that ECRB is the most affected structure in LE victims. For example, an ultrasonographic study of tennis players with LE showed that multiple lesions, including enthesopathy, peritendinitis, tendinitis, bursitis and intramuscular haematoma, were all associated specifically with ECRB damage (Maffulli, Regine, Carrillo, Capasso & Minelli, 1990). Also, a clinical study involving patients with LE demonstrated that forced finger extensions, which are performed mainly by the extensor digitorum communis muscle, did not induce any pain, whereas forced wrist extension and radial deviation, both functions of ECRB, did induce pain (Goldie, 1964). This suggests that even though the extensor digitorum communis muscle is involved in wrist extension, the fact that it does not produce pain during its other functions indicates that it is not damaged in LE sufferers.

Physicians today are confident that LE is an injury that is primarily associated with damage to the ECRB tendon where it originates at the lateral epicondyle. Pathologically, the main damage is believed to be in the form of either tendinitis (Nirschl & Pettrone, 1979; Shields, 1987; Hess, Cappiello, Poole & Hunter, 1989; and Harvey, Glick, Stanish & Teitz, 1990) or an enthesopathic lesion (Burry, 1987 and Kamien, 1990).
2. Functional Anatomy of ECRB

Structurally, ECRB is a two-joint muscle since it crosses both the wrist and elbow joints. Functionally, however, the muscle is not considered to contribute to elbow movements because its origin lies on the elbow flexion/extension axis. Therefore, it is reasonable to analyze only the actions of ECRB about the wrist when assessing the mechanisms behind LE (Goldie, 1964 and McLaughlin & Miller, 1980). This is further justified by the fact that Goldie (1964) found that LE patients only had problems with hand/wrist functions and not elbow functions.

ECRB is one of four wrist extensor muscles, although it is considered to be the main one, especially when the hand is clenched (McFarland, Krusen & Weathersby, 1962). It is assisted, under different circumstances, by the extensor carpi radialis longus, extensor digitorum communis and extensor carpi ulnaris muscles (Bäckdahl & Carlsöö, 1961; McFarland et al., 1962; and Basmajian & De Luca, 1985). ECRB is also considered to be a prime mover in radial deviation of the hand, along with flexor carpi radialis and extensor carpi radialis longus (McFarland et al., 1962 and Basmajian & De Luca, 1985). Although the precise contribution of ECRB to wrist extension and radial deviation has not been quantified, the line of action of its tendon of insertion with respect to
the wrist joint indicates that it must be a major contributor to both of these movements (Dempster & Finerty, 1947).

Another important function of ECRB is stabilization of the wrist joint during contraction of the finger/wrist flexors (Fidelus, 1967 and Snijders et al., 1987). This means, for example, that ECRB is active whenever the fingers are grasping an object. Since this action, as well as wrist extension and radial deviation, are involved in tennis, most notably in the backhand stroke, and the other activities that produce LE, the ECRB muscle is likely to be highly active in these contexts.

The anatomy of a musculotendinous structure has a significant bearing on the forces that it experiences. As mentioned earlier, ECRB, via the common extensor tendon, originates at the lateral epicondyle of the humerus. The tendon crosses over the head of the radius before forming the muscle belly. The muscle crosses the superior half of the forearm posterolaterally and then becomes a long, slender tendon of insertion. This tendon passes underneath three thumb muscles, extensor pollicis longus and brevis and abductor pollicis longus, and the extensor retinaculum before obliquely inserting on the lateral edge of the base of the third metacarpal bone (O'Rahilly, 1986: p. 126) (see Figure 1).
3. Etiology

a. General - Tendon Damage

Biomechanics research centred around the understanding of soft-tissue injury etiology, including tendon damage, is in its infancy (Viano, King, Melvin & Weber, 1989). Much of the research being carried out today is based on qualitative hypotheses as opposed to quantitative evidence. For example, Viano and Lau (1988) have suggested that there is a direct relationship between the force applied to a biological tissue and the risk of injury. This implies that a tendon, as an example of a biological tissue, is damaged by the application of great forces. There certainly is a limit to the amount of stress (force per unit of cross-sectional area) that a tendon, like any other material, can normally withstand (Elliott, 1965 and Fung, 1981), but the role of this in tendon injury etiology has not been firmly established.

A tendon comprises fibres of collagen and elastin, which are embedded in a proteoglycan-water matrix. Collagen accounts for 70-75 percent of the tendon's dry weight. The collagen fibres are held together in a loose parallel arrangement with the aid of cross-linkages. This structure enables the tendon to perform its main function of pulling on a bone with a tensile force dictated by the contraction of its attached muscle (Crisp, 1972 and Hess et al., 1989). The
tensile strength properties of a tendon depend on the amount and precise orientation of collagen fibres (Elliott, 1965).

The mechanical properties of a tendon are typically represented by a stress-strain relationship such as the one in Figure 2. This illustrates the fact that the amount of tensile stress experienced by the tendon is influenced by the amount of applied strain (change in length divided by rest length). There is an initial range of strains during which stress remains close to zero (0 to A). This is followed by a near elastic range, during which stress increases almost linearly with added strain (A to B). Finally, when the tendon is nearing rupture, it exists in a so-called plastic region, during which a minimal amount of additional stress produces a large amount of additional strain (B to C) (Elliott, 1965 and Fung, 1981).

The magnitude of stress at which rupture occurs is labelled the ultimate stress, corresponding to the ultimate strength of the tendon. Values ranging from about 50 to 100 Newtons/square millimetre have been measured on in vitro human tendons. The strains corresponding to tendon rupture range between 10 and 15 percent (Elliott, 1965; Yamada, 1970; and Fung, 1981). It is important to point out that since these experiments involved very slow strain rates, the ultimate strengths are probably inapplicable in vivo (McCully & Faulkner, 1986 and Viano et al., 1989). The studies by Van
Brocklin and Ellis (1965) and Abrahams (1967) demonstrated that higher rates of strain produce steeper stress-strain relationships. In other words, the stress experienced by a tendon is increased not only by added strain, but also by increased rate of strain. This may have implications for the magnitude of stress at which tendon rupture occurs (Curwin & Stanish, 1984).

![Diagram of stress-strain curve]

Figure 2. A typical stress-strain curve for human tendon (stress represented by “load”; strain represented by “deformation”). (Copied with permission from Fung, 1981: p. 210.)

As whole structures tendons can withstand very high tensile forces, but it is still common for microtears (i.e.,
rupturing of individual collagen fibres) to occur while tendons are experiencing normal physiological forces. This is perhaps because of the addition of compressive, shear and frictional forces to these tensile forces (Frost, 1973: p. 167). Tendons are capable of functioning normally even after a number of microtears have occurred. In fact, normally these microtears are good for the integrity of the tendon as they stimulate ongoing turnover of collagen fibres, keeping the tissue young and healthy. It is only when this turnover is insufficiently rapid to meet the demands placed on the muscle attached to the tendon, that serious macrotears can occur (Frost, 1973 and Hess et al., 1989). Also, a discontinuity in a tendon brought on by an accumulation of microtears can raise the stress concentration in the damaged area and contribute further to the onset of macrotears, in agreement with mechanical engineering principles (Shigley, 1986: p. 206). This extreme form of tendon damage is then labelled tendinitis (Frost, 1973 and Curwin & Stanish, 1984).

Breakage of a material caused by repeated or fluctuating stresses within the static stress design limits of the material is known as fatigue (Shigley, 1986: p. 228). If a tendon, as an example of a material, is fatigued, it can be damaged by repetitive stresses below its ultimate stress (Frost, 1973 and Hess et al., 1989). Progressive weakening of a tendon (i.e., lowering of its ultimate strength) upon
repetitive loading has been clearly demonstrated in studies involving rat tail tendons (Rigby, Hirai, Spikes & Eyring, 1959). Therefore, any activity which involves repetitive loading of a tendon, particularly when muscular contraction is combined with external stretching forces, makes the tendon susceptible to fatigue-like failure.

Tendon injuries can be divided into two distinct categories. Those which result from one violent stress, presumably greater than the ultimate stress of the tendon, are known as acute strains. Those which arise from repetitive loading of stresses presumed to be below the ultimate stress are known as chronic strains (Keene, 1985). The etiology of these injuries may not be identical. Although both involve tearing of collagen fibres, the causes of tearing may be quite different.

In summary, a tendon has limited stress tolerance to either a single high stress or repeated lower stresses. If these limits are exceeded, then damage will occur. This damage can be repaired, but only if given adequate time and normal, healthy conditions. Unfortunately, little is presently known about the stress limits of human tendons in vivo (Curwin & Stanish, 1984).
b. Specific

Even though LE has been studied for over one hundred years, its etiology is poorly understood (Bernhang et al., 1974 and Burry, 1975). Curwin and Stanish (1984) have provided a reasonable summary of the various etiological contributors that have been suggested by the numerous tennis elbow researchers of the recent past. The following are mentioned as potential contributors to LE: massive overload of the wrist extensor muscles in eccentric contractions; multiple repetition of wrist movements; old age; inadequate strength, endurance and/or compliance in the wrist extensor musculotendinous unit; hormonal imbalance (in females only); abnormal elbow joint design; mechanically unfavourable equipment used for the movements; and lack of skill, or inefficiencies, in performing movements of the hand. They conclude that some, presently unknown, combination of these factors is responsible for inducing stresses in the damaged tendon which exceed its strength capabilities. It is quite possible that different combinations of factors are involved in different instances of LE. Unfortunately, there is no consensus on the importance of any one of the suggested factors.

Both acute and chronic cases of LE have been reported in the literature, but chronic cases predominate. Elliott (1965) and Curwin and Stanish (1984) state that tendons have
ultimate strengths four times as great as any load they experience during normal activities. If tennis playing can be considered one of these normal activities (perhaps it cannot be during ball-racquet contact), then the loads placed on the ECRB tendon must typically be too low for acute rupture to occur.

