

**The Effect of *PowerAngle* Diagonal Stringing on  
Levels of Vibration and Overall Performance  
of a Tennis Racket**

Micah Joselow

Ossining High School, Ossining, New York

*(i) Personal Section*

I'll never forget the first time I was introduced to my high school's fundamentals in science research program. Sitting in biology as an unsuspecting freshman, Mr. Piccirillo and Ms. Holmes, two of the defining figures of my high school education, walked into my class to discuss the opportunity to apply to become a part of Ossining High School Science Research. After watching their short introductory video, I couldn't fathom being a part of the program; I'd always been a strong science student, but I'd never truly had a passion for the subject in general. For as long as I could remember, I had wanted to be a politician, not a scientist. Plus, I couldn't imagine working under the guidance of what appeared to be two of the most frightening figures I had ever come across in "P" and "Holmes." Nevertheless, after a great deal of coaxing from my parents and teachers, I decided to apply. Little did I know back then, but that simple decision truly changed my life.

While my vocational aspirations still remain in the political realm, the last three years I spent cramped up in room 109 as a science research student truly shaped the person I am today. As I head off to college as a finished product of Ossining's research program, I know that I am truly prepared for any challenge that may come my way. Science Research has not only taught me the essential skill of how to carry out an extended project, but has also given me the intellectual confidence to pursue what interests me, regardless of what those around me may say or think.

Going into OHS Science Research, I was under the impression that every student was stuck in a lab doing monotonous test tube work. After being accepted into the program, I knew that if I was going to remain a research student all through high school I was going to have to break the mold I had in my mind. I was going to pursue something I was truly interested in, not something that I thought would garner me large accolades as an upperclassman. While I later

found out the idea I had of what the average research project was like in my head was not entirely true, I knew that type of research was most definitely not for me. Thus, at my first bi-weekly (the mandatory one-on-one meetings students in my research program have every other week with either P or Holmes), when asked what topic I wanted to pursue, it was an easy decision. “Tennis,” I bluntly replied, as Mr. Piccirillo stared at me blankly in confusion.

Ever since my first tennis lesson at the age of 10, the game of tennis has been an integral part of my life. After reluctantly taking the court for the first time as a fourth grader, I was instantly hooked. Over the years, I had begun playing USTA tournaments, joined the Varsity Tennis Team as an eighth grader, become a certified tennis instructor, and even established a program in my diverse community to promote wider participation in the game. Thus, the topic of “tennis” seemed to be the perfect category for me. I knew that the 10 hours a week being a dedicated science research student entails would not bother me if it dealt with something that was so much a part of my everyday interests. The only problem was that “tennis” was not exactly a field of science research on the Intel STS application, and I had no idea what I would pursue.

For whatever reason, Mr. Piccirillo had enough faith in me to allow me to pursue my interest in “tennis” research. As the weeks went flying by and I read seemingly ever professional paper on tennis I could get my hands on, the practicality of this topic that interested me to such a great extent began to appear dubious. Each time the professional tennis researchers neglected to respond to my carefully thought out emails, I started to feel more and more as if science research just was not for me. Without P and Holmes constantly encouraging me and reminding that in the end, hard works does in fact pay off, I do not think I would have made it to where I am today.

As what appeared to be every other student in my grade had already decided upon his or her final research topic and secured a mentor, I was still attempting to find a single practical subject to pursue. One fateful Sunday afternoon, I sat down to read the weekend edition of the

Journal News (my area's regional newspaper), and was met with a pleasant surprise. As I opened up the local section, I saw an image of a tennis racket strung in a strange fashion. This intrigued me, so I decided to read the article. I soon discovered that several years earlier a local woman named Madeline Hauptman had co-patented a diagonally strung tennis racket featuring opposite pairs of equidistant strings strung in a diagonal fashion. She claimed that as a result of this congruency of string length, vibrations are more evenly dispersed following a tennis shot, reducing the level of vibration directed onto a given player's forearm and possibly preventing tennis elbow. The article I was reading was a profile of *PowerAngle*, Mrs. Hauptman's small diagonally strung racket company. I immediately rushed to my computer to find out some more information on *PowerAngle*. To my excitement, I found out that Mrs. Hauptman's diagonally strung tennis rackets had never been scientifically tested or compared to conventional rackets.

The following day, I rushed into the research room to let Mr. Piccirillo and Ms. Holmes know of the good news. They immediately encouraged me to call *PowerAngle* headquarters; it later turned out that I was calling Mrs. Hauptman's home. During my brief conversation with Mrs. Hauptman I explained Ossining High School's science research program and proposed the idea of testing her rackets as compared to conventionally strung rackets for my research project. The two of us arranged for a formal meeting, which ended in an agreement that would allow me to pursue research on her novel rackets free of charge. I finally had a research project, but I found myself more anxious than ever. There I was, a 16-year old high school sophomore with the research of a sporting goods company on my shoulders and no professional assistance. Newly equipped with half-a-dozen diagonally and conventionally strung rackets for the purpose of my study, I was up for the challenge.

Initially, I decided to test the rackets only for the level of vibration brought on to the racket's handle, the variable that Mrs. Hauptman designed her rackets to reduce. However, as

time went on, I realized that these possible vibration reductions could not be utilized in tennis in the case that they hampered an individual's ability to play the game. I knew that for practical purposes, the possible safety improvements that diagonal stringing may offer could not compromise a given racket's performance. As a result, I decided that testing the overall performance (ball control and power) of the diagonally strung tennis racket against the conventional racket was also necessary.

For the testing of vibrations, I took into account my review of literature to make several significant novel improvements to a previously used method for vibration quantification known as a piezoelectric disk vibration testing system. This process required countless hours of detailed, devoted preparation, and is explained in the research report section of this paper. For the testing of overall performance on the other hand, I did not have the luxury of previous modern research to assist in developing my methodology for quantifying ball control and power. Thus, after hours of careful thought, I drew up a novel method featuring a high-speed camera. There was only one problem: I didn't have access to such a camera.

As a result, I went about the extensive process of attempting to procure the donation of a camera of this sort. After sending my research plan to a number of sources, Vision Research, the largest high-speed camera company in the world, sent me an email letting me know that they would be willing to lend me a camera for an extended period of time. Normally, renting a high-speed camera can cost thousands of dollars a week; in the end, Vision Research was generous enough to allow me to use the camera for over a year. A few days after receiving this email, I went out to New Jersey to spend the afternoon at the company's corporate headquarters to pick up the camera and receive training on how to use this advanced equipment. As I drove back home across the George Washington Bridge at the end of the day, I knew that the methodology of my project was finally all set.

