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

Micah Joselow

Abstract

40-50% of all tennis players suffer from lateral epicondylitis (tennis elbow). Vibrations from contact between the tennis racket and ball during play have been shown to be transferred onto the tendons of the arm, causing this upper-extremity injury. *PowerAngle* diagonal stringing, a novel method that incorporates the stringing of a racket with opposite pairs of equidistant strings in an angular fashion, has been developed to reduce these excessive vibrations.

A piezoelectric disk racket vibration setup measured levels of vibration of both a diagonally strung tennis racket and a conventionally strung racket of identical physical properties. The rackets were also compared for overall performance (power and ball control) through the use of a high-speed camera and a tennis ball projection device. Power was measured as the speed that the projected tennis ball left the face of the rackets, while ball control was defined as the amount of time the ball spent on the strings of the rackets during each video.

PowerAngle diagonal stringing was shown to reduce vibrations by 39.7% (p-value = 0.000) without causing a statistical discrepancy in power or ball control. A power value of 33.149 m/s was shown for *PowerAngle* diagonal stringing, while conventional stringing brought about a speed 32.877 m/s (p-value = 0.431). Ball control for *PowerAngle* diagonal stringing was quantified as 5310 μs, while the conventionally strung tennis racket had a ball control of 5270 μs (p-value = 0.336). Our data suggests that *PowerAngle* diagonal stringing can be used in tennis to significantly reduce vibrations without compromising racket performance. Thus, *PowerAngle* diagonal stringing may be able to alleviate the widespread problem of lateral epicondylitis in the game of tennis, warranting further investigation.

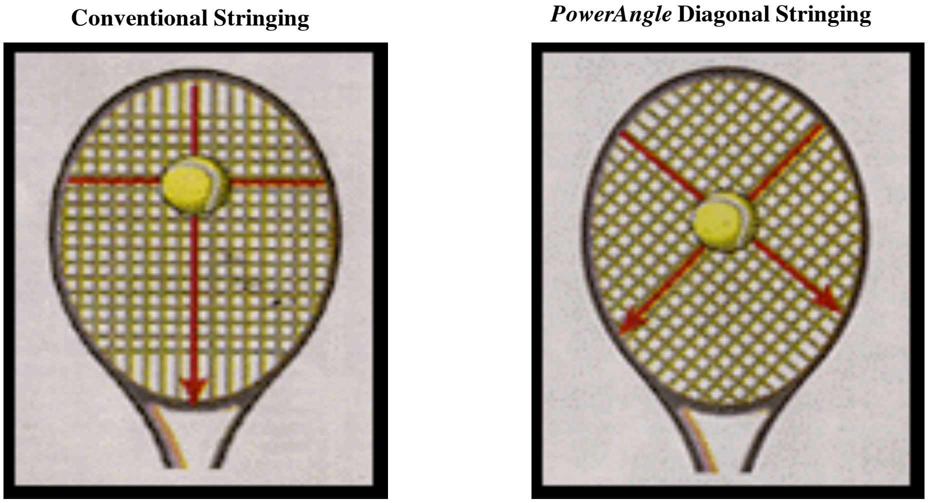
Introduction

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 *PowerAngle* diagonal stringing has been developed in an effort to reduce the vibrations of the racket (Hauptman, 2000). *PowerAngle* 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 *PowerAngle* 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 *PowerAngle* 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 *PowerAngle* 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^2, 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.

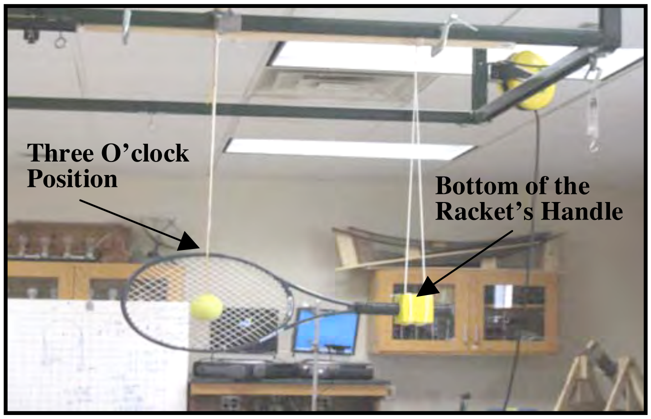


Figure 3.1 The piezoelectric disk vibration testing system used in testing. Arrows point to the bottom of the handle and the three o'clock position of the racket's face where ropes were attached.

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.