LE has been labelled an overuse syndrome by numerous researchers (Gruchow & Pelletier, 1979; Nirschl & Pettrone, 1979; Curwin & Stanish, 1984; Allman et al., 1987; and Hess et al., 1989). Overexertion of the ECRB muscle, through massive repetition of great forces, is the presumed general etiology of the injury (McLaughlin, 1978; Nirschl & Pettrone, 1979; and Briggs & Elliott, 1985). It is apparent that the activities noted to induce LE all involve massive repetition of wrist extension and radial deviation. A reasonable hypothesis, then, is that the forces generated in the ECRB tendon of origin during these activities are great enough, when repeated numerous times, to induce tendon damage.

It is important to point out that forces other than the tensile ones that the ECRB tendon was designed to withstand may be involved in damaging the tendon. When a tendon is experiencing tensile forces and bending, for example around a bony prominence, compressive and frictional forces are induced. The compressive forces act normal to the bony prominence and the frictional forces act in directions
opposing the tensile ones (Frost, 1973: p. 167). These additional forces are proportional in magnitude to the tensile forces. The intricate winding course of ECRB is an example of this type of situation. The specific bending that occurs around the radial head produces additional compressive and frictional forces, which increase as tensile forces increase. Some researchers have suggested that this may be a significant contributor to LE (Goldie, 1964; Nirschl, 1975; McLaughlin, 1978; and Briggs & Elliott, 1985). Briggs and Elliott (1985) have also suggested that additional shear forces are produced in the ECRB tendon of origin because of unequal tension applied to other attached soft tissues. They state that the tendon does not simply originate at the lateral epicondyle. Rather, it adheres by means of filamentous attachments to the adjacent members of the common extensor tendon, the radial collateral ligament, the orbicular ligament, the capsule of the elbow joint and the surrounding deep fascia. The shear forces produced by these attachments are proportional in magnitude to the tensile forces. It is reasonable to hypothesize that excessive tensile force in the ECRB tendon leads to excessive shear as well as compressive and frictional forces. The precise combination of these forces involved in the etiology of LE is unknown.
B. Novice Tennis Players With Lateral Epicondylitis

Presently, there is no clear consensus regarding the etiology of lateral epicondylitis in tennis players. Various potential factors contributing to the onset of LE in tennis players have been proposed in the vast amount of literature written on the topic. The most notable ones, in no particular order of rank, are hitting backhand shots with a poor technique and/or using excessive grip pressure; inadequate wrist extensor musculotendinous strength, endurance and/or compliance; elbow joint anatomical abnormality; old age; hormonal imbalance (in females only); playing frequently and with high intensity; using a racquet with force- or vibration-enhancing characteristics; playing in cold, wet weather or without adequate warm-up; and contacting the ball away from the centre of the racquet (for further details, the reader is referred to the following: Sykes, Scott & Kellett, 1971; Bernhang et al., 1974; Nirschl, 1975; Brody, 1979; Fiott, 1979; Plagenhoef, 1979; Elliott & Blanksby, 1980; Plagenhoef, 1980; Priest et al., 1980; Brannigan & Adali, 1981; Roy & Irvin, 1983; Briggs & Elliott, 1985; Groppel, 1986; Allman et al., 1987; Kamien, 1988; Brody, 1989; and Widing & Moeinzadeh, 1990). All of these potential factors have in common the fact that forces are produced which can exceed the strength capabilities of the ECRB tissue at a particular instant in time during tennis.
play. It is possible that any one, or combination of these factors can bring about lateral epicondylitis in a particular tennis player.

One distinct group of tennis players which commonly acquires LE comprises novice players. These are people who play recreationally and who use poor stroke techniques, most obviously on the backhand. Nirschl (1975) found that novice players are about four times more prone to the injury than are advanced players. The question as to why novice players are so susceptible to LE has not been adequately answered.

C. The Significance of Poor Backhand Technique as a Factor in Lateral Epicondylitis Etiology

1. General Differences Between Novice and Advanced Techniques

Many researchers believe that poor backhand technique contributes somewhat (if not completely) to LE etiology in novice tennis players (Bernhang et al., 1974; Cohen, 1980; McLaughlin & Miller, 1980; Nirschl & Sobel, 1981; Legwold, 1984; Levisohn & Simon, 1984; Allman et al., 1987; and Stites, 1988). The evidence supporting this belief, however, is qualitative, coming mostly from epidemiological studies of which that by Kamien (1988) is a representative example. Kamien found the most common response of tennis players with tennis elbow, when asked what they thought caused their injury, to be poor stroke techniques. These same tennis
elbow sufferers also claimed that they had a 100 percent success rate if they sought coaching to alleviate their tennis elbow symptoms. In fact, alteration of tennis strokes is considered by some to be the most successful form of treatment of LE (Priest et al., 1980). Although many researchers have suggested that poor technique is the most significant factor in LE etiology, they have not produced any quantitative evidence to support this.

The greatest loading of the wrist extensor muscles during tennis play is likely to occur during backhand shots because of the need to resist wrist flexion after ball-racquet contact. It follows that the overloading associated with LE in tennis players may occur during backhand shots. In looking at the possibility of poor backhand technique being a predisposer to LE in novice players, it is noted that many of these players use the so-called "leading elbow" backhand technique. This has been suggested as being a highly potential source of the problem for novice players (Bernhang et al., 1974 and Elliott, 1989).

The leading elbow backhand technique has been described as follows: swinging the racquet with body weight back on the heels, wrist flexed, forearm pronated, and elbow flexed and pointing towards the net (see Figure 3a). Also, many novice players are known to have poor use of their hip, trunk and shoulder muscles, to use poor timing, and to snap their
wrists extraneously into extension after hitting the ball (Bernhang et al., 1974; Nirschl, 1975; Cohen, 1980; Roy & Irvin, 1983; Legwold, 1984; and Macken, 1991). This is contrasted with the following general attributes of the classic advanced players' backhand technique: weight forward, wrist firm and neutral, and elbow extended and pointing down at impact (see Figure 3b); good footwork; transferring momentum efficiently by taking a step towards the ball, rotating the hips and trunk, and then using shoulder, elbow, forearm and wrist muscles in the proximal to distal sequence to generate high racquet velocities; and good timing (Groppel, 1978; Douglas, 1982; Roy & Irvin, 1983; Groppel, 1986; Elliott, Marsh & Overheu, 1989; and Macken, 1991).
Figure 3a. Novice player using the leading elbow backhand technique. (Copied with permission from Bernhang et al., 1974: p. 253.)

Figure 3b. Advanced player using the classic advanced players' backhand technique. (Copied with permission from Douglas, 1982: p. 64.)
The important qualitative differences between these techniques are that advanced players utilize the large moments of force produced by the strong leg, hip, trunk and shoulder muscles and well-timed transfers of momentum between body segments, whereas novice players rely more on the weak elbow and wrist muscles to perform the dynamic action of racquet movement (Bernhahg et al., 1974; Groppel, 1978; Legwold, 1984; and Groppel, 1986). Van Gheluwe and Hebbelinck (1986), in performing an electromyographic analysis of tennis strokes, demonstrated that advanced players utilize strong contractions of shoulder muscles to execute even moderate strokes. If novice players are not capable of using their shoulder, as well as hip and trunk, muscles adequately, then LE may be induced by the consequent overloading of their elbow and wrist muscles.

Nirschl (1975: p. 309) states that more skillful tennis players have better "economy of muscle utilization and efficiency of stroke patterns". This agrees with the theory that training results in decreased antagonistic muscle activity (Basmajian & De Luca, 1985). Furthermore, Nirschl (1975) and Legwold (1984) claim that advanced tennis players actually protect their relatively weak wrist muscles by only relying on them for racquet control rather than for powering the stroke as do novice players. They also suggest that novice players have to rely heavily on their weak wrist
muscles in order to compensate for the fact that their shoulder muscles are also too weak for the demands of tennis play.

The literature provides little quantitative evidence to support the theory that novice players produce greater forces in their wrist extensor musculature than do advanced players during backhand shots. Yoshizawa, Itani and Jonsson (1987) found that novice players exhibited higher levels of ECRB muscle activity and Bernhang et al. (1974) found that novice players used maximal grip pressure for longer durations, as compared to advanced players, in their studies. These results suggest that novice players may fatigue their ECRB muscles sooner than advanced players, which may lead to tendon damage.

The backhand techniques used by novice tennis players, including the leading elbow technique, appear to be mechanically unfavourable in terms of excessive force production in ECRB. Since novice players are predisposed to LE, it is reasonable to hypothesize that poor backhand technique may induce forces which are great enough in magnitude, and/or long enough in duration, to produce the characteristic tearing of the ECRB tendon of origin. This hypothesis has not yet been tested validly.
2. Quantification of Tendon Force

If a poor backhand technique, such as the leading elbow technique, is somewhat responsible for tearing the ECRB tendon of origin, then this technique may induce greater forces in the tendon than other, more advanced techniques. This, of course, is based on the assumption that there is no difference between the strength capabilities of the ECRB tendons of the people using the different techniques. To determine whether or not the leading elbow technique is an important factor in LE for novice players, it would be useful to quantify the forces transmitted to the ECRB tendon during backhand shots.

a. Direct Method - Force Transducer

Direct measurement of force in a tendon can only be accomplished by surgically implanting a miniature "buckle"-type force transducer around the tendon. This method has been used in a few in vivo studies with cats (Gregor, Hager & Roy, 1981 and Sherif, Gregor, Liu, Roy & Hager, 1983), horses (Barnes & Pinder, 1974), monkeys (Peres, Maton, Lanjerit & Philippe, 1983), and, recently, humans (Gregor, Komi & Järvinen, 1987 and Komi, Salonen, Järvinen & Kokko, 1987). The human studies have only involved measurement of achilles tendon forces.
Although this method may sound encouraging, it is not appropriate for the measurement of ECRB tendon forces during tennis strokes. Invasive techniques such as this are not common in human in vivo research mainly for ethical reasons. Furthermore, buckle transducers are only designed for use on well-defined external tendons such as the achilles tendon (Zajac & Gordon, 1989). Even with such a tendon there exists the serious problem of tendon length disturbance due to bending of the tendon around the transducer (An, Berglund, Cooney, Chao & Kovacevic, 1990). Until technology allows the production of miniature force-detecting devices that are more suitable for measuring forces in tendons such as ECRB, a direct method of force measurement cannot be used on tennis players while hitting backhand shots. Even then the major problem of convincing subjects to participate in invasive testing would still exist.

b. Indirect Methods

i). Inverse Dynamics Approach

For studies involving live human subjects researchers usually have to rely on indirect methods of tendon force quantification. The most established of these methods is based on the Inverse Dynamics Technique. McLaughlin (1978) and Winter (1990) provide good descriptions of the Inverse Dynamics Technique. The thesis by McLaughlin (1978)
describes the Inverse Dynamics Technique as applied to backhand tennis strokes. Essentially, muscle moments are calculated from Newtonian equations of motion, using segment kinematics (i.e., displacements and displacement-time derivatives) and kinanthropometric quantities (i.e., masses, centre of mass positions, lengths, and moments and products of inertia) as inputs.