Given that I had no professional research mentor, I decided to work under the loose guidance of my A.P. Physics teacher Mr. Scinta in the back of my school's Physics classroom. While this was not the most professional of settings, I made the most of what I had, keeping track of every minute detail to make my research as valid as possible. Over the course of my Junior year, I spent many long hours in that lab area. Thousands of trials later, I had truly completed an independent science research project. In the end, I showed that *PowerAngle* diagonally strung tennis rackets can reduce vibrations by roughly 40% (39.7 to be exact) without compromising a given player's ability to play the game. From these findings, it can be inferred that diagonal stringing holds potential for combating tennis elbow associated with the game.

As I look back on my research project, I can unquestionably state that I have no regrets. While the numerous accolades I've received for my project are terrific, I've found the most satisfaction in all that science research has taught me. Ossining Science Research has truly turned me into the person I am today, having afforded me the opportunity to grow both personally and intellectually. I can only hope that all the young students unsure if science research is right for them, the position I was once in three long year ago, choose to take advantage of such an amazing opportunity as I did. No matter who you are or where your interests may lie, science research is for you. That is, as long as you're willing to work hard, of course.

## ***(ii) Research Report***

### **Introduction**

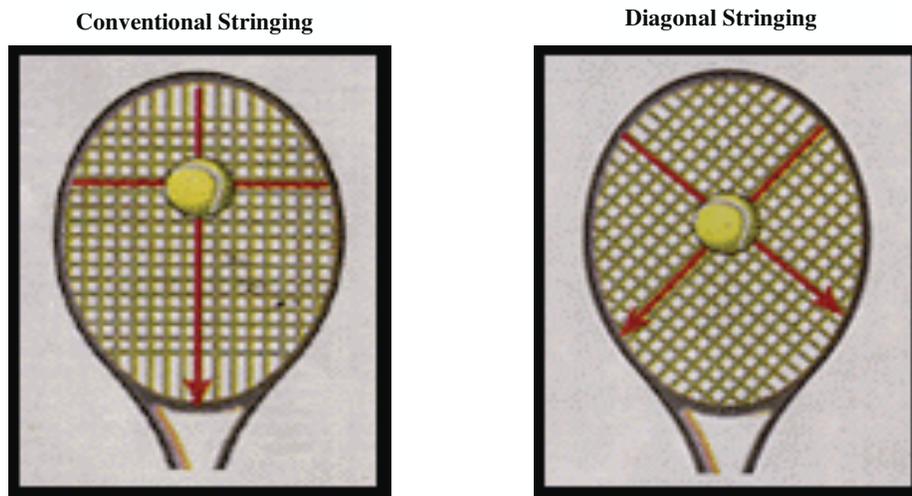
Lateral epicondylitis, commonly known as tennis elbow, is the second most common injury of the upper extremity of the body (Haahr & Anderson, 2002; 2003). The injury occurs in the common extensor origin of the elbow, most frequently in the tendon known as the Extensor Carpi Radial Brevis (ECRB). Tendonitis occurs in this region, causing pain in the lateral aspect of the elbow elicited by movement of the arm (Paolini, Appleyard, & Murrell, 2003; Ingraham, 2004).

It has been estimated that approximately 40-50 percent of all tennis players suffer from some degree of lateral epicondylitis due to the repetitive nature of the game of tennis (Roetert & Brody, 1995). The high prevalence of lateral epicondylitis among tennis players results from vibrations streaming from the tennis racket when contact is made with the ball (Pallis, 2002). Although a racket is in contact with a ball for only 5-7 ms during a shot, it continues to vibrate for approximately the next 40 ms (Hatze, 1976). During this extended period of time, the racket oscillates between 150 and 250 times, and these vibrations are transferred onto the human forearm, causing tendonitis, pain and swelling (Brody, 1979; Hennig, Rosenbaum, & Milani, 1992). It has been suggested by several studies that tennis racket design has a direct correlation to the amount of vibration generated during a tennis shot (Brody, 1981; Brody, 1987; Hatze, 1991, 1992; Tomosue, 1991; Brody, Cross, & Lindsey, 2002; Hauptman, 2001). In response to these claims, prior research has been conducted to better understand the properties of the racket.

Research has attempted to reduce racket vibrations through an alteration of the physical properties of the tennis racket (Pallis, 2002). In 1981, Brody established that striking the ball at a location known as the “sweet spot” can reduce the pain and discomfort associated with vibrations in tennis by allowing for the optimum dispersal of vibration. It has been reported that the “sweet

spot” is located approximately 16 cm from the tip of a racket (Brody, 1981). However, off-center ball impacts outside of the “sweet spot” can cause 1.9 to 3.1 times greater levels of amplitude of vibration, thus failing to adequately prevent lateral epicondylitis (Tomosue, 1991). In 1997, Brody proposed the concept that an increase in the head-size of a tennis racket would increase the size of this “sweet spot.” Although these oversized rackets possess a larger “sweet spot” than standard tennis rackets, the increased size does not compensate for human error. The average player is still incapable of consistently hitting this specific “sweet spot,” showing only minimal improvement over the standard racket (Pallis, 2002). Grip bands were also suggested as a possible method of vibration reduction, however it was later found that even the highest quality bands are only capable of reducing vibrations by up to 5% (Hatze, 1991).

Another proposed method for the reduction of excessive vibrations is altering the pattern of stringing. An innovative stringing method known as diagonal stringing has been developed in an effort to reduce the vibrations of the racket (Hauptman, 2001). Diagonal stringing involves the stringing of a tennis racket with opposite pairs of diagonal strings of equal length (Fig 1.1). With this congruency of string length, it has been purported that vibrations will be more evenly dispersed, reducing the level of vibration directed onto the player’s forearm. In conventional stringing, strings of varying lengths vibrate at several different frequencies, thus poorly distributing vibrations (Brody, Cross, & Lindsey, 2002). These uneven dispersions may lead to a larger force of vibration being placed upon the elbow, contributing to the pain and injury associated with lateral epicondylitis.



Hauptman, 2006

**Figure 1.1** Diagonally and conventionally strung tennis rackets. Diagonal stringing consists of opposite pairs of equidistant string strung in a diagonal fashion, while conventional stringing incorporates horizontal and vertically positioned strings of differing lengths. It has been suggested that this discrepancy in stringing method can cause an alteration in level of vibration.

Although several public claims attest to the advantages of diagonal stringing over conventional stringing, research supporting this concept has yet to be conducted (Hauptman, 2001). If research confirms that diagonally strung tennis rackets produce a lower level of vibration, such rackets may greatly aid in the prevention of lateral epicondylitis.

Testing the overall performance of the diagonally strung tennis racket against the conventional racket is also necessary. As established within past research, changes in the physical properties of the tennis racket can have adverse effects on a tennis racket's overall performance (control and power). For practical purposes, the possible safety improvements that diagonal stringing may offer cannot compromise a given racket's performance. If research shows that diagonally strung rackets can perform at the same or relatively similar levels, such rackets can be used interchangeably in the game of tennis without compromising quality of play.