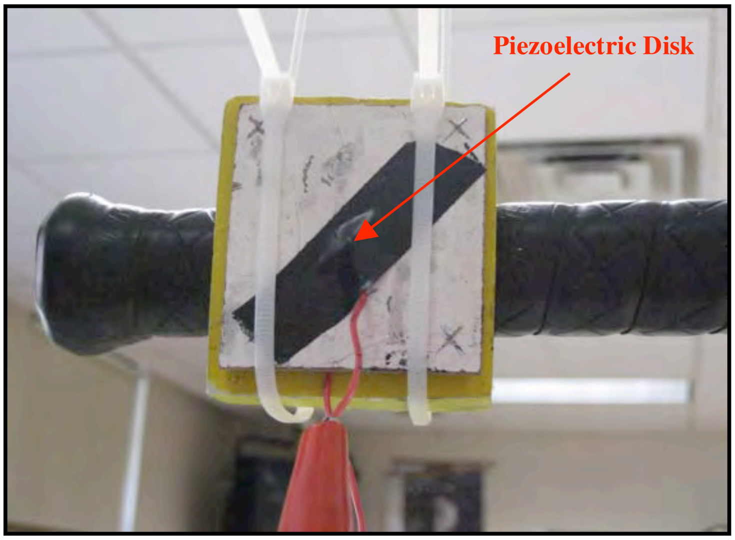


Figure 3.2 The thermal-set plastic block used for the attachment of the piezoelectric disk to the tennis racket during testing. A piezoelectric disk is found underneath a piece of standard electrical tape at the location indicated by the above arrow.

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 then 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 with 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 1cm 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^2 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.

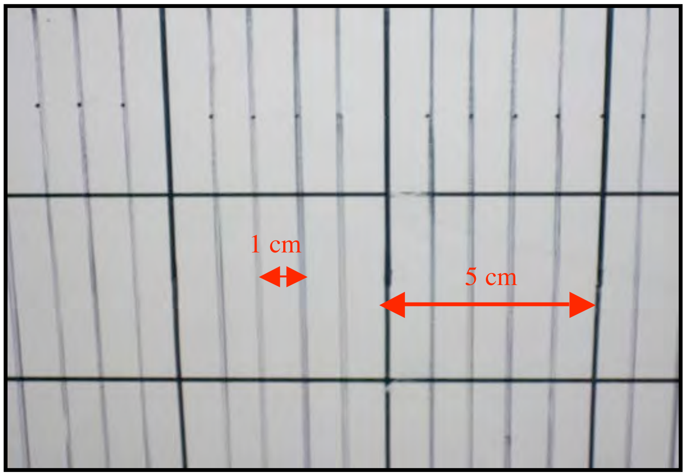


Figure 3.5 The distance quantification grid employed in testing. As exemplified by the arrows in the image, this grid shows values of 1 cm horizontally and 5 cm vertically.

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 μs and an exposure time of 470 μs.

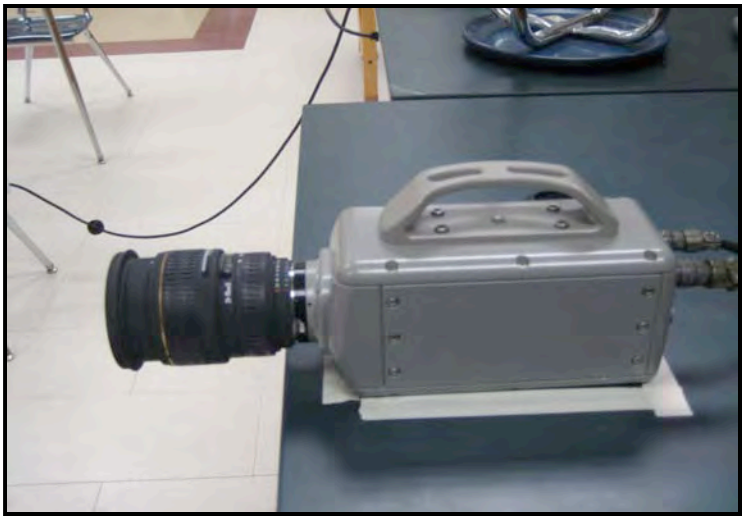


Figure 3.6 The *Phantom* 7.0 high-speed camera used during testing.

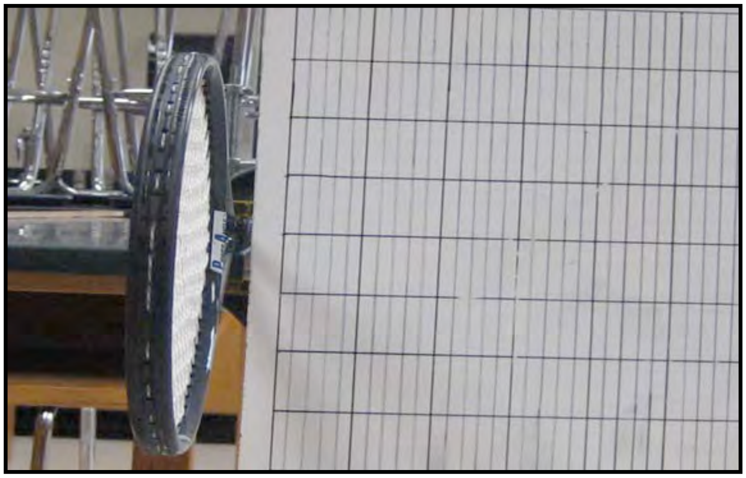


Figure 3.7 The view of the high-speed camera during testing. The camera's view was positioned parallel to the tennis racket, and perpendicular to both the path of the projected tennis ball and the distance quantification grid.

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.