A muscle moment determined in this manner is considered to be a generalized moment about the joint axis, representing the sum of moments produced by all muscles crossing the joint. If the contribution a particular muscle makes to the total moment and an estimation of the muscle's moment arm can be determined, then an estimate of that muscle's force can be calculated. It follows that the attached tendon is experiencing an equivalent tensile force because tendons are attached in series to their corresponding muscles.

Unfortunately, it is presently impossible to determine the contribution a specific muscle makes to the generalized joint moment (Andrews, 1982). Attempts have been made at solving this "general distribution problem" for simple planar motion at specific joints (ankle: Hof & van den Berg, 1977 and elbow: Caldwell & Chapman, 1991), but the distribution of forces amongst the synergistic extensors and radial deviators of the wrist is much more complex. The main problem, besides the fact that these muscles function in at least two planes,
lies in the great number of functionally single-joint muscles, each with potentially different moment contributions at different joint angles. Since ECRB, for example, acts to extend and radially deviate the wrist, as well as provide antagonistic stabilization forces when the hand is grasping an object (such as a tennis racquet), it is presently impossible to discern from generalized wrist moments the contribution of ECRB to the different actions. It will be necessary to make direct muscle/tendon force measurements to solve this problem in the future.

McLaughlin (1978) and McLaughlin and Miller (1980) describe an attempt that has been made at quantifying the tensile forces in the ECRB tendon during the backhand tennis stroke. Although their intentions were good (success might have solved the problem of LE etiology), their results included force values that were physiologically impossible. Their approach was far too complex for our present knowledge regarding muscle force estimation. It involved too many unknowns and unjustified assumptions, including the implementation of optimization techniques as a means of overcoming the general distribution problem, for their results to be meaningful. This approach needs to be refined in various ways before it can be used to estimate ECRB tendon forces during the backhand tennis stroke.
ii). Muscle Model Approach

Another indirect method of force estimation has been proposed by various researchers in the field of muscle mechanics. They suggest the use of a Hill-type muscle model, comprising a contractile component, a series elastic component and a parallel elastic component, in a mathematical or electrical force processor (see Bouisset, 1973; Hof, 1984; Chapman, 1985; Winters, 1985; and Zajac, 1989). Basically, three parameters associated with muscle force, namely activation, length and contractile component velocity, are the required inputs to the processor and an estimate of force is the output. Various assumptions involving the relationships between EMG and muscle activation, joint angle and muscle length and joint angular velocity and contractile component velocity are utilized.

Chapman (1985) provides a thorough review of the literature regarding muscle mechanics, in which force-activation, force-length and force-velocity relationships are discussed. Basically, the greatest force that a muscle can produce occurs when activation is maximal, length is optimal (typically near the upper limit of the physiological range) and contractile component velocity is negative. An example of such a combination is in a baseball pitcher who experiences "stretch-shortening cycles" in the muscles crossing the shoulder, elbow and wrist joints prior to
releasing a ball (Herring, 1989). Stretching a muscle prior to contracting it in the desired shortening direction increases the force in the muscle. Figure 4 illustrates the types of relationships required by muscle modellers for the estimation of muscle forces.

![Diagram showing the relationships of muscle force to various factors: activation, length, and contractile component velocity.]

Figure 4. Typical relationships of muscle force to activation (upper graph), length (middle graph) and contractile component velocity (lower graph). (Graphs adapted from Bouisset, 1973.)
Presently, muscle models are only capable of estimating generalized muscle moments during static contractions or slow dynamic activities such as walking (Hof & van den Berg, 1978; Hof & van den Berg, 1981a; Olney & Winter, 1985; and Hof, Pronk & van Best, 1987). Results from the walking studies, which demonstrated parallels between estimated and calculated (Inverse Dynamics Technique) moments, indicate that this approach has promise for the future. However, Hof and van den Berg (1981a), who have one of the most accepted of the present muscle models, indicate that their model is not suitable for determining muscle moments during fast dynamic activities. This may be due to problems in determining precise parameters associated with the properties of the contractile and series elastic components (Hof & van den Berg, 1981a,b,c). It is also possible that the Hill model is too simple, perhaps with an insufficient representation of muscle/tendon viscosity, to be used for fast dynamic activities. The Hill model, for example, is insufficient for the determination of the "force-enhancement" caused by rapid muscle stretch, which has been observed by Edman, Elzinga and Noble (1978) in stimulated isolated frog muscle fibres and Thomson and Chapman (1988) in voluntarily maximally activated human muscles.

The rapid effects of ball-racquet forces on wrist musculature occurring just after impact in tennis shots limit
the usefulness of present muscle models. Further model development, as well as a solution to the general distribution problem for the extensors and radial deviators of the wrist, is required before such an approach can be utilized in determining the forces in ECRB during the backhand tennis stroke. A recent attempt at implementing individual synergistic and antagonistic muscle models to a dynamic joint action illustrates the great deal of development that is required (see Caldwell & Chapman, 1989).

3. Measurement of Parameters Associated With ECRB Force

Even though an accurate muscle model cannot presently be designed for use in tennis elbow research, it would be useful to compare the parameters associated with ECRB muscle force between novice and advanced tennis players while hitting backhand shots. A gross comparison of muscle forces could be made between the different players based on the assumptions that increased activation, length and eccentric velocity are associated with greater force. This information could be used as the basis of a preliminary investigation of the potential force differences between novice and advanced techniques.

Significant force parameter differences found in this study could inspire future muscle modellers to use improved models to make more precise ECRB force comparisons. This
would prove unnecessary if either no significant force parameter differences were found or all differences were indicative of greater forces in one of the groups of tennis players. If, for example, novice players were found to have higher muscle activities, greater muscle lengths and greater eccentric muscle velocities, then quantitative evidence would finally exist to support the hypothesis that the leading elbow backhand technique induces greater ECRB forces than the classic advanced players' backhand technique.

a. Muscle Activation - Electromyography

Muscle activation can be observed by using techniques of electromyography (EMG). The electrical signal transmitted along a muscle's fibres when it is contracting reflects the neural excitation, or activation, of that muscle. Basically, the more active a muscle is, the higher will be the relative amplitude and frequency of the muscle's electrical signal (Basmajian and De Luca, 1985). This signal can be detected by attaching surface electrodes to the skin overlying the muscle belly and, when processed in an appropriate manner and if careful to avoid cross-talk from neighbouring muscles, can be correlated to the relative level of activity of the muscle (Winter, 1980 and Hof, 1984).

Besides level of muscle activation, an EMG is dependant on electrode size and positioning. Basically, the smaller
the electrodes are and the closer they are to active motor units, the more representative is the EMG of a particular muscle's level of activation. Also, selectivity of the signal is dependant on spacing between bipolar electrodes, with narrower spacing increasing specificity. Zipp (1982a,b) and Basmajian and De Luca (1985) provide guidelines regarding the size and positioning of surface electrodes on small muscles such as ECRB. It is recommended that miniature electrodes (less than 5 mm in diameter) should be placed on the skin overlying the middle of the muscle belly and they should be placed between 1 and 2 centimetres apart.

Various methods of converting a raw EMG signal into a quantifiable signal have been used by different researchers. A practical method commonly used is the linear envelope. This involves smoothing of the rectified version of the raw signal with the use of a low-pass filter. Essentially, a signal is produced which represents the averages of muscle activities occurring during particular intervals of time. The greater is the desired signal smoothing, the greater is the time interval used in averaging the signal (Winter, 1980).

Recently, computer technology has made it easier to perform high-speed digital filtering, involving the calculation of a time-varying moving average with a window size of approximately 25 milliseconds, for the quantification
of EMG signals (Gottlieb, Corcos & Agarwal, 1989). A 25 millisecond moving average leaves the EMG signal fairly rough, but this can be smoothed sufficiently and in a more reliable fashion by averaging a number of trials, being cautious not to induce fatigue in the subjects (Calvert & Chapman, 1977). A sampling rate of 1000 Hertz is appropriate for EMG digitization because EMG signals have their greatest power below 300 Hertz (Shwedyk, Balasubramanian & Scott, 1977). This rate agrees with the recommendation of Dainty and Norman (1987: p. 81) that signals should be digitized at 3 to 4 times the highest frequency of interest.

It should be noted that the EMG signal recorded from a person's muscle is unique to that muscle and that particular person, so on its own it cannot be used for inter-subject comparison. This problem is overcome by quantifying the muscle's EMG while the person performs maximal voluntary contractions (MVCs) under specific contraction conditions (Hof, 1984 and Basmajian & de Luca, 1985). This enables the quantification of different levels of EMG as percentages of the predetermined MVC. Such percentages can then be used for inter-subject comparison.