### **Statement of Purpose**

The purpose of this study is twofold:

1. To assess the diagonal stringing method by the following criteria:
  - a. Level of vibration of the tennis racket.
  - b. Overall performance (ball control and power).
2. To statistically compare these values to those of conventional stringing.

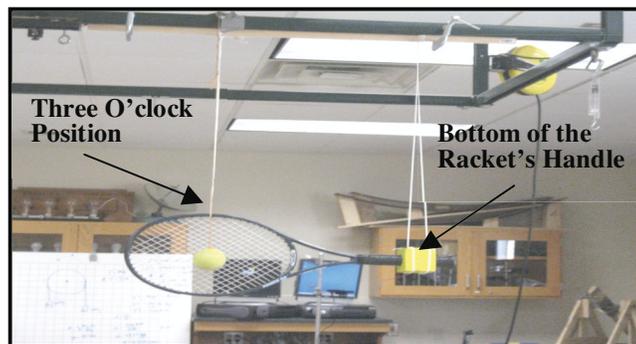
## Methodology

### The Rackets

Two rackets were used during testing, each with a head size of 632.3 cm<sup>2</sup>, a length of 68.5 cm, a strung weight of 322 g, a balance of 12 pts. head light, a swingweight of 290, a stiffness of 63, and a beam width of 19 mm (Tennis Warehouse, 2006). The rackets were strung with a *Gamma 5003* stringing machine using *Penn Topspin Plus* string at 60 lbs of tension. The control racket was strung conventionally, while the experimental racket was strung diagonally. These values were measured periodically during testing to ensure consistency.

### Level of Vibration

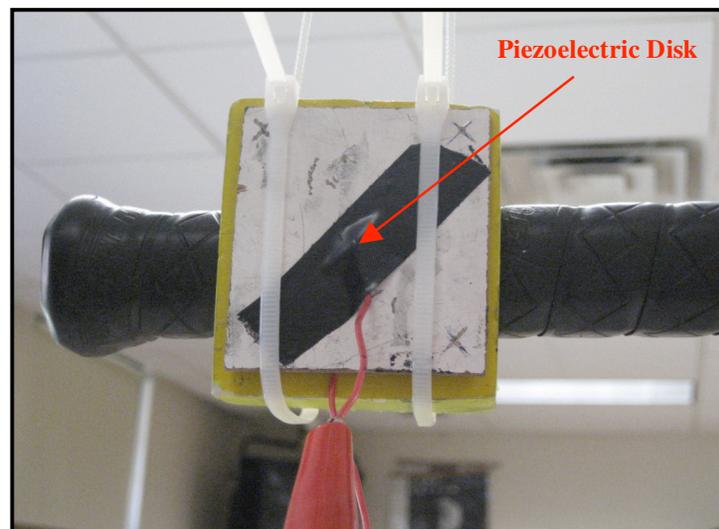
A piezoelectric disk vibration testing system was constructed for the analysis of vibrations (Fig 3.1). In this system, the racket was supported as a freely moving pendulum by two 134 cm ropes attached to a metal frame. The ropes were attached at two fixed locations a distance of 45 cm away from one another to the metal frame, and tied to the racket at the bottom of its handle and at the three o'clock position on the racket's face.



**Figure 3.1** The piezoelectric disk vibration testing system used in testing. Arrows point to the bottom of the handle and the three o'clock position of the racket's face where ropes were attached.

A piezoelectric disk was used as a force gauge in this experimentation. When vibrated, a piezoelectric disk generates a piezo-signal in the form of voltage that can be measured by a voltage sensor (Brody, Cross, & Lindsey, 2002). To measure vibrations, a piezoelectric disk was attached to the handle of the racket, modeling the location from which vibrations are transferred onto the arm during a tennis shot.

Two thermal-set plastic blocks were employed to attach a piezoelectric disk to each tennis racket (Fig 3.2). Identical blocks were molded for each respective racket to fit firmly over each racket's handle and attach this disk; these blocks were attached to each racket through the use of two 30 cm plastic wire wraps. A piezoelectric disk was epoxyed to one side of the blocks to prevent movement during testing. Following this attachment, the disk was connected to a voltage sensor at its two electrical terminals by standard electrical wire.



**Figure 3.2** The thermal-set plastic block used for the attachment of the piezoelectric disk to the tennis racket during testing. A piezoelectric disk is found underneath a piece of standard electrical tape at the location indicated by the above arrow.

In order to simulate the interaction between the ball and strings in a standard tennis shot, a tennis ball was mounted on a rope as a pendulum on the same metal frame as the freely moving tennis racket. This experimental design is similar to the setup described by Brody, Cross, and

Lindsey in 2002. During each test, the ball was dropped toward the racket's face from a fixed location directly perpendicular to the racket's strings along a horizontal plane. The ball was mounted as a pendulum in order to standardize its speed and impact location during each test. In order to control impact speed, the ball was moved an equal height and distance off of the strings by a mechanical stop. Following the tennis ball's contact with the racket, level of vibration was measured. During each piezoelectric vibration test, the ball made contact with the "sweet spot" of each racket, exactly 16 cm from the racket's tip.

Piezoelectric testing was repeated on both the diagonally and conventionally strung racket for 100 trials. During each test, level of vibration was determined through the use of *PASCO* Data Studio software (Data Studio CI-6859C, September 2006); graphs were generated by the voltage sensor attached to the piezoelectric disk on the handle of each tennis racket. The highest voltage value during each test was recorded as the level of vibration during testing, as this peak amplitude value has the greatest impact on the arm of a given tennis player (Brody, Cross, & Lindsey 2002). The first positive peak in the piezo signals was disregarded while calculating vibration values, as this value is mostly a result of the flexation and rotation of the handle, rather than the vibration of the strings (Brody, Cross, & Lindsey, 2002). Following the identification of each vibration amplitude, mean values were calculated for both diagonal and conventional stringing. Data underwent a t-test through the use of Statistical Program for the Social Sciences (SPSS Version 13.0, September 2004).

### Overall Racket Performance

Racket performance was determined by measuring ball control and power. Ball control was defined as the amount of time that the tennis ball stayed in contact with the racket's strings during a given shot, while power was defined as the speed of the tennis ball following contact

with the tennis racket. Both ball control and power were measured through a novel method featuring a *Phantom 7.0* high-speed video camera. During testing, each racket was clamped to a set table, exactly 1 m above the ground. Four metal clamps were placed 1 cm and 4 cm from the top and bottom, respectively, of the grip of each racket during testing (Fig 3.3), keeping the racket still and eliminating outside sources of vibration.