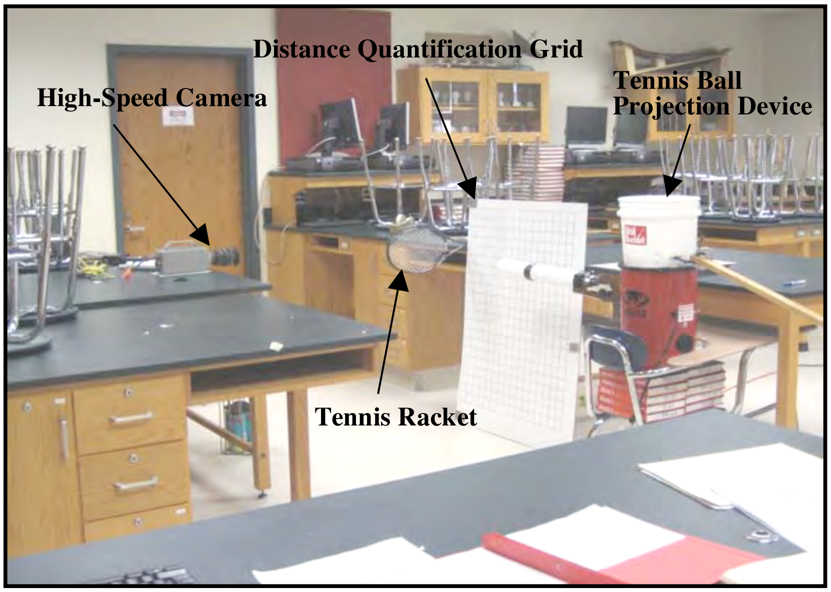


Figure 3.8 The compete setup utilized for the quantification of overall performance. Arrows indicate the tennis racket, tennis ball projection device, distance quantification grid, and high-speed camera used during testing.

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 μs.

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

PowerAngle 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).

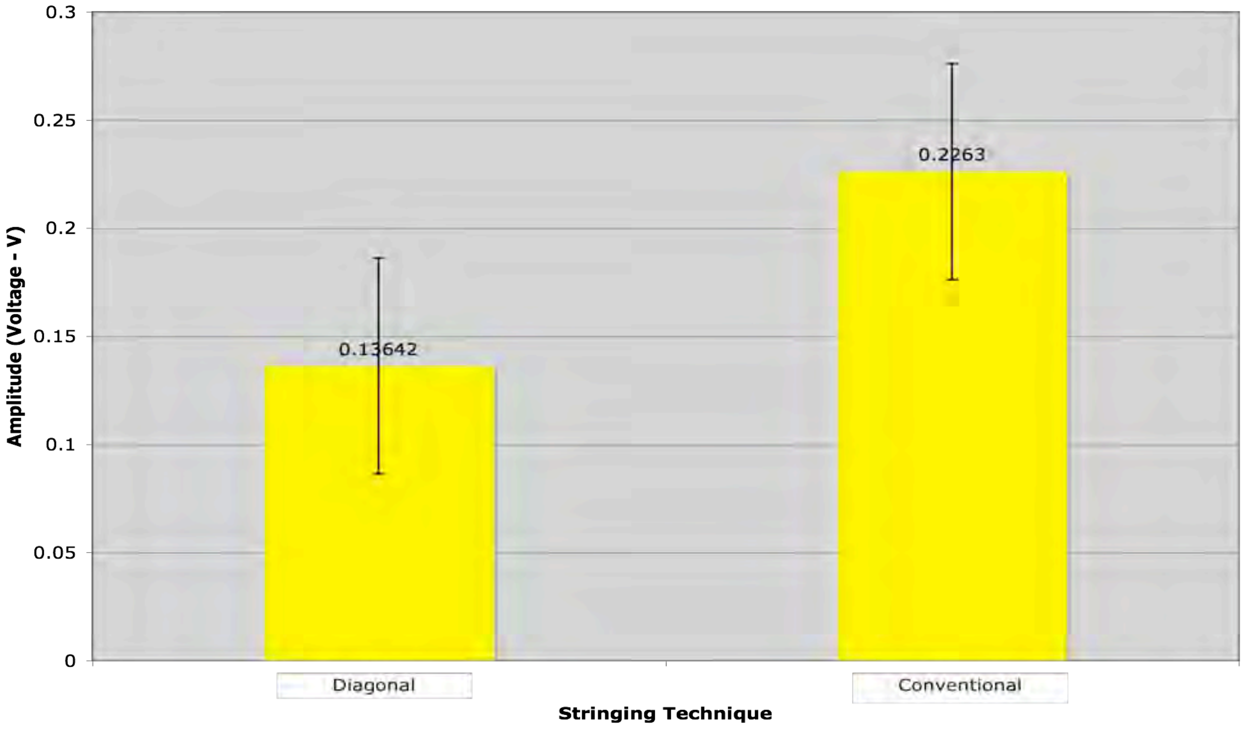


Figure 4.1 Comparison of amplitude of vibration data for diagonally and conventionally strung tennis rackets. Amplitude of vibration was defined as the peak voltage (V) value recorded during each of 100 piezoelectric disk vibration tests. *PowerAngle* diagonal stringing was found to have a mean amplitude 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.