In associating an EMG signal with a muscle force it is necessary to include the time delay, known as the electromechanical delay (EMD), between the muscle's activation and the ensuing produced force. This can be
estimated by having subjects perform fast isometric contractions against a force transducer and measuring the time difference between the onset of EMG and the onset of force (Corser, 1974; Ralston, Todd & Inman, 1976; Norman & Komi, 1979; and Winter, 1990). The estimated EMD can then be used as a guide for the synchronization of EMG and muscle force. As long as this and other necessary steps are taken, EMG techniques can justifiably be used to quantify ECRB muscle activation and, thus, assist in the estimation of ECRB force during backhand tennis strokes.

b. Muscle Length and Velocity - Electrogoniometry

The length and velocity of a muscle, when active, are related respectively to the angular displacement and velocity of the joint that it crosses. Youm, Ireland, Sprague and Flatt (1976) showed that the ECRB tendon of insertion does not change significantly its position with respect to the bones of the hand in different wrist positions. This implies that the tendon stretches around the wrist bones with a fairly consistent radius of curvature. Grieve, Pheasant and Cavanagh (1978) studied the relationship between ankle joint angle and tendocalcaneous length and found the relationship to be linear. Armstrong and Chaffin (1978) also found a near linear relationship between wrist joint angle and change in wrist flexor tendon length. Since the wrist extensor tendons are similar in structure to the wrist flexor tendons, it is
assumed that a near linear relationship exists between ECRB muscle length and wrist angle (i.e., the wrist bones function like a pulley for the ECRB tendon of insertion to be stretched around). The exact relationship is not presently known, but it can be stated, at least in a basic sense, that ECRB lengthens as the wrist flexes and/or ulnar deviates, in a near linear fashion.

Wrist angular displacements in the planes of flexion/extension and ulnar/radial deviation can most directly and accurately be measured with an electrogoniometer (elgon) (Nicol, 1989b). This is an instrument which converts angular position into voltage. An elgon has recently been designed by Nicol (1987) which incorporates a thin, flexible beam containing a number of strain gauges. Angular displacement between the two ends of the beam is measured by summing the strains experienced by the strain gauges throughout the beam. This light-weight elgon provides a linear relationship between voltage output and angle subtended and it avoids many of the error sources inherent in elgons of the past, such as skin movement and malalignment, which are increased in impact situations, such as hitting tennis balls (Chao, 1978 and Nicol, 1987, 1989a,b).

To obtain wrist angular velocities, proportional to ECRB velocities, the angular displacement versus time data provided by the elgon can be differentiated using finite
differentiation. Smoothing, using typically a fourth-order, zero time lag Butterworth filter, is usually required before the differentiation is carried out (Dowling, 1987 and Winter, 1990). It is important to note that angular velocities determined in this manner are not always proportional to the velocities experienced by the contractile component of ECRB. When rapid changes of muscle length occur in response to external impact forces the initial changes are due mostly to the series elasticity (i.e., stretching of the series elastic component) of the muscle. There is a lag in time before the length of the contractile component is drastically affected due to its viscosity (Ford, Huxley & Simmons, 1977). This means that high angular velocities resulting from external impact forces overestimate contractile component velocities initially.

The electrogoniometry approach can provide the information used in the estimation of ECRB length and velocity during backhand tennis strokes. Together with the EMG data, this information can be used to make gross estimates of ECRB muscle force. These estimates are limited by the insufficient knowledge regarding the precise properties of ECRB, especially those related to quick application of force. It is assumed, nonetheless, that they are adequate for gross comparison between groups of tennis players.
4. Past Attempts at Measuring Parameters Associated With ECRB Force During Backhand Tennis Strokes

a. Muscle Activation

A few studies involving EMG have been performed which have provided qualitative indications about ECRB forces during the backhand tennis stroke (McLaughlin & Miller, 1980; Yoshizawa et al., 1987; and Morris, Jobe, Perry, Pink & Healy, 1989). The study by Morris et al. (1989) found that the ECRB muscles of advanced players were used to over 60 *MVC near impact during normal backhand strokes. It was also found in this study that ECRB was the only wrist extensor muscle expressing high activity for a great proportion of the stroke. Unfortunately, no comparison was made with novice players. The study by Yoshizawa et al. (1987) did compare novice and advanced players, and their results indicated higher muscular activities in the ECRBs of novice players than in those of advanced players. This finding, however, should be considered with caution because over half of the advanced subjects used the two-handed backhand technique, a technique which undoubtedly reduces ECRB activity.

Although the study performed by McLaughlin and Miller (1980) failed at its main objective of determining ECRB tendon forces, it did, at least, determine that the wrist extensor muscles on the radial side, namely ECRB and extensor carpi radialis longus, exhibited near maximal activities in
an advanced player around the time of impact. They also attempted to determine differences between novice and advanced techniques, but to do this they only utilized one advanced player, who hit backhand shots while using his normal technique as well as a simulated leading elbow technique. The validity of this approach is highly questionable because the accuracy of the simulated technique is uncertain. It is possible, for instance, that the kinematics were accurately simulated, but that the muscle activities used to achieve the kinematics were very inaccurate. A further problem with this study was that post-impact ball velocity was not controlled, so the subject hit balls with his normal stroke with greater velocity than he did with the simulated stroke. This, as McLaughlin and Miller admitted, invalidated any comparison between the two types of strokes. In summary, this study had considerable potential for leading to a better understanding of LE etiology, but this potential could not be realized because of methodological flaws.

The need still exists to compare ECRB muscle activities during backhand strokes between novice and advanced players. More precisely, it would be useful to make this comparison between the leading elbow backhand technique used by most novice players and the classic one-handed backhand technique used by most advanced players.
b. Muscle Length and Velocity

Besides differences in the activation of ECRB, it is likely that there are differences in wrist joint kinematics between novice and advanced tennis players which affect the forces induced in the ECRB tendon. One study has looked specifically at the kinematics of advanced backhand techniques (Elliott et al., 1989), but it appears that no studies have looked at the kinematics of backhand techniques used by novice players. It is essential that both types of techniques be analyzed, and then compared, so that estimates of ECRB force differences can be determined.

General differences between the backhand techniques of novice and advanced tennis players have been noted in the literature, but the specific differences associated with ECRB tendon force have not yet been adequately quantified. A more complete analysis of ECRB EMG and wrist joint angular kinematics during the backhand stroke, specifically comparing the novice players' leading elbow technique with the classic advanced players' technique, would provide quantitative evidence to implicate the relevance of poor backhand stroke technique to the etiology of LE.

Although the question of poor backhand technique being an important factor in LE etiology for novice tennis players cannot be fully answered until a valid estimate of ECRB tendon force is made, the comparison of parameters associated
with this force between novice and advanced techniques would provide some insight into the problem. If significant differences were found between ECRB EMGs, wrist joint angular disacements and/or wrist joint angular velocities, which indicate the presence of greater forces in novice players, then this would support the hypothesis that poor backhand technique induces overloading of ECRB.
III. METHODS

A. Subjects

Twenty male tennis players, aged 18 to 59 years, participated as subjects in this study. The Advanced Group (mean age: 31.1 years) consisted of ten players who demonstrated characteristics of the classic advanced players' backhand technique and the Novice Group (mean age: 28.5 years) consisted of ten players who demonstrated characteristics of the leading elbow backhand technique. Distinct kinematic characteristics were used by an experienced professional tennis instructor, Gerry Macken (Jericho Tennis Club, Vancouver, British Columbia), in determining the suitability of the subjects. Based on the description in the Literature Review section of the classic advanced players' technique, each Advanced Group subject was required to demonstrate the following characteristics: complete weight transfer, adequate rotation of hips and trunk, elbow extended and pointing towards the ground at impact, no extraneous wrist motion, good timing, and complete follow-through (Groppel, 1978; Douglas, 1982; Roy & Irvin, 1983; Elliott et al., 1989; and Macken, 1991). Based on the description in the Literature Review section of the leading elbow technique, each Novice Group subject was required to demonstrate the following: incomplete weight transfer, insufficient hip and trunk rotation, elbow flexed and
pointing towards the net prior to impact, excessive wrist movement, poor timing, and limited follow-through (Bernhang et al., 1974; Nirschl, 1975; Cohen, 1980; Roy & Irvin, 1983; Legwold, 1984; and Macken, 1991). Although these characteristics are qualitative in nature, the tennis instructor had no difficulty with subject classification.

Most of the subjects were recruited from tennis clubs in the Lower Mainland of British Columbia. Notices describing the inclusion and exclusion criteria of the study were posted at these locations. Potential subjects were interviewed about these criteria and, if they were met, their backhand techniques were recorded on video. If their techniques were deemed appropriate by the professional tennis instructor, then experimental sessions were arranged. Informed consent was given in writing by all subjects prior to participating in the study.

Two of the Novice subjects had histories of LE, but tests were carried out to ensure that they were symptom-free at the time of experimentation. The experimenter pushed against the dorsum of their dominant hands, which were made into fists, as they attempted to move forcefully into extension. No pain was experienced either during these tests or upon palpation of their lateral epicondyles, so the subjects were considered suitable for the study (Hoppenfeld, 1976 and Schafer, 1987). These subjects also indicated that
they had not improved their backhand techniques since acquiring LE, so it could be assumed that the novice techniques demonstrated prior to participation in the study were the same as those used when they acquired LE.