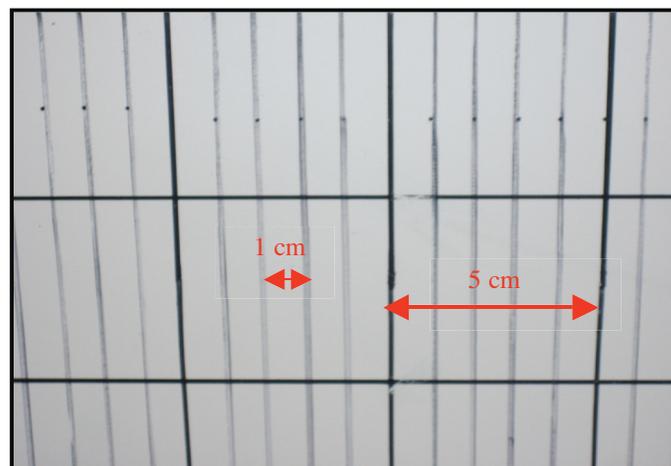
**Figure 3.3** The method used for the clamping of tennis rackets during testing of both ball control and power. Four clamps were placed 1 cm and 4 cm away from both the top and bottom of the grip of each racket.

*Penn ATP Extra Duty* tennis balls were projected upon both the diagonally and conventionally strung rackets using a *Lobster Model 3* tennis ball projection device while the rackets were securely clamped to the testing setup. These tennis balls were projected at 72 km/hr from a distance of 2 m away from the apparatus. The balls were aimed at the “sweet spot,” exactly 16 cm from the tip of each racket. The flight of these projected tennis balls was perpendicular to the strings of the tennis rackets employed in testing (Fig 3.4).



**Figure 3.4** The path of the tennis balls projected during the testing of both ball control and power. The tennis balls made contact with each racket exactly 16 cm from the tip, at the “sweet spot,” perpendicular to the strings of the tennis rackets.

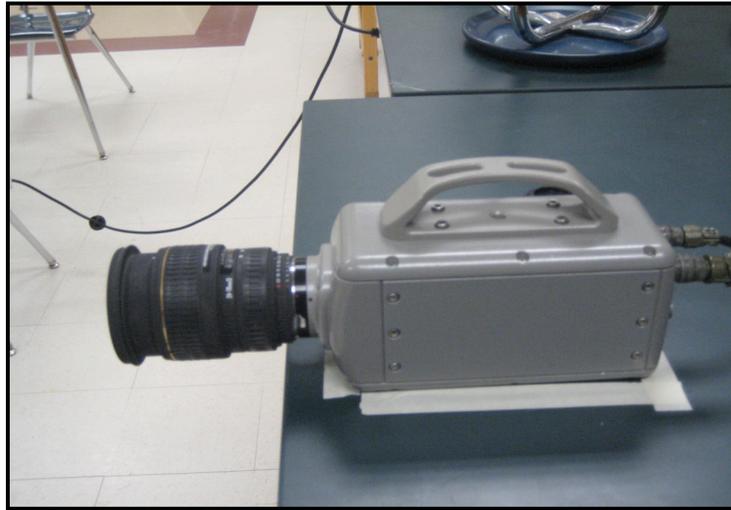
A grid of 1.44 m<sup>2</sup> in size, showing values of 1 cm horizontally and 5 cm vertically, was constructed for the purpose of distance quantification (Fig 3.5). During each high-speed video, this grid was used for the standardization of distance. This grid was placed perpendicular to the tennis racket, parallel to the path of the tennis ball during each trial.



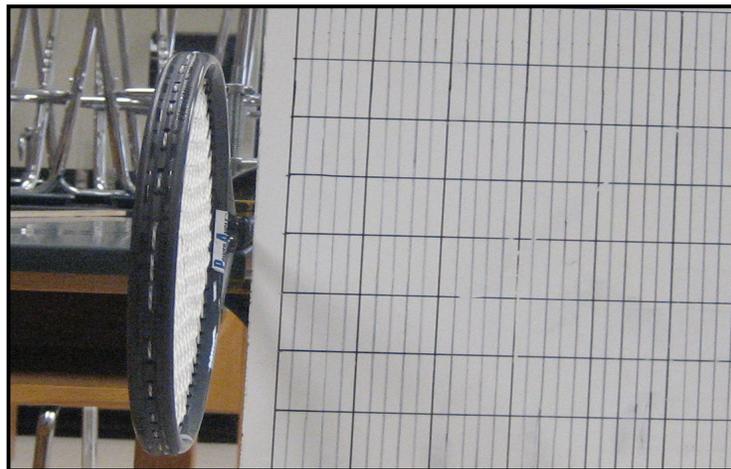
**Figure 3.5** The distance quantification grid employed in testing. As exemplified by the arrows in the image, this grid shows values of 1 cm horizontally and 5 cm vertically.

The *Phantom 7.0* high-speed camera utilized in testing was then positioned exactly 1 m in distance away from the tennis racket (Fig 3.6). The view of the high-speed camera was positioned parallel to the tennis racket, and perpendicular to both the path of the projected tennis

ball and the distance quantification grid (Fig 3.7). The high-speed camera was placed at identical visual settings during all tests. The camera was set to a sample rate of  $500 \mu\text{s}$  and an exposure time of  $470 \mu\text{s}$ .



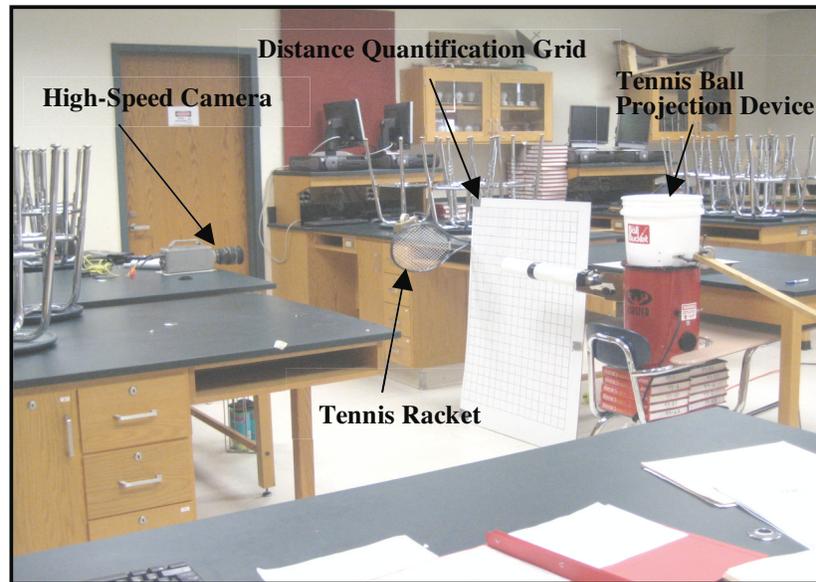
**Figure 3.6** The *Phantom 7.0* high-speed camera used during testing.