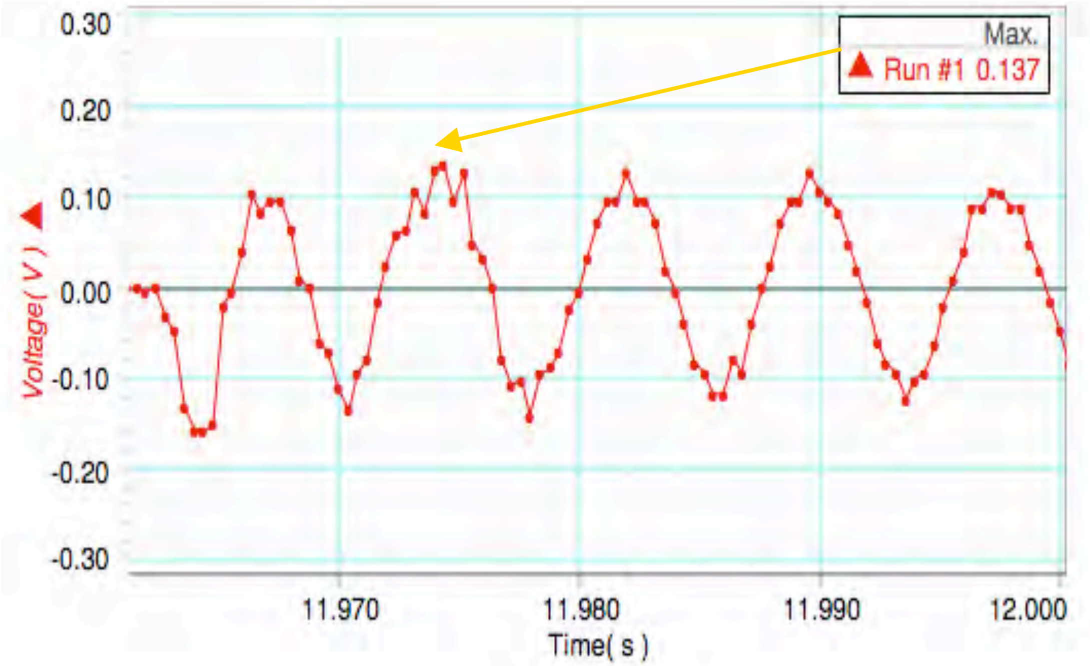


Figure 4.2 A sample vibration graph for *PowerAngle* diagonal stringing. Amplitude of vibration was defined as the peak voltage (V) value recorded during each of 100 piezoelectric disk vibration trials. A peak amplitude of vibration of 0.137 is evident within the above figure. An arrow indicates the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

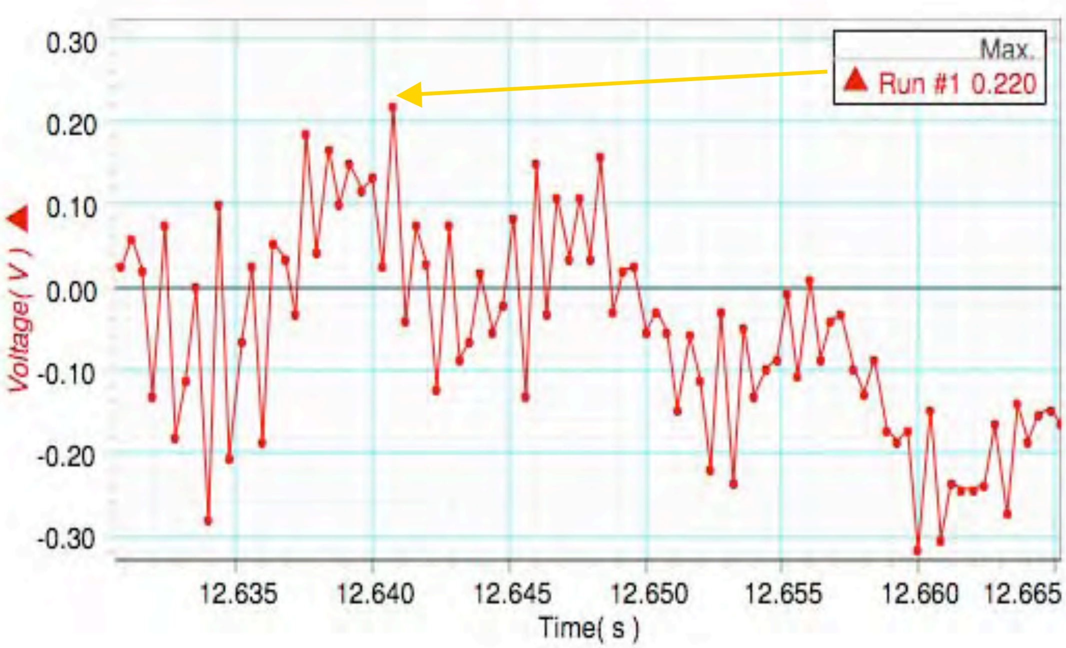


Figure 4.3 A sample vibration graph for conventional stringing. Amplitude of vibration was defined as the peak voltage (V) value recorded during each of 100 piezoelectric disk vibration trials. A peak amplitude of vibration of 0.220 is found within this graph. An arrow indicates the location of this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

Ball Control

Video analysis found that the tennis ball remained in contact with the *PowerAngle* 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 *PowerAngle* diagonally strung tennis racket for approximately 5310 μs, and on the conventionally strung tennis racket for roughly 5270 μs (Fig 4.5, 4.6). 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).