A controlled variable in this study was wrist extensor strength. Isometric strength measurements were made with a modified hand-grip dynamometer as shown in Figure 5. A velcro strap was attached to the handle of the dynamometer and positioned around the subject's clenched dominant fist a distance of 8 centimetres from the wrist joint axis. The subject was required to push maximally against the strap in wrist extension. The forearm was held down by the tester to prevent unwanted elbow and shoulder movements. The highest moment measurement from three trials was used as the measure of strength. The range of wrist extensor strengths for the subjects was 16.5 to 21.2 Newton-metres, the Novice Group with a mean of 18.0 Newton-metres and the Advanced Group with a mean of 18.9 Newton-metres (no significant difference: \( p = 0.250 \)). The subjects were required to have strength values within the range of plus and minus one standard deviation from the mean strength of a group of forty healthy male tennis players previously tested by the investigator (mean: 19.4 Newton-metres; standard deviation: 3.2 Newton-metres). The dynamometer was calibrated with weights similar to the resistance forces produced by the subjects.
Figure 5. Measurement of wrist extensor strength using a modified hand-grip dynamometer.

B. Experimental Set-up and Task

The main experiment involved the subject hitting flat backhand tennis drives in a laboratory setting (Biomechanics
Figure 5 illustrates a subject performing this task in the experimental test condition. A ball was fed to the subject by being rolled down a descending chute. After leaving the chute, the ball bounced off the floor and travelled like a projectile towards the subject, who then struck it back towards a target on a large net. Although this set-up was considerably different than that on a tennis court in a game situation, it was assumed that the subject's stroke technique was not significantly different. This assumption was qualitatively validated by having the professional tennis instructor compare videos of various subjects hitting backhands on a tennis court with those in the experimental test condition. He indicated that basic stroke patterns were similar. Furthermore, the subjects were given ample practice time in the lab so that they could become comfortable with the experimental set-up.
Figure 6. Experimental set-up (photograph above and schematic diagram below).
Since this study was designed to compare different backhand techniques used by different tennis players, the task was identical for all subjects. Therefore, both external input and output were controlled. In terms of the tennis shot, balls were fed to the subjects with a controlled velocity and position and the balls were returned by the subjects with a controlled velocity and position. Although literature suggests that ball positioning on the racquet at impact may play a role in creating high stresses in the wrist extensors (Plagenhoef, 1979), this was not measured in the present study. It is assumed that ball position was similar for the different subjects since ball input and output were kept constant. Any differences found in the muscle force parameters are assumed to be reflective of different ways in which the racquet was swung by the different subjects.

The incoming horizontal ball velocity was 3 metres/second. This was controlled by rolling balls down the chute from a fixed height. Since the chute was in a fixed location, ball positioning was also controlled. The subject was not required to perform excessive amounts of footwork in this experiment due to the controlled ball positioning. Also, the subject was allowed to contact the balls at his preferred impact height. This removed any variability that may have been caused by the different heights of the subjects.
The subject was required to hit a target with the ball. Only those trials in which the ball hit the target were counted as successful trials. Post-impact ball velocity was calculated by measuring the time between impact and contact with the target and dividing this into the distance between the point of impact and the target. The time period was measured by taking the difference between the sound of ball-racquet contact and the sound of ball-target contact, as detected by a microphone and displayed on an oscilloscope. A typical distance between racquet and target at the time of impact was 3.5 metres and the corresponding time difference between impact and target contact was about 0.14 seconds. This would be equated to a ball-return velocity of 25 metres/second. A success range for velocities was chosen to be between 20 and 30 metres/second, based on pilot studies involving both advanced and novice players. The two groups of subjects had very similar means, 24.75 metres/second for the Advanced Group and 24.55 metres/second for the Novice Group (no significant difference: $p = 0.823$).

All subjects used the same tennis racquet for the experimental trials. It was a mid-sized, graphic composite Fischer Vacuum Twintechnic racquet with string tension set at 60 pounds. Grip size was matched to the subject's hand size by changing the number of grip wraps applied to the handle. Two grip sizes, 4 1/2 inches and 4 5/8 inches, were suitable
for small and large hands, respectively. All subjects indicated that they had no problems adjusting from their own racquets to the experimental one.

Tennis balls were also controlled by having at least twenty different balls available for each subject's experimental session that were tested for their bounce characteristics. Prior to use, each ball was rolled down the chute and was only deemed usable if it bounced into a box (25 centimetres wide, 29 centimetres long and 23 centimetres deep) positioned on the floor just past the impact zone.

C. Analysis Period

Pilot studies performed by the investigator showed that racquet movement during a typical backhand shot lasts between 0.5 and 1.0 seconds and ECRB EMG can last up to about 1.5 seconds. To be sure to capture all of the subjects' ECRB EMGs during the experiments, 2.0 seconds were analyzed, 1.0 seconds prior to and 1.0 seconds after impact. 3.0 seconds of data were captured from which the relevant 2.0 seconds were extracted. The tester was adequately trained at initiating the data collection approximately 1.5 seconds prior to impact for each trial.

Impact time was determined by looking for an abrupt change in voltage of a microphone signal. A microphone was placed at a specific distance away from the position of ball-
racquet contact to detect the sound of impact. The sound delay was calculated using the constant 340 metres/second for the speed of sound in air at room temperature. All signals, EMG and elgon, were synchronized to the estimated time of impact.

For analysis purposes the time of impact was considered to occur in the middle of the stroke, at 1.0 seconds. The stroke was divided into a Preparation Phase (0.0 to 0.8 seconds), a Movement Phase centred around impact (0.8 to 1.2 seconds) and a Recovery Phase (1.2 to 2.0 seconds). These times corresponded with distinct changes observed in the EMG patterns of all subjects (see Results section).

D. ECRB Activation - Electromyography

The subject’s ECRB muscle activity was quantified by using techniques of EMG. Firstly, the investigator located the ECRB muscle belly by having the subject perform wrist extensor contractions and then palpating the upper posterolateral region of the forearm. Then, hair overlying the muscle was shaved and the underlying skin was abraded and cleaned with a scouring pad and ethanol, respectively. This was performed in order to decrease the resistance across which the muscle’s electrical signal travelled. Miniature silver-silverchloride bipolar surface electrodes (Beckman, 2.5 millimetres in diameter), with electrode gel applied to
their surfaces, were attached above the muscle belly with
double-sided adhesive collars and cellophane tape. Also, an
elastic tensor bandage was wrapped loosely around the
electrodes in order to prevent excessive skin movement (i.e.,
to keep them in a fairly constant position relative to the
underlying muscle fibres). The electrodes were placed near
the middle of the ECRB muscle belly, 1.5 centimetre apart
(kept constant by sticking the two adhesive collars together
and identically for each subject). A ground electrode was
placed at the distal end of the anterior aspect of the
forearm for the safety of the subject.

Testing was carried out to ensure that the signal was
representative of ECRB activity (i.e., electrode positioning
was correct). Greatest EMG levels were obtained when the
subject performed contractions in the directions of wrist
extension and radial deviation. The signal was increased
further by clenching the fist.

The raw signal picked up by the electrodes was amplified
by a TECA AA6 MKIII A.C. amplifier (input impedance: >100
megaohms // 15 picofarads; common mode rejection ratio: >
10,000:1 at 60 Hertz), before being converted to a digital
signal by a LabCard 12-bit analog-to-digital board
controlled by an IBM-compatible AT 286 personal computer.
The input range to the analog-to-digital board was +/- 2.5
Volts, so amplification was set to give values optimally
within this range. Frequencies between 27 and 545 Hertz were passed through the amplifier, as controlled by the high- and low-pass filters of the amplifier, respectively. (Precise -3 decibel cut-offs were determined with a signal generator by the investigator.) The resulting signal was digitized at a sampling rate of 1000 Hertz. Power spectral density functions of raw EMG signals in experimental conditions were calculated by the investigator prior to selecting the filter cut-offs and sampling rate. No signal power above 300 Hertz existed in the experimental conditions, in accordance with the results of Shwedyk et al. (1977), so the filter cut-offs and sampling rate were deemed appropriate. The raw EMG data were stored on disk for later quantification and analysis.

Two steps were involved in the processing of the raw EMG signal for quantification purposes. Firstly, it was full-wave rectified by computing absolute values of the digitized data points. Secondly, a moving average, using a twenty-five millisecond window, was calculated. This method was chosen on the basis of techniques used by Gottlieb et al. (1989) and pilot studies performed by the investigator. The size of the moving average window was selected subjectively on the basis that it provided the greatest amount of signal smoothing without causing serious distortion. No time lag was produced by this procedure.
The subject had his maximal ECRB activity estimated so that measured EMGs during the experiments could be quantified with respect to this maximal value. This was carried out by having the subject perform maximal voluntary wrist extensions isometrically against resistance. A padded handle, aligned horizontally, was used as the means of providing resistance against an upward push with the dorsum of the hand (see Figure 7). The subject had his forearm secured horizontally in the midprone position and his wrist in the neutral position. These forearm and wrist positions were considered best because they could be easily controlled and they are similar to those used in tennis backhand strokes. The subject was also required to clench his fist maximally to simulate the muscle activity involved in tightly gripping a tennis racquet.

Each maximal voluntary contraction (MVC) trial involved the subject clenching his fist and pushing upwards as hard as possible for about 3 seconds. Verbal encouragement was provided by the tester. The maximal quantified value during the 3 seconds of data was recorded.
This procedure was carried out six times, leaving ample periods of rest (approximately 1 minute) between trials in an effort to avoid fatigue. Three measurements were taken before the main experimental trials and three after to account for any fatigue that might have resulted from the experimental trials. The average of the three highest values from these six measurements was considered to be the MVC. The lowest three values were not considered because of potential problems in motivating the subject to contract his muscles maximally every time. An average of the three
highest values was chosen as the final step, so that smoothing biases created during the calculation of moving averages could be limited.

For the experimental trials, the activity of ECRB at each sampled point in time was measured and given as a percentage of the MVC. This provided the means for assessing the quantity of ECRB muscle activity, as well as performing intersubject comparisons.