**Figure 3.7** The view of the high-speed camera during testing. The camera's view was positioned parallel to the tennis racket, and perpendicular to both the path of the projected tennis ball and the distance quantification grid.

During each test, the high-speed camera was triggered prior to the projection of the tennis ball by the tennis ball projection device. High-speed videos of the ball's motion prior to contact with the racket, while in contact with the racket's strings, and following contact with the racket

were then recorded for data analysis. 100 high-speed videos were taken for both diagonally and conventionally strung rackets.



**Figure 3.8** The complete setup utilized for the quantification of overall performance. Arrows indicate the tennis racket, tennis ball projection device, distance quantification grid, and high-speed camera used during testing.

Through the use of *Phantom* high-speed video measurement analysis software, ball control and power were recorded (Phantom Software Version 650, January 2007). Ball control was defined as the amount of time the ball spent on the strings of each racket. This value was determined based upon the number of frames that the ball visually remained in contact with the tennis racket during each high-speed video. By multiplying the number of frames of contact by 500 (the number of microseconds within each individual frame), ball control was recorded in  $\mu\text{s}$ .

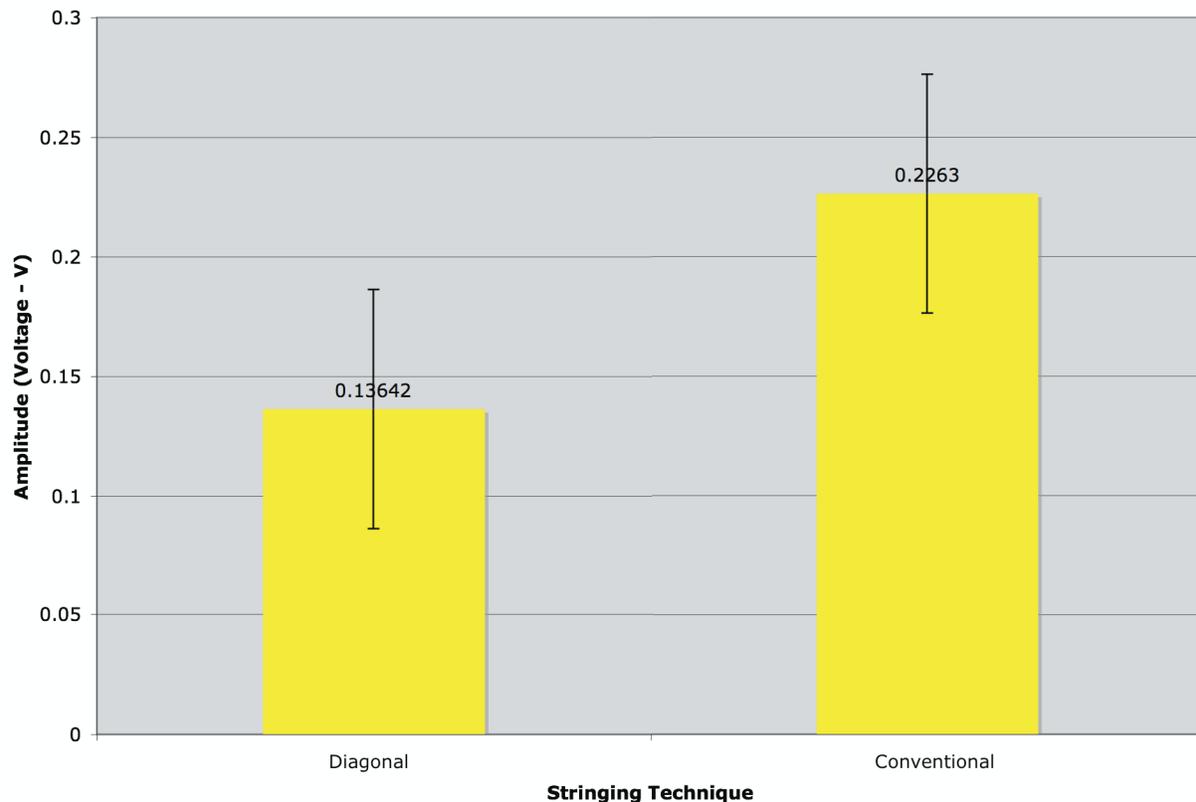
Power was defined as the speed that the projected tennis ball left the face of the racket in each video over a 5 cm interval. The number of frames necessary for the ball to travel this distance, based upon the distance quantification grid in each high-speed video, was used to determine the amount of time involved in each trial. Power findings were recorded in km/hr.

For both ball control and power, data was compared using a t-test through the use of Statistical Program for the Social Sciences (SPSS Version 13.0, September 2004). Position and velocity graphs were then formulated through the use of *PASCO* Data Studio software (Data Studio CI-6859C, September 2006).