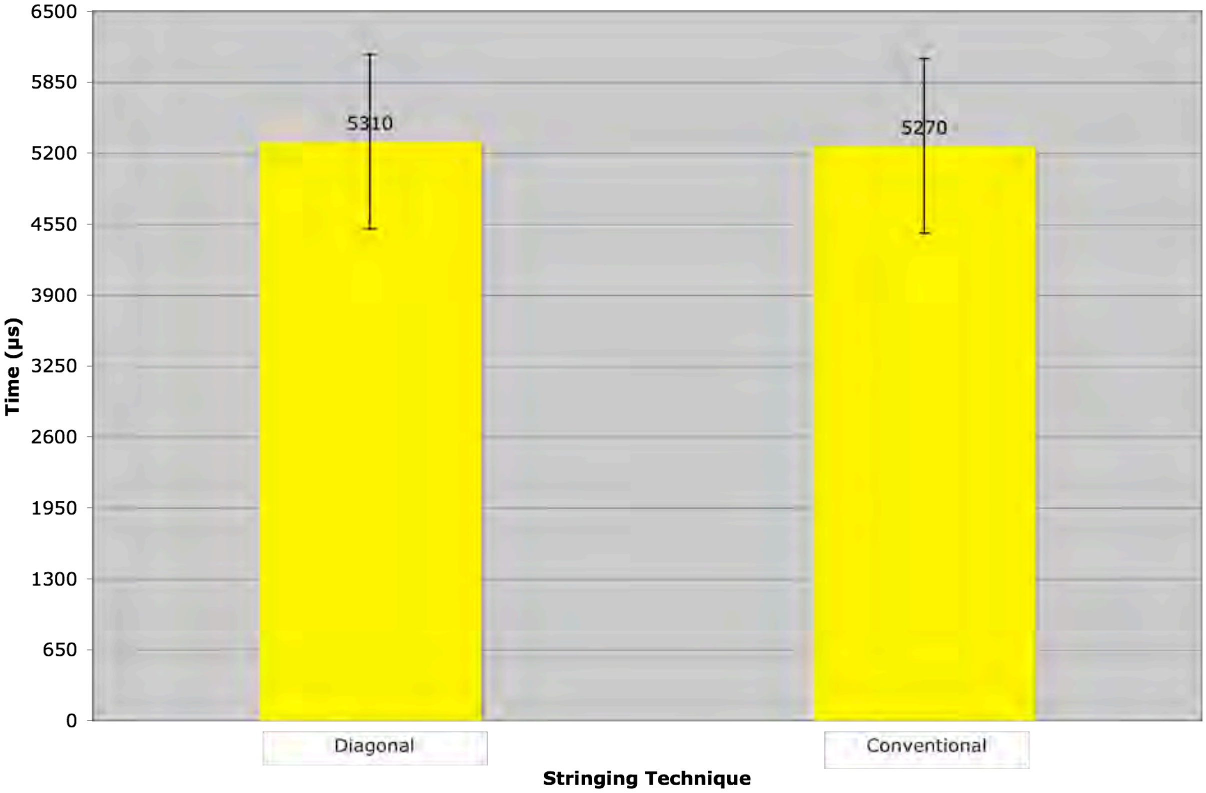


Figure 4.4 Comparison of ball control data for diagonally and conventionally strung tennis rackets. This value was measured as the amount of time the ball spent on the strings of each racket and was based upon the number of frames that the ball visually remained in contact with the tennis racket during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