An additional step in quantifying ECRB activity was the calculation of electromechanical delay (EMD). This was carried out with a procedure similar to that used in the MVC test. A strain-gauge attached to the resistance handle, unpadded in this case, provided the needed measure of force production (see Figure 7). Five rapidly developed, submaximal isometric contractions against the handle were used in determining the EMD. Time difference between EMG onset and force onset was measured on a digital oscilloscope. The average of the measured values from the five trials was used as the EMD. This could then be used to synchronize the EMG data with the elgon data, when estimating ECRB forces, by simply moving each EMG data point forward in time by an amount equal to the EMD. EMDs for subjects in this study ranged from 10.5 to 25.1 milliseconds, with a mean of 18.2 milliseconds.
E. Wrist Joint Angular Kinematics - Electrogoniometry

Wrist joint angular displacements in the planes of flexion/extension and radial/ulnar deviation were measured directly with a Penny & Giles M110 twin-axis elgon. The two end blocks of the elgon were attached to the posterior aspect of the subject’s hand (above the third metacarpal) and forearm (between the radius and ulna). Single- and double-sided tape were used to secure the endblocks to the skin. They were positioned in line with the longitudinal hand and forearm axes while the forearm was held in the midprone position. Calibration of the neutral wrist position (0 degrees in both the flexion/extension and ulnar/radial deviation planes) was carried out by recording elgon data while the subject held his forearm, midprone, and hand, palm down, in a specific location on a table at a height level with his shoulder (see Figure 8). All angles were referenced to their respective zero-calibration values.

The voltage outputs of the elgon were digitized with a Penny & Giles DL1001 "data logger" at a rate of 1000 Hertz and stored on disk for later analysis. This sampling rate was deemed appropriate because it is fast enough to facilitate the capture of an adequate number of data points during the 4 to 8 millisecond impact period of a tennis stroke (Bernhang et al., 1974 and Hatze, 1976). It was
desirable to determine, within 1 millisecond, when impact occurred.

Figure 8. Electrogoniometer calibration.

The accuracy and precision of the elgon was estimated by attaching it to a manual goniometer and making repeated measurements at known angles within the range of +/- 60 degrees for each plane of motion. This range encompassed the angular deviations observed in the experimental trials (see Results section). Five randomly positioned measurements were
made at each angle corresponding to a multiple of 15 degrees. The mean error in the flexion/extension plane was 2.21 degrees with a mean standard deviation of 0.10 degrees, whereas the mean error in the ulnar/radial deviation plane was 0.44 degrees with a standard deviation of 0.22 degrees. These respective accuracy and precision estimations were considered acceptable for the purposes of this study.

Wrist angular velocities were calculated by finite differentiation of angular displacements. Smoothing of displacements was required prior to performing these calculations, so the "separation" technique described by Dowling (1987) was used. The displacement data were first reduced in frequency from 1000 Hertz to 200 Hertz by selecting every fifth data point, including the ones occurring at 0.0, 1.0 (impact) and 2.0 seconds. Then, a digital fourth order, zero time lag Butterworth filter (low-pass frequency 10 Hertz) was implemented with the computer. This was followed by the reinsertion of the raw data points corresponding to the time period between 50 milliseconds before and 50 milliseconds after impact. Finally, a second fourth order, zero time lag Butterworth filter (low-pass frequency 45 Hertz) was implemented. This technique was determined to be most appropriate from pilot studies performed by the investigator, for smoothing data which includes sharp changes in angular displacement such as those
occurring just after impact (see Results section). It was also used by Knudson (1990) for smoothing angular displacement data of forehand tennis strokes.

F. Experimental Protocol

After a brief explanation of the experiments and having the subject sign the informed consent form, the subject was required to perform a few minutes of stretching exercises with the wrist of the dominant hand. After the subject felt ready approximately fifty balls were fed to his backhand so that he could slowly warm up and get comfortable with the experimental task and set-up. When the subject indicated that he was warm and comfortable, the measurement of wrist extensor strength was carried out. After this the EMG electrodes were attached. The subject was then required to hit approximately fifty more warm-up shots with the electrodes in place. The reason for this was that it was desirable to have the ECRB muscle warm while performing the EMD and MVC experiments, comparable to its temperature during the main experiment. The five EMD trials, followed by the first three MVC trials, were then carried out. Then the elgon was mounted and calibrated.

After everything for measurement purposes was attached to the subject's arm and calibrated, the main experimental trials were initiated. Each trial, or backhand shot, lasted
approximately forty-five seconds due to the length of time it took for the computer to digitize the collected EMG data. The subject continued to hit backhand shots until twenty successful trials (i.e., ball hitting target and output velocity within the controlled range) were accomplished. The first fifteen of these that proved adequate for analysis purposes were used in the experimental analysis. The reason that five extra trials were required is that some trials could be deemed inappropriate because of either microphone signal ambiguities or human errors in data acquisition. The number of trials was chosen on the basis of variability shown in pilot studies. The average of ten trials was unrepresentative of a subject’s stroke technique, whereas the average of twenty trials was no more representative than the average of fifteen trials, in terms of both EMG and elgon data. This number was also suitable for the avoidance of fatigue. To accomplish twenty successful trials the subject typically had to perform between thirty and forty attempted trials. Also, the subject performed two or three practice shots between each trial in order to maintain stroke rhythm.

After twenty successful trials were completed the elgon was removed so that the final three MVC trials could be carried out. This being the last step, the EMG electrodes were then removed and the subject was able to wash the
electrode gel from his forearm. Each subject's experimental session lasted between two and a half and three hours.

G. Data Analysis

Five main time-varying parameters involved in the backhand tennis stroke were analyzed in this study. They were ECRB EMG (time-lag corrected with the EMD), wrist flexion angular displacement, wrist ulnar deviation angular displacement, wrist flexion angular velocity and wrist ulnar deviation angular velocity. The flexion and ulnar deviation directions were chosen as positive because they correspond to increased ECRB muscle length and eccentric ECRB contraction velocity, both related to increased force. This makes it relatively easy for the reader to look at graphic displays of the time-varying data and associate higher values on any of the graphs with potentially greater forces.

For each point in time during the two second analysis period, the time-varying parameters were averaged amongst the fifteen trials of each subject. These averages were assumed to be representative of the subject's stroke. The signals were subsequently reduced from 1000 Hertz to 200 Hertz by selecting every fifth data point, including the ones occurring at 0.0, 1.0 (impact) and 2.0 seconds.

Multiple two-way analyses of variance with repeated measures were performed on the time-varying group data.
Group differences and group-time interaction effects were tested firstly for the Preparation Phase (0.0 to 0.8 seconds), the Movement Phase (0.8 to 1.2 seconds) and the Recovery Phase (1.2 to 2.0 seconds). Further divisions were made when necessary in order to determine more specifically when significant group differences occurred. The 0.05 level of significance was used in the testing process and the Huynh-Feldt adjustment was made to account for group variance and covariance differences.

It is important to note that the time-varying parameters are all associated with muscle force, so they cannot validly be assessed separately when making force estimates. For example, markedly different angular displacements and velocities do not indicate a difference in force if EMGs at the same time are zero. For this reason, the parameters were only initially compared separately. The ultimate comparison in this study involved a more qualitative assessment of all of the parameters together.

Two additional parameters compared between the two subject groups were maximal ECRB EMG and total ECRB EMG-time integral. Averages of these parameters from each subject's fifteen trials were calculated. These discrete EMG parameters were analyzed in addition to the time-varying EMG parameter in order to determine more specifically differences between the EMGs of the two subject groups. If maximal EMGs
occurred at different times for the different subjects in a group, then the average maximal EMG determined for the group (time-varying EMG parameter) would not be sufficient for group comparison of EMG. This would only correspond to the average value at a specific time when all subjects had relatively high EMGs, not at the times that all subjects' EMGs were maximal. Comparison of maximal EMGs (irrespective of time) between groups was considered best for this purpose. Of note is the fact that the average of the discrete maximal EMG values for subjects in a specific group is always higher than the maximal value from the group's average time-varying EMGs. Total ECRB EMG-time integrals were also compared between groups in order to achieve an overall representation of EMG differences during the backhand stroke. It was suggested that this comparison might lead to implications regarding ECRB fatigue caused by the backhand tennis stroke. The means of these discrete EMG parameters were compared between groups using two-tailed t-tests.

The analyses were carried out for the most part with a signal analysis software package (DSP Development Corporation: DADiSP 1.05) in combination with computer programs written by the investigator. Simon Fraser University mainframe (UNIX: SAS 6.03) and personal computer statistical software packages were also utilized.
H. Ethics Approval

The experimental protocol for this study was ethically approved by the University Ethics Review Committee at Simon Fraser University. There were minor risks involved, most notably with the administration of EMG, but they were not deemed significant by the committee. Subjects were fully informed of these risks prior to participation in the experiments.
IV. HYPOTHESES

The following Novice Group results, if found to be significantly different from those of the Advanced Group, would support the theory that the leading elbow backhand technique produces excessive loading of ECRB:

1). Higher ECRB EMG;
2). Greater wrist flexion angle;
3). Greater wrist ulnar deviation angle;
4). Greater wrist flexion angular velocity
5). Greater wrist ulnar deviation angular velocity
6). Greater maximal ECRB EMG;
7) Greater total ECRB EMG-time integral.

In agreement with the literature, it was hypothesized that, overall, the results would indicate the presence of greater ECRB forces in the Novice Group during certain regions of the backhand stroke. Higher levels of muscle activity, longer muscle lengths and greater velocities in the directions of eccentric contraction were assumed to indicate the presence of greater forces.
V. RESULTS

Since there were no significant differences between the characteristics of the two groups of subjects other than in their backhand stroke techniques (see Methods section), it was assumed that any differences found in this study reflected solely their stroke technique differences. No other differences between subject groups were considered relevant to the issue of ECRB muscle force comparison.

A. General Patterns Throughout the Stroke

1. Electromyography

The patterns of the mean EMG versus time profiles were similar for the two groups of subjects (see Figure 9). Both groups demonstrated minimal EMGs during the Preparation and Recovery Phases (less than 10 %MVC) and moderate values during the Movement Phase (up to about 40 %MVC for the Novice Group and 55 %MVC for the Advanced Group).