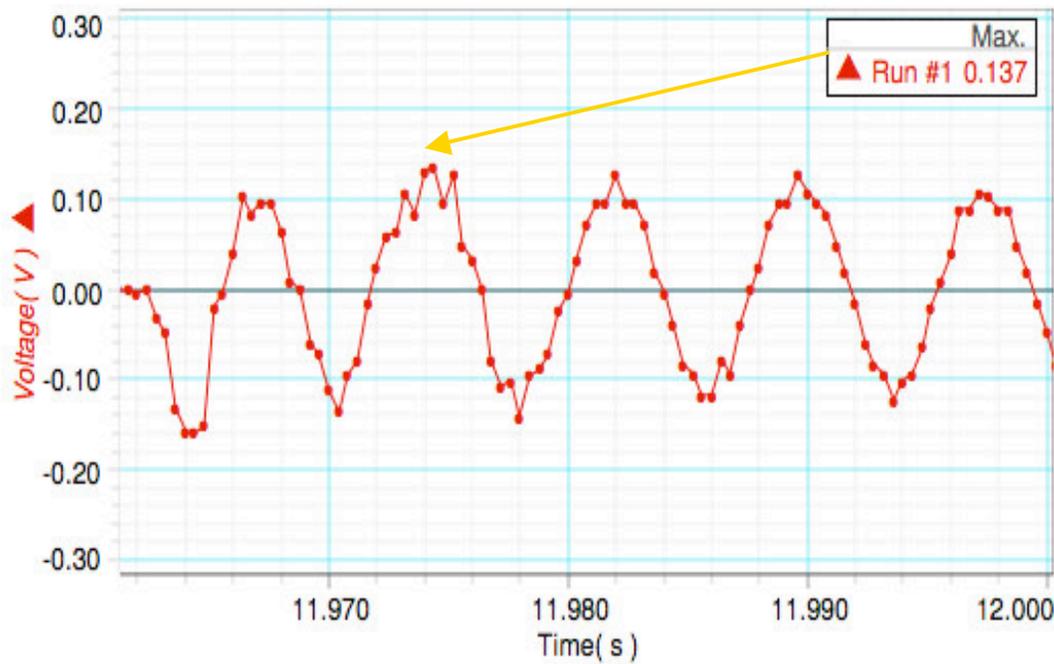
## Results

### Level of Vibration

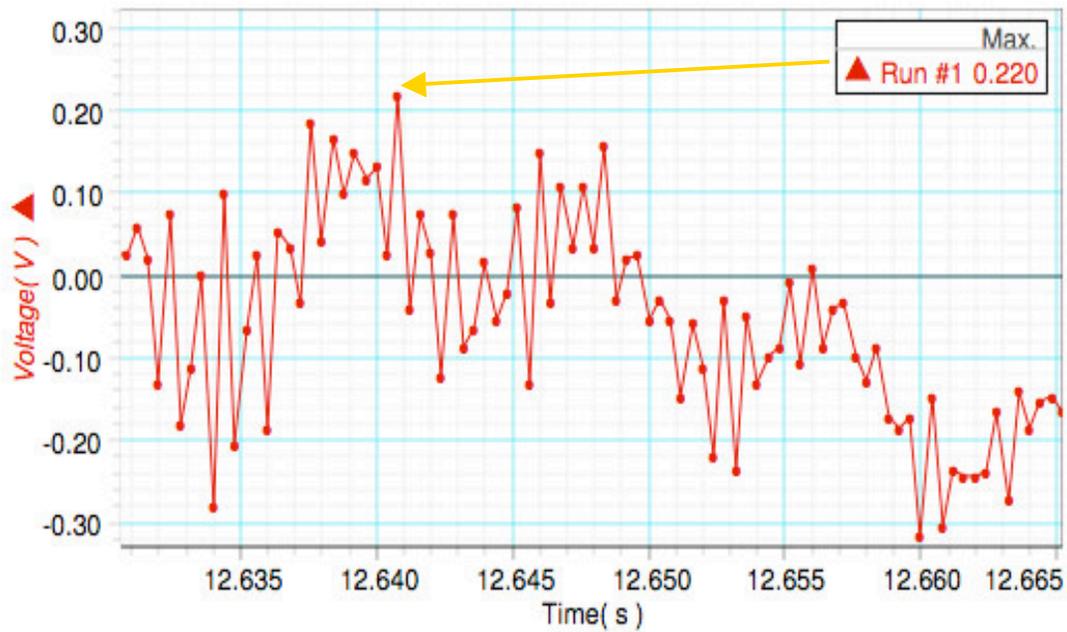
Diagonally strung rackets were found to have a mean vibration amplitude of 0.13642 volts (V), whereas the conventionally strung rackets' mean amplitude was 0.22630 V (Fig 4.1, 4.2, 4.3). Following analysis, diagonal stringing was shown to reduce the level of vibration on the racket handle by 39.72%, a difference that was strongly significant ( $p$ -value = 0.000).



**Figure 4.1** Comparison of amplitude of vibration data for diagonally and conventionally strung tennis rackets. Amplitude of vibration was defined as the peak voltage (V) value recorded during each of 100 piezoelectric disk vibration tests. Diagonal stringing was found to have a mean amplitude of 0.136 V, while conventional stringing was shown to have a mean amplitude of 0.225 ( $p$ -value = 0.000). Error bars show the range of amplitude findings.



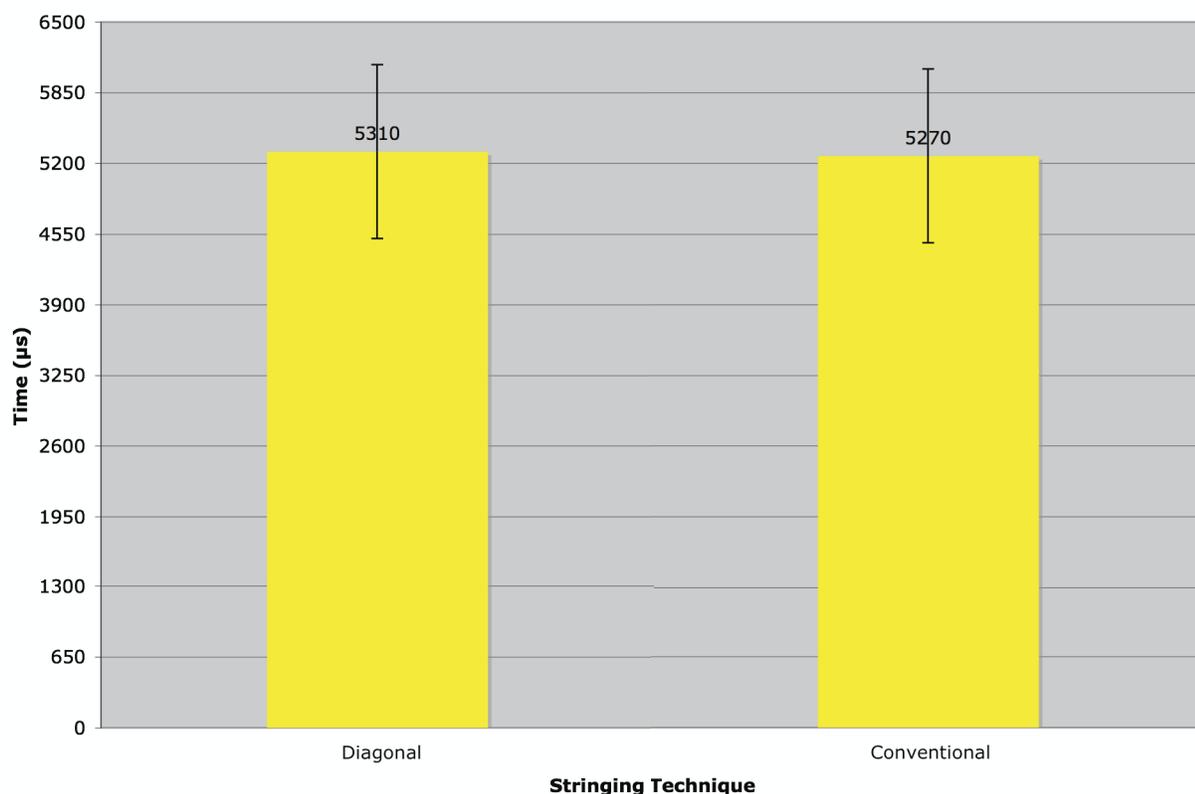
**Figure 4.2** A sample vibration graph for diagonal stringing. Amplitude of vibration was defined as the peak voltage (V) value recorded during each of 100 piezoelectric disk vibration trials. A peak amplitude of vibration of 0.137 is evident within the above figure. An arrow indicates the location of this peak amplitude.