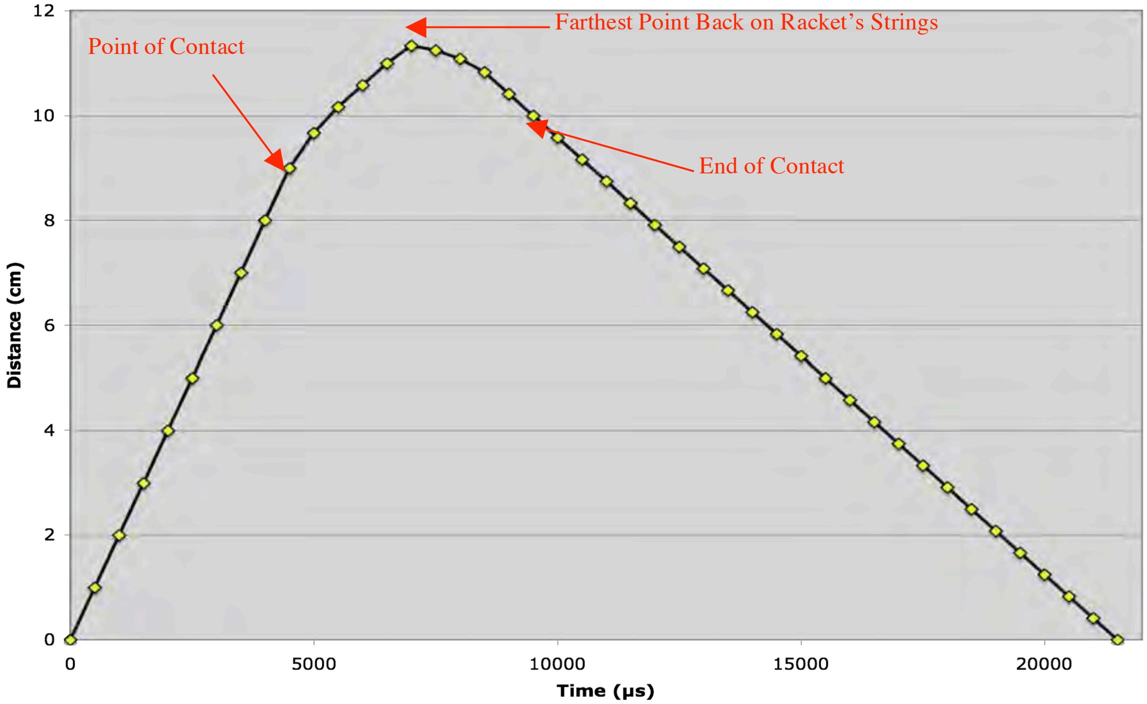


Figure 4.5 A sample position graph of *PowerAngle* diagonal stringing ball control findings. Labels indicate the location at which the tennis ball came in contact with the racket, reached it's farthest point back on the racket's strings, and left the racket. Within the present trial, the tennis ball stayed in contact with the racket's strings for 10 frames (5000 μs).

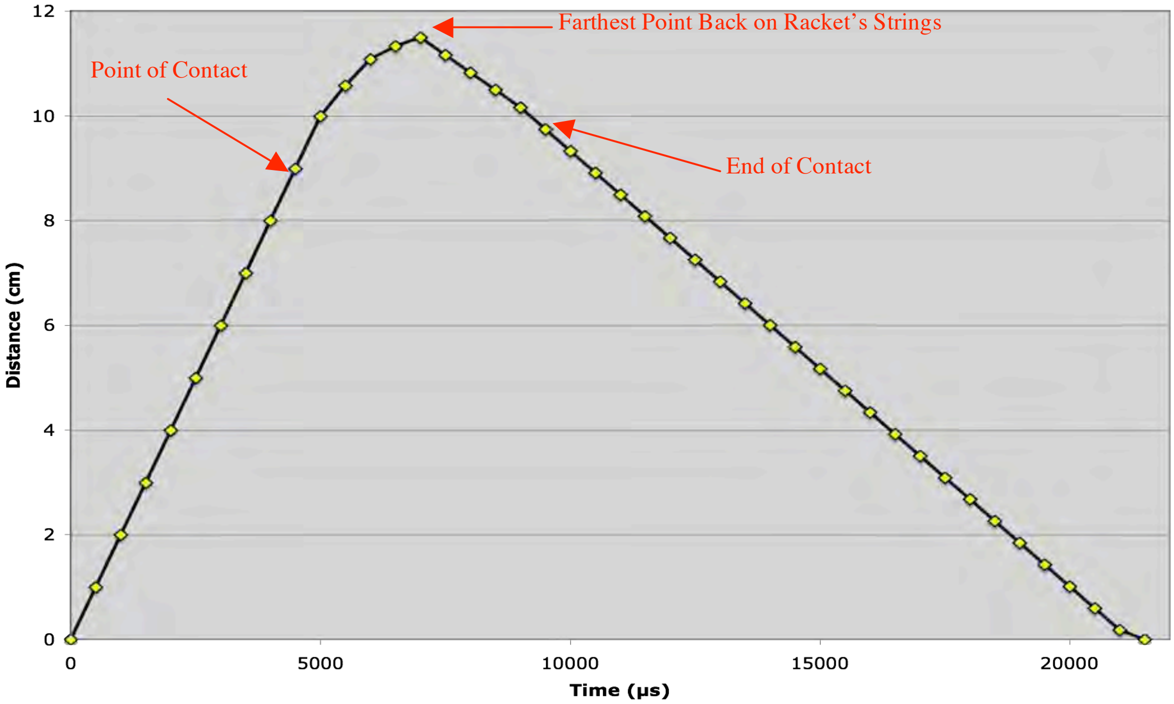


Figure 4.6 A sample position graph of conventional stringing ball control findings. Labels indicate the location at which the tennis ball came in contact with the racket, reached it's farthest point back on the racket's strings, and left the racket. Within the present trial, the tennis ball stayed in contact with the racket's strings for 10 frames (5000 μs).

Power

A tennis ball leaving a *PowerAngle* 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, *PowerAngle* diagonal stringing caused the tennis ball to travel at an average speed of 33.149 m/s (Fig 4.8) while conventional stringing brought about a speed of 32.877 m/s (Fig 4.9), a difference that was not statistically significant (p-value = 0.431).