The mean total EMG-time integrals for the two groups of subjects were not significantly different, with the Advanced Group having a slightly higher value of 26.013 %MVC-seconds compared to 22.969 %MVC-seconds for the Novice Group (p = 0.390). The Preparation and Recovery Phases showed no significant group differences in mean EMG (p = 0.1522 and 0.1904, respectively), whereas the Advanced Group had
significantly higher values during the Movement Phase ($p = 0.0446$).

![EMG versus time graph](image)

**Figure 9.** EMG versus time graph.

2. Electrogoniometry

a. Flexion

The mean flexion versus time profiles were nearly parallel for the two groups of subjects, with the Novice Group displaying angles more towards the flexion direction throughout the stroke (see Figure 10). Both groups had their wrists extended at the beginning of the stroke, moved towards
flexion during the backswing and then moved back towards extension through impact. Impact appeared to produce a high frequency flexion/extension motion in the Novice Group, which would indicate a rapid stretch-shortening cycle of the active ECRB muscle. Conversely, impact had little affect on the Advanced Group's flexion angle. After impact both groups completed the stroke with their wrists extended. The Novice Group had flexion angles significantly greater than the Advanced Group throughout the stroke (Preparation Phase: \( p = 0.0082 \), Movement Phase: \( p = 0.0240 \) and Recovery Phase: \( p = 0.0014 \)).

Figure 10. Flexion versus time graph.
b. Ulnar Deviation

The mean ulnar deviation versus time profiles were also virtually parallel for the two groups of subjects, with the Novice Group displaying angles more in the ulnar deviation direction throughout the stroke (see Figure 11). The Novice Group was positioned in slight ulnar deviation for the first 0.9 seconds, whereas the Advanced Group was positioned in slight radial deviation during this period. Both groups were positioned in ulnar deviation for the remainder of the stroke. The Novice Group had ulnar deviation angles significantly greater than the Advanced Group throughout the stroke (Preparation Phase: $p = 0.0021$; Movement Phase: $p = 0.0257$; and Recovery Phase: $p = 0.0367$).
c. Flexion Velocity

Mean flexion velocity was similar for the two groups of subjects during the Preparation and Recovery Phases, but markedly different during the Movement Phase (see Figure 12). The subjects had minimal velocities except around the time of impact, where abrupt changes from extension to flexion and then back to extension velocities were observed in both groups. The most notable difference between the groups occurred just after impact with the Novice Group displaying a high, sharp peak of flexion velocity. This gave a clear indication of the fact that the Novice Group experienced a much greater ECRB stretch-shortening cycle.
The Preparation and Recovery Phases were not significantly different for the two groups \((p = 0.1965\) for both phases). Although there also was not a significant group difference during the Movement Phase \((p = 0.1753)\), there was a highly significant group-time interaction effect during this time period \((p = 0.0001)\). This was determined to be more from the 1.0 to 1.2 seconds time period (significant group-time interaction at \(p = 0.0001\)) than the 0.8 to 1.0 seconds time period (insignificant group-time interaction at \(p = 0.1913\)).
d. Ulnar Deviation Velocity

The mean ulnar deviation velocity versus time profiles appeared very similar between the two groups of subjects (see Figure 13). They both had minimal velocities during the Preparation and Recovery Phases and fairly high ulnar deviation velocities just prior to impact. Just after impact both groups changed rapidly to radial deviation and then sharply back to ulnar deviation velocities. The velocities in this plane were generally small relative to those in the flexion/extension plane.

![Figure 13. Ulnar deviation velocity versus time graph.](image-url)
The Preparation and Recovery Phases were not significantly different for the two subject groups (p = 0.1318 and 0.9847, respectively). There was a significant group difference, however, during the Movement Phase (p = 0.0366), which was further analyzed because the Advanced Group had slightly greater ulnar deviation velocities prior to impact whereas the Novice Group had slightly greater ulnar deviation velocities after impact. The significant group difference was determined to exist during the 0.8 to 1.0 seconds time period (p = 0.0040), but not during the 1.0 to 1.2 seconds time period (p = 0.4419).

B. Specific Differences Around the Time of Impact

The greatest differences between subject groups typically occurred just after impact, at 1.01 seconds. At this time the Advanced Group had a mean EMG value of 53.68 %MVC, which was significantly higher than the 33.35 %MVC value of the Novice Group (p = 0.0119). The Advanced Group also had a significantly higher average of the subjects' individual maximal EMG values (irrespective of time), 63.37 %MVC compared to 46.80 %MVC for the Novice Group (p = 0.039). These values occurred close to impact, with the Advanced Group averaging 0.003 seconds and the Novice Group averaging 0.026 seconds prior to impact (no significant time difference at p = 0.298).
Just after impact the Novice Group had a mean flexion angle of 1.75 degrees, compared to 16.82 degrees of extension for the Advanced Group (significantly different at $p = 0.0068$), as well as a mean ulnar deviation angle of 13.24 degrees, compared to 8.52 degrees for the Advanced Group (insignificantly different at $p = 0.2924$). At the same time, the Novice Group had a mean flexion velocity of 574.8 degrees/second, compared to 68.8 degrees/second for the Advanced Group (significantly different at $p = 0.0002$), as well as a mean ulnar deviation velocity of 53.8 degrees/second, compared to a mean radial deviation velocity of 71.2 degrees/second for the Advanced Group (insignificantly different at $p = 0.0951$).

C. Summary of Significant Differences

There were various differences between the ECRB EMGs and wrist kinematics of the Novice and Advanced Groups throughout the stroke. However, since EMGs of both groups were minimal (less than 10 %MVC), as well as similar, during the Preparation and Recovery Phases, the investigator decided that further analysis need only focus on the Movement Phase. Table 1 displays the significant group differences that occurred during the Movement Phase.
Significant group differences in EMG, flexion and ulnar deviation were observed throughout the Movement Phase. On average, the Advanced Group used 9.46 %MVC more EMG than the Novice Group (34.04 versus 24.58 %MVC), whereas the Novice Group was positioned 15.66 degrees more towards the flexion direction (-1.84 versus -17.50 degrees) and in 9.42 degrees
more ulnar deviation (12.21 versus 2.79 degrees) than the Advanced Group. Also, the Advanced Group had an average ulnar deviation velocity 50.51 degrees/second greater than the Novice Group (85.62 versus 35.11 degrees/second) during the first half of the Movement Phase (0.8 to 1.0 seconds).

Just after impact, at time 1.01 seconds, significant group differences existed in EMG, flexion and flexion velocity. The Advanced Group used 20.33 %MVC more EMG than the Novice Group, whereas the Novice Group was positioned in 18.57 degrees more flexion and experienced 506.0 degrees/second more flexion velocity than the Advanced Group (see Table 1).
VI. DISCUSSION

A. Comparison of Results With Those in the Literature

The EMG results for advanced players compare favourably with literature results. Advanced players in this study averaged about 55 %MVC near impact, which is slightly less than the over 60 %MVC reported by Morris et al. (1989) and considerably less than the near maximal value reported by McLaughlin and Miller (1980). It is understandable that the present study would have lower values than the values in these studies because a lesser input ball velocity was used in this study. Balls were fed to subjects in both of the other studies with a ball machine, so their input velocities must have been closer to those experienced in a normal game situation. Subjects in the present study commented that the experimental task involved backhand shots that were less intense than those involved in a normal game situation.

The most surprising result in this study was that the advanced players, on average, used higher EMGs than the novice players for the entire Movement Phase of the stroke. This contradicts the findings of Yoshizawa et al. (1987). It was mentioned previously (see Literature Review section) that this study had a serious control problem in that over half of the advanced subjects used two hands to perform their backhand shots, so further comparison between its findings
and the results of the present study would be futile. The present study appears to be the first to make a valid comparison of ECRB EMGs of novice and advanced tennis players while hitting backhand shots.

The only relevant kinematic comparison that can be made with past literature results is of wrist angular velocity just prior to impact for advanced players. Elliott et al. (1989) found that advanced players had an average peak resultant velocity (somewhere between extending and ulnar deviating) of approximately 285 degrees/second, 20 milliseconds prior to impact. This is somewhat less than the 351.06 degrees/second resultant value (136.10 and 323.60 degrees/second extension and ulnar deviation velocities, respectively) observed in this study, at the same time. There appear to be no novice wrist kinematic values in the literature to make comparisons with.

It also appears that no other investigator has analyzed data either during or just after impact in backhand tennis strokes. This most important region of time has been overlooked by tennis elbow researchers of the past. Recent technological advances, especially with the design of the elbow used in this study, made this analysis possible. Furthermore, it appears that the acquisition of EMG and kinematic data at 1000 samples/second, the minimum frequency
necessary for capturing impact information, was not attempted in past tennis stroke studies.

B. Implications for ECRB Force Comparisons

The results of this study indicate that there are various differences, as well as similarities, between novice and advanced tennis players in terms of parameters associated with ECRB muscle/tendon forces during backhand shots. Since the principle objective of the study was to determine whether the novice players' leading elbow technique involves parameters which suggest greater forces than the classic advanced players' technique, the parameter differences, rather than the similarities, are focused on here. Only those differences which were determined to be statistically significant are discussed.

Three parameters have been associated with elevated muscle force: high level of muscle activation, long muscle length and eccentric contractile component velocity (Chapman, 1985) (see Figure 14). In this study muscle activation was estimated by EMG, muscle length was estimated by angular displacement and muscle velocity (not identical to contractile component velocity) was estimated by angular velocity. Differences in these parameters were assumed to be indicative of differences in ECRB muscle forces.
Figure 14. Typical relationships of muscle force to activation (upper graph), length (middle graph) and contractile component velocity (lower graph). (Graphs adapted from Bouisset, 1973.)