**Figure 4.3** A sample vibration graph for conventional stringing. Amplitude of vibration was defined as the peak voltage (V) value recorded during each of 100 piezoelectric disk vibration trials. A peak amplitude of vibration of 0.220 is found within this graph. An arrow indicates the location of this peak amplitude.

## Ball Control

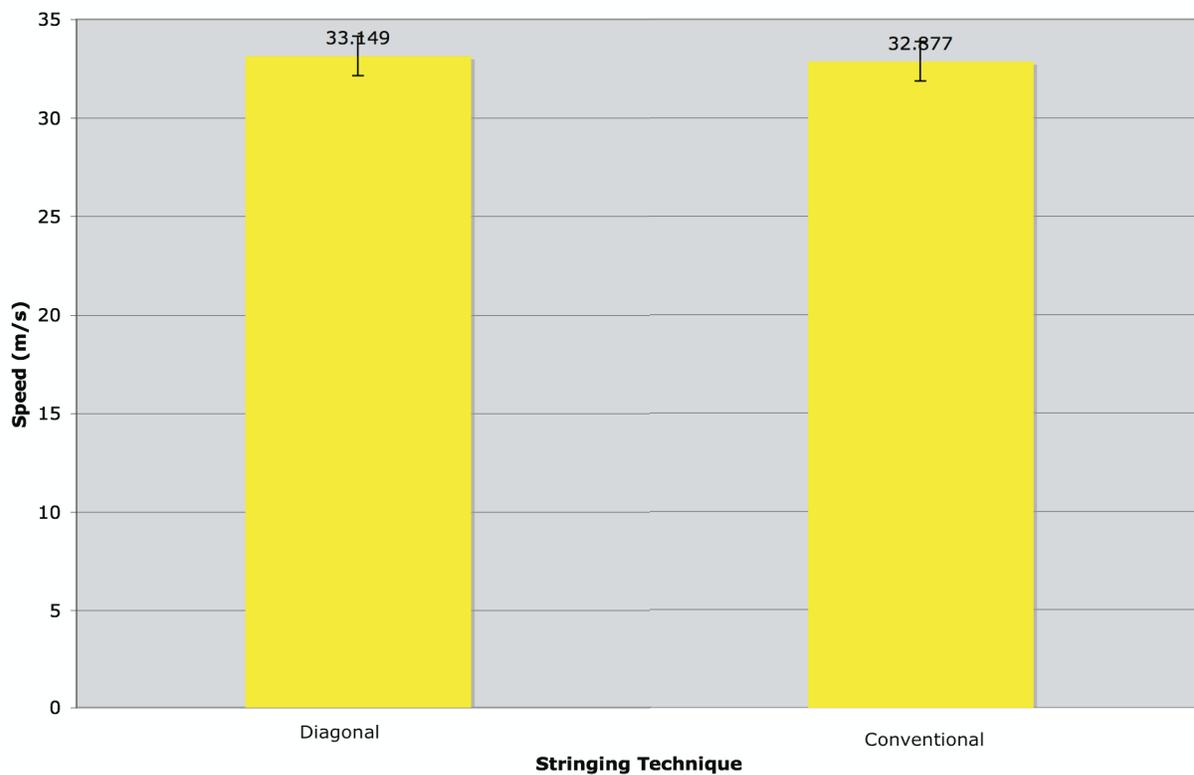
Video analysis found that the tennis ball remained in contact with the diagonally strung tennis racket an average of 10.62 frames during each test, while the ball stayed on the conventionally strung tennis racket an average of 10.54 frames (Fig 4.4). Therefore, the tennis ball stayed on the diagonally strung tennis racket for approximately 5310  $\mu$ s, and on the conventionally strung tennis racket for roughly 5270  $\mu$ s. Although a small discrepancy was shown between the two different stringing techniques, the t-test showed that there was no significant difference in the data, suggesting that both stringing methods perform at a similar level (p-value = 0.336).



**Figure 4.4** Comparison of ball control data for diagonally and conventionally strung tennis rackets. This value was measured as the amount of time the ball spent on the strings of each racket and was based upon the number of frames that the ball visually remained in contact with the tennis racket during each high-speed video. Diagonal stringing was found to have an average of 5310  $\mu$ s, while the conventionally strung tennis racket was recorded as having an average of 5270  $\mu$ s (p-value = 0.336). Error bars show the range of ball control findings.

## Power

A tennis ball leaving a diagonally strung tennis racket was shown to need an average of 10.86 frames to travel 5 cm during the high-speed videos, while a ball leaving a conventionally strung tennis racket was shown to need an average of 10.95 frames (Fig 4.7) Therefore, diagonal stringing caused the tennis ball to travel at an average speed of 33.149 m/s while conventional stringing brought about a speed of 32.877 m/s, a difference that was not statistically significant (p-value = 0.431).



**Figure 4.7** Comparison of power data for diagonally and conventionally strung tennis rackets. This variable was measured as the speed that the projected tennis ball left the face of the racket in each video. The number of frames necessary for the ball to travel 5 cm based upon the distance quantification grid in each high-speed video was used to determine this speed. Diagonal stringing was recorded as causing the tennis ball to need a mean of 10.86 frames (33.149 m/s), while conventional stringing caused a mean of 10.95 frames (32.877 m/s) (p-value = 0.431). Error bars show the range of power findings.

## Discussion

Within the present study, levels of vibration and overall performance of the diagonally strung racket were compared to those of the conventionally strung racket for the first time. Prior research involving the testing of vibration and overall performance of tennis rackets has ignored diagonal stringing as a variable in experimentation (Hauptman, 2001). Thus, the results found in this study warrant further investigation into the potential of diagonal stringing in alleviating the condition of lateral epicondylitis in tennis players.

The diagonal stringing method was found to decrease amplitude of vibrations by 39.7% as compared to the conventionally strung racket ( $p$ -value = 0.000), while exhibiting a nearly identical level of performance (ball control and power). These similarities in the racket performance of the diagonally and conventionally strung tennis rackets are especially noteworthy, as they suggest that a given player will be able to use a racket strung by this novel technique without hampering their playing ability. Unlike past attempts by Hatze (1991) and Brody (1997), which utilized physical alterations such as grip bands and an increase in racket head size to decrease levels of vibration, the present study offers a viable technique, in diagonal stringing, to be used in the game of tennis to significantly reduce vibrations without compromising a given player's performance.

This study improved upon the methodology used by previous research for assessing the level of vibration of a tennis racket. The handle was selected as the location for the attachment of the piezoelectric disk because it is the location from which vibrations are transferred onto a player's arm. The thermal-set plastic block utilized during testing was specifically molded to precisely fit the handle of the diagonal and conventionally strung rackets utilized during testing. Because the handle of a tennis racket is not perfectly flat, and due to the sheer size of a piezo disk (1/2 in. in diameter, 0.3 mm thick), the attachment of a flat surface (the thermal-set plastic

blocks) was necessary to achieve stability during testing. The combined weight of the block/piezo disk structures was approximately 170 grams, a value roughly equivalent to the weight of an average human hand, thus simulating the weight placed upon a tennis racket during a given shot (Brody, Cross, & Lindsey, 2002).