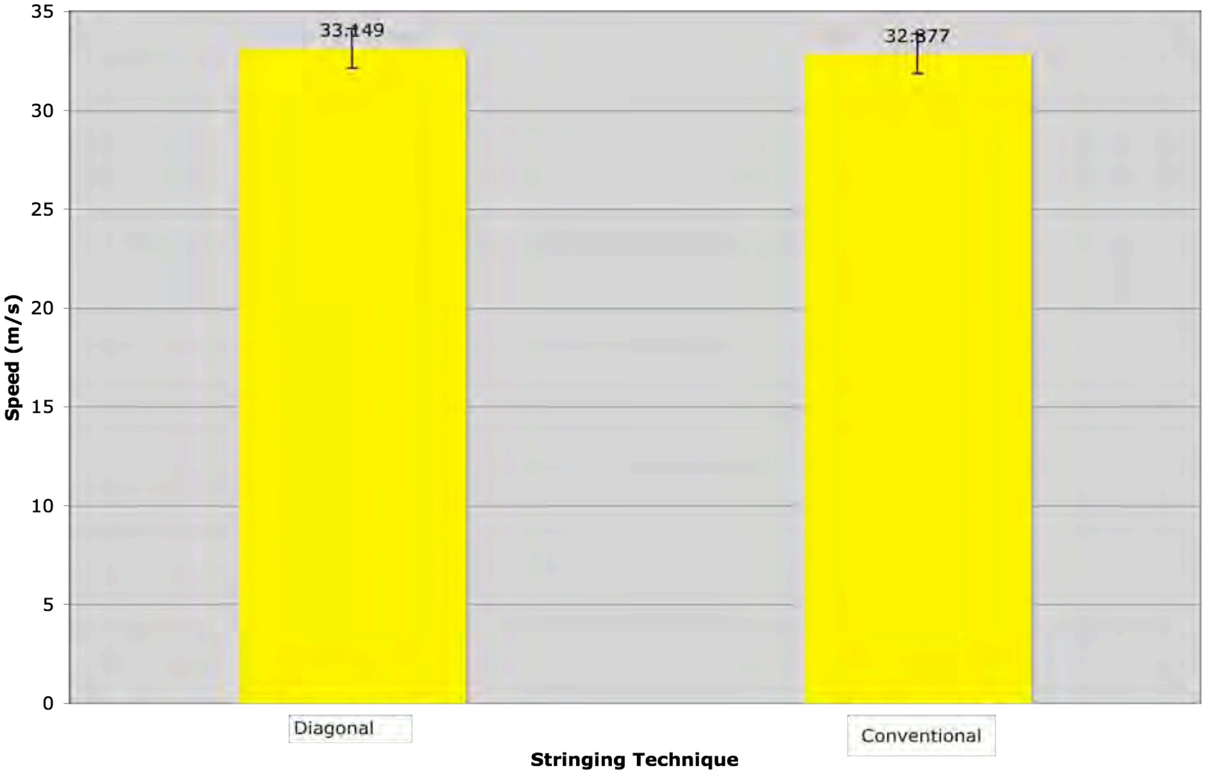


Figure 4.7 Comparison of power data for diagonally and conventionally strung tennis rackets. This variable was measured as the speed that the projected tennis ball left the face of the racket in each video. The number of frames necessary for the ball to travel 5 cm based upon the distance quantification grid in each high-speed video was used to determine this speed. *Power Angle* 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.