1. Movement Phase

On average, during the Movement Phase of the stroke, the Advanced Group had almost 1.4 times as high a level of ECRB EMG as compared with the Novice Group (34.04 %MVC vs 24.58
%MVC). Without regards to kinematic differences, this would imply that the Advanced Group experienced ECRB forces approximately 1.4 times as great, on average, as those of the Novice Group. Wrist kinematics, of course, cannot be disregarded. The Novice Group was positioned in greater flexion and ulnar deviation during the Movement Phase, meaning they were probably at a higher point on the force-length relationship. Unfortunately, the precise ECRB force-length relationship is not presently known, so it is impossible to predict accurately how much of an effect these angular deviation differences had on ECRB forces.

A final difference to mention during only the first half of the Movement Phase was that the Advanced Group had approximately 2.4 times as great of an ulnar deviation velocity as compared with the Novice Group. Since this is in the eccentric direction for ECRB, this means that force was probably elevated more, due to this effect, in the Advanced Group than in the Novice Group. It should be emphasized that this difference was only in the overall velocities of the subjects' ECRB muscles and not in their contractile component velocities. Separation of the overall velocities into contractile and series elastic component velocities was not possible. Furthermore, the precise force-velocity relationship of the ECRB contractile component is not known. Therefore, the effect of velocity differences on muscle
forces can also not presently be predicted with known accuracy.

While there is no way of determining the exact muscle force magnitudes of the two subject groups during the Movement Phase, due to various insufficiencies in present muscle models, it can at least be stated that parameter differences were observed during this time period that were indicative of force differences. Most significantly, muscle activation was higher in the Advanced Group, whereas muscle length was greater in the Novice Group. (These were considered to be more relevant contributors to force differences than the greater eccentric muscle velocity of the Advanced Group during the first half of the Movement Phase.) It is postulated by the investigator that these differences effectively cancel each other out, in terms of their effects on muscle forces, but considerable muscle model improvements are required before this can be confirmed. The Movement Phase results, along with the similarities found during the Preparatory and Recovery Phases, suggest that the ECRB forces of novice and advanced players are similar, on average, during the backhand stroke. This contradicts the hypothesis that poor backhand technique induces excessive loading of ECRB.
2. Just After Impact

Even though the Movement Phase results suggest that average ECRB forces during the stroke are similar for novice and advanced players, their maximal forces may be quite different. The maximal ECRB forces of the subjects in this study occurred just after impact, at approximately 1.01 seconds. This is the time at which muscle activation was near maximal, muscle length was long and muscle velocity was most eccentric. At no other time during the 2.0 seconds of the stroke were these three parameters in such an obvious force-elevating combination (review Figures 9 to 14). Furthermore, additional "force-enhancement" must have occurred at and just after this point in time due to the rapid muscle stretches (Edman et al., 1978 and Thomson & Chapman, 1988).

The Advanced Group had about 1.6 times as much ECRB EMG (higher level of muscle activation) as did the Novice Group (53.68 vs 33.35 %MVC) just after impact. The Novice Group, however, was positioned in 18.57 degrees greater wrist flexion (longer muscle length) (1.75 vs -16.82) and had about 8.4 times as great of a wrist flexion velocity (greater eccentric muscle velocity) (574.8 vs 68.8 degrees/second) as compared to the Advanced Group. As was the case during the Movement Phase, the Advanced Group had a positive muscle activation force-elevating effect, whereas the Novice Group
had a positive muscle length force-elevating effect. A clear difference at this point in time, however, was with the positive muscle velocity force-elevating effect of the Novice Group. Additionally, the Novice Group had a positive "force-enhancement" force-elevating effect as a consequence of its greater velocity of muscle stretch, in agreement with the findings of Thomson and Chapman (1988). The force-elevating effects which occurred just after impact are summarized in Table 2.

Table 2. Positive ECRB force-elevating effects which occurred just after impact.

<table>
<thead>
<tr>
<th>SIGNIFICANT MUSCLE PARAMETER DIFFERENCE</th>
<th>GROUP DISPLAYING POSITIVE FORCE-ELEVATING EFFECT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higher Level of Muscle Activation</td>
<td>Advanced Group</td>
</tr>
<tr>
<td>Longer Muscle Length</td>
<td>Novice Group</td>
</tr>
<tr>
<td>Greater Eccentric Muscle Velocity</td>
<td>Novice Group</td>
</tr>
<tr>
<td>More &quot;Force-enhancement&quot;</td>
<td>Novice Group</td>
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</tbody>
</table>
Figure 15 illustrates the post-impact mean flexion velocity versus time profiles of the Novice and Advanced Groups. It is obvious from this graph that the Novice Group had a significantly greater eccentric ECRB velocity during this 20 millisecond period of time. If it can be assumed that the muscle activation and muscle length force-elevating effects approximately cancel each other out between the two groups of subjects (as was suggested for the Movement Phase), then this difference in muscle velocities indicates that the Novice Group experienced somewhat greater maximal ECRB forces just after impact. It should once again be emphasized that this difference was only in the overall velocities of the subjects' ECRB muscles and not in their contractile component velocities. Because of this it is not possible at present to make accurate force comparisons.
Nonetheless, to give the reader an idea of the magnitude of the positive muscle velocity force-elevating effect of the Novice Group, the ECRB force (normalized) - velocity (contractile component) relationship utilized in a recent muscle model by Winters and Stark (1985) is displayed in Figure 16. Similar to the general force-velocity relationship in Figure 14 (lower graph), forces are greater in the negative (eccentric) velocity direction than in the positive (concentric) velocity direction, with appropriate time constants incorporated. While the exact relationship is
not presently known, Winters and Stark (1985) consider this to be a reasonable approximation.

![Force-velocity relationship for ECRB](image)

**Figure 16.** Force-velocity relationship for ECRB. (Based on the relationship utilized by Winters & Stark, 1985.)

The velocities from Figure 15 were used as inputs to the equations involved in the force-velocity relationship of Figure 16 (see Winters & Stark, 1985). (Flexion velocities had to be multiplied by -1 in order for them to be converted to ECRB shortening velocities.) This enabled the calculation of normalized ECRB forces, which are shown in Figure 17.
This figure illustrates the estimated force differences between the two subject groups. To quantify this difference over the 20 millisecond time period, impulses (force-time integrals) were calculated. The Novice Group had an impulse of 0.0229 normalized(force unit)-seconds, compared to 0.0180 normalized(force unit)-seconds for the Advanced Group. This corresponds to a ratio of 1.27 of Novice Group impulse to Advanced Group impulse.

Figure 17. ECRB force versus time graph (post-impact time period).
If the force-velocity relationship utilized in this estimation can be considered to be a reasonable approximation of the true relationship and the assumption that the positive muscle activation and muscle length force-elevating effects of the two subject groups cancel each other out, then it can be stated that the Novice Group had at least a 1.27 times greater ECRB impulse than the Advanced Group just after impact. Inclusion of the additional "force-enhancement" of the Novice Group would increase this value further.

The elevating effects of greater eccentric velocities on the ECRB forces of the Novice Group subjects, as compared to those of the Advanced Group subjects, may well have outweighed the effects of activation and length differences just after impact. Unfortunately, this can only be confirmed by future muscle modellers. If this did prove to be the case, then it could be stated that tennis players who use the leading elbow backhand technique experience greater maximal ECRB forces just after impact than do those who use the classic advanced players' backhand technique. This would support the hypothesis that poor backhand technique induces excessive loading of ECRB.

C. Conclusions

Various significant ECRB muscle force parameter differences, as well as similarities, were observed in this
study between novice and advanced tennis players while performing backhand shots. Average differences observed during the Movement Phase, in combination with their similarly low levels of muscle activation during the Preparation and Recovery Phases, lead to the conclusion that novice and advanced tennis players probably experience similar ECRB forces, on average, during backhand tennis shots.

During the short (20 millisecond) time period just after impact, when ECRB forces were most likely maximal, the novice players demonstrated muscle velocities in the eccentric flexion direction which were considerably greater than those of the advanced players. This difference probably outweighed all other observed differences in this study, in terms of its effect on the comparison of ECRB muscle forces. It is concluded, based on this difference and the presumed cancelling effects of muscle activation and length differences, that novice tennis players who use the leading elbow backhand technique probably experience greater maximal ECRB impulses (and forces) just after impact in backhand shots. Since ECRB force overload is the suggested mechanism behind LE, the main implication from this conclusion with regards to LE etiology is that poor backhand technique is probably a significant contributor to the injury for novice players. The objective of determining whether or not the
leading elbow technique induces forces great enough to cause LE was not fully met, but some of the necessary steps to this end were taken in performing this study. Considerable further research is suggested by the investigator in order for the ultimate etiological objective to be fully met.

**Future Research**

It is hoped that future muscle modellers will gain incentive from the present study to quantify the ECRB forces of novice and advanced tennis players during backhand shots. Two major muscle modelling problems must first be solved. Firstly, a solution to the general distribution problem for all muscles crossing the wrist joint must be found. Research on this problem will have to rely on improved methods of direct muscle/tendon force measurement (Caldwell & Chapman, 1991). Secondly, and equally challenging, the precise ECRB muscle properties corresponding to conditions of rapid stretch (up to the equivalent of about 600 degrees/second wrist flexion velocity) must be determined (Hof & van den Berg, 1981a). It is suggested that a means of including "force-enhancement" in a Hill-based model is necessary. Improved methods of direct force measurement will prove useful for this task as well.

Once these problems are solved, it will be possible to quantify ECRB forces during tennis shots. Then the
hypothesis regarding poor backhand technique inducing excessive loading of ECRB can more accurately be tested. Until then, unfortunately, LE etiology for novice tennis players will not be completely understood. Hopefully the popularity of tennis does not decline while the incidence of LE remains high.
List of References


Macken, G. (1991). Personal communication regarding backhand tennis techniques. (Gerry Macken is a professional tennis instructor at the Jericho Tennis Club in Vancouver.)