Despite the improvements made to the piezoelectric disk vibration testing system, the thin ropes used to hang the tennis rackets as freely moving pendulums were shown to clearly impact the voltage emitted by the piezoelectric disk stationed on the grip of the rackets. As a result of the freely moving nature of the connection wires attached to the terminals of the piezoelectric disk, the ropes caused an excess stress on the piezo disk, resulting in an increase in emitted voltage, artificially inflating amplitude of vibration findings. In order to prevent the tugging of these wires, standard electric tape was placed upon their site of connection to the disk's terminals in an attempt to limit their impact on vibration findings. Despite this alteration, it is possible that results may have been influenced by the free motion of the rackets following impact with the tennis ball. Nevertheless, past research has upheld that a similar piezoelectric disk vibration setup is a valid setup for the testing of vibrations (Brody, Cross, & Lindsey, 2002).

Past research has suggested that levels of vibration in the game of tennis are primary contributors to lateral epicondylitis associated with the sport (Hatze, 1976; Brody, 1979; Brody, 1981; Tomosue, 1991; Hennig, Rosenbaum, & Milani, 1992; Pallis, 2002; Brody, Cross, & Lindsey, 2002; Hauptman, 2001). A reduction of these levels of vibration may be able to reduce the 40-50% incidence rate of lateral epicondylitis in all tennis players that currently suffer from some degree of the upper-extremity injury (Roetert & Brody, 1995). The present study suggests that diagonal stringing can reduce the amplitude of vibrations of a tennis racket by 39.72%. It

can thus be inferred that diagonal stringing may be able to be utilized in the game of tennis to reduce the prevalence of lateral epicondylitis.

Although the findings of this study showcase the potential of this novel stringing technique in reducing lateral epicondylitis, no conclusions can be drawn on the direct impact of diagonal stringing on the prevalent upper extremity injury. Further research should investigate if the stringing method has the potential to prevent lateral epicondylitis and alleviate its symptoms. As a result, biomechanical analysis of the human arm while using a diagonally strung tennis racket as compared to a conventionally strung tennis racket should be conducted. This research should include a long-term study of the potential impact diagonal stringing may have on preventing and alleviating the symptoms of lateral epicondylitis.

## **Conclusion**

The findings of this study suggest that diagonally strung tennis rackets can be utilized in the game of tennis to significantly reduce vibrations (39.72 %) without compromising the quality of play of a given tennis player. From these findings, it can be inferred that diagonal stringing holds potential for combating lateral epicondylitis associated with the game. Thus, the results found in this study warrant further investigation into the potential of diagonal stringing in alleviating the condition of lateral epicondylitis in tennis players.

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## References

- Brody, H. (1979). Physics of the tennis racket. *American Journal of Physics*, 47(6), 482-487.
- Brody, H. (1981). Physics of the tennis racket II: the “sweet spot.” *American Journal of Physics*, 49(9), 816-819.
- Brody, H. (1987) *Tennis Science for Tennis Players*. Philadelphia, PA: University of Pennsylvania Press.
- Brody, H. (1997). The Physics of tennis III: The ball-racket interaction. *American Journal of Physics*, 65(10), 981-987.
- Brody, H., Cross, R. and Lindsey, C. (2002). *The Physics and Technology of Tennis*. California: USRSA.
- Cooke, A.J., and Haake, S. (2002). Correlation between racquet design and arm injuries. *Fourth International Conference of the Engineering in Sport*, 4(11). 15-20.
- Haahr, J.P. and Anderson, J. (2002). Prognostic Factors in Lateral Epicondylitis: A randomized trial with one-year follow-up in 266 new cases treated with minimal occupational intervention or the usual approach in general practice. *Rheumatology*, 42(10), 1216-1225.
- Haahr, J.P. and Anderson J. (2003). Physical and Psychological Risk Factors for Lateral Epicondylitis: A Population Based Case-Referent Study. *Occupational Environment Medicine*, 1(60), 322-329.
- Hatze, H. (1991). The effectiveness of grip bands in reducing racquet vibration transfer and slipping. *Medicine and Science in Sports and Exercise*, 24(2), 226-230.
- Hatze, H. (1992). Forces and duration of impact, and grip tightness during the tennis stroke. *Medicine and Science in Sports*, 24(10), 88-95.
- Hauptman, Madeline M. (2001) *PowerAngle*. Retrieved January 6, 2006 from PowerAngle. Web site: <http://www.powerangle.net>
- Hennig, E.M., Rosenbaum D., and Milani, T.L. (1992). Transfer of tennis racket vibrations onto the human forearm. *Medicine and Science in Sports and Exercise*, 24(10), 1134-1140.
- Ingraham, Paul (2004). *Save Yourself from Tennis Elbow*. Retrieved December 15, 2006 from Save Yourself. Web site: <http://saveyourself.ca/articles/tennis-elbow.php>
- Mackay, D., Rangan, A., Hide, G., Hughes, T. and Latimer, J. (2003). The Objective Diagnosis of Early Tennis Elbow. *Occupational Medicine*, 53(5), 309-312.
- Pallis, Jani M. (2002). *Tennis Elbow and Racquet Design – Part I*. Retrieved November 20, 2005 from Tennis SET. Web site: [http://www.tennisserver.com/set/set\\_02\\_07.html](http://www.tennisserver.com/set/set_02_07.html)
- Pallis, Jani M. (2002). *Tennis Elbow and Racquet Design – Part II*. Retrieved November 21, 2005 from Tennis SET. Web site: [http://www.tennisserver.com/set/set\\_02\\_07.html](http://www.tennisserver.com/set/set_02_07.html)
- Paolini, Justin A, Appleyard, RC, Murrell, GAC. (2003) The Orthopedic research Institute – Tennis Elbow Testing System: A modified chair pick-up test - Interrater and intrarater reliability testing and validity for monitoring lateral epicondylitis. *Journal of Shoulder and Elbow Surgery*, 13(1), 72-77.
- Roetert, E.P. and Brody, H. (1995). The biomechanics of tennis elbow: an integrated approach. *Clinics in Sports Medicine*, 14(1), 47-57.
- PowerAngle Power 98/K Racquets*. Retrieved December 23, 2006 from Tennis Warehouse. Web site: <http://www.tennis-warehouse.com/descpageRCPA-PA98K.html>
- Tomosue, R. (1991). Measuring the vibrations of a racket handle and the wrist joint in the tennis forearm drive. *Abstracts from International Society of Biochemists*, 8(1), 138-139.