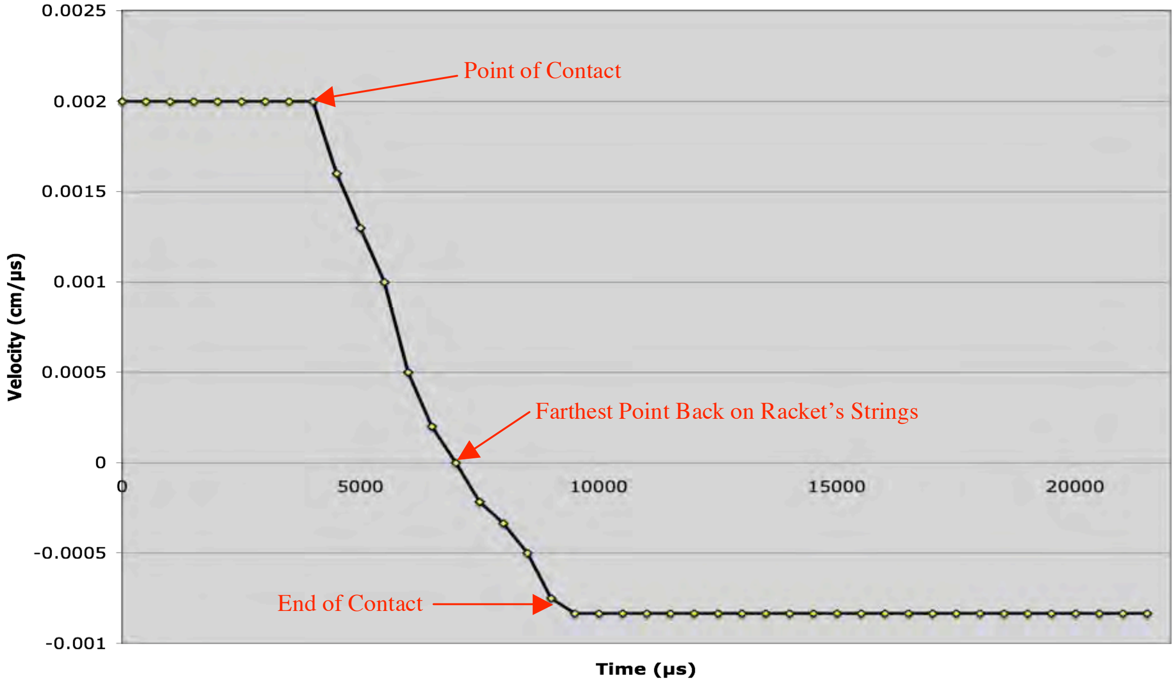


Figure 4.8 A sample velocity graph of *PowerAngle* diagonal stringing power findings. Arrows indicate the location at which the tennis ball came in contact with the racket, reached its farthest point back on the racket's string, and ended contact with the racket. Within the present trial, the ball's velocity began at 0.002 cm/μs (72 km/hr), and ended at -0.000844 cm/μs (-33.120 km/hr).

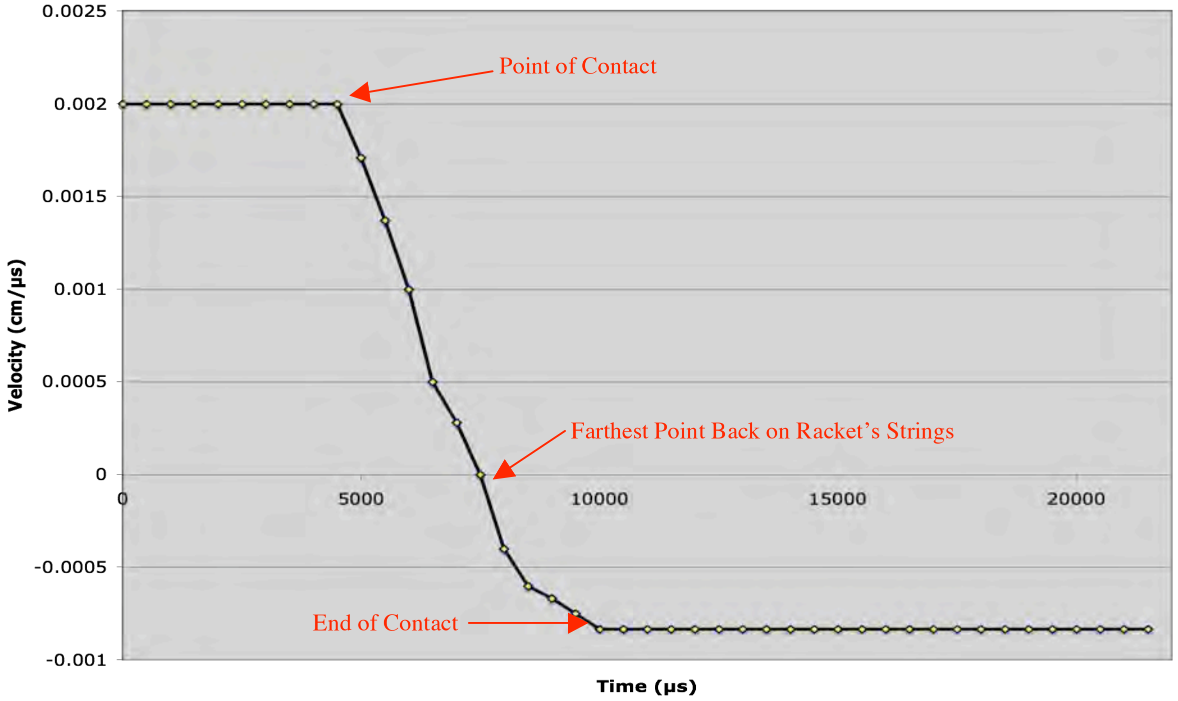


Figure 4.9 A sample velocity graph of conventional stringing power findings. Arrows indicate the location at which the tennis ball came in contact with the racket, reached its farthest point on the racket's strings, and ended contact with the racket. Within the present trial, the ball's velocity began at 0.002 cm/μs (72 km/hr), and ended at -0.00085 cm/μs (-33.395 km/hr).

Discussion

Within the present study, levels of vibration and overall performance of the *PowerAngle* 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 *PowerAngle* diagonal stringing as a variable in experimentation (Hauptman, 2000). 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 *PowerAngle* 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 *PowerAngle* diagonal stringing can reduce the amplitude of vibrations of a tennis racket by

39.72%. It can thus be inferred that *PowerAngle* 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 *PowerAngle* 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 *PowerAngle* 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 *PowerAngle* 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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