WSU Libraries
Student Research Excellence Award
Application Cover Sheet

Name: Ian Linde

Title of Paper/Project: The Four Causes of Energy Loss during a Tennis Stroke

Class standing: Sophomore

Major: Biochemistry and Philosophy

Contact information for faculty member supporting this application

Faculty member’s name: Linda Kittell

Faculty member’s department: English

Name of course for which work was completed: Honors Researching and Writing

Department and course number: English 298

When course was taken: Fall 2008

If I win the Award, I agree to contribute materials to an exhibit on my research for display in the WSU Libraries. I also agree that this paper will become the property of The Libraries; winning papers will be added to the WSU Research Exchange (online research and publication repository).

Signature: Ian Linde

Date: 3-1-09
I took a very unique perspective in my report on the physics of a tennis racket. Every source that I found studied specific aspects of tennis rackets, such as string tension, and analyzed their effect on the resulting motion of the ball when they were changed. This gave a very fragmented view of how tennis rackets worked, and it meant that anyone who wanted to do something specific, like increase the racket's power, would need to search through all of the research on the different characteristics of the tennis racket to find what changes to which characteristics would increase power. I synthesized all of this information and presented it in a completely different form. I started with one effect of tennis rackets on the motion of the ball, increasing ball speed, and defined four main categories of energy loss in rackets that influenced this speed. I then detailed specific changes to aspects of the racket that could affect these categories, resulting in an increase in ball speed. I was able to create this hierarchical description that unified the effects of each minor racket characteristic into several main categories, making it much easier to understand the relationships between all of these aspects and apply them to choosing a racket and playing a match.

In order to put together this unique perspective, I needed to synthesize information from a wide variety of sources. I began my project by narrowing my topic through various prewriting exercises that we did in class. The most helpful of these exercises involved writing out a complete list of possible topics and having classmates comment on them. I then took the best of these topic possibilities and searched Griffin and journal article databases for information about them. These searches brought up another topic that I found interesting, and after researching that topic, I stumbled upon my final topic, which was one that I had not even thought about initially.
By searching the library’s catalogs and databases for information that I found interesting, I was able to find a topic that I would not have been able to think of by myself.

After I had my topic, I went with my class to several sessions where research librarians explained how to use the library’s resources and gave us exercises to practice and improve our ability to use them. This turned out to be very helpful, since I used a wide variety of sources in my paper. The most helpful resource in my research was the library's access to databases that searched peer-reviewed journals, and I have continued to use these databases for many other classes. I also searched Griffin and checked out a bunch of books from the library, one of which was also a very important resource in writing my paper. Lastly, I used the microfiche machines to get information from three dissertations that I found on Griffin. All of these different sources from the library were invaluable in helping me create the unique perspective in my paper.

I learned a lot about tennis rackets during my project. As I said in my paper, although I played tennis, I knew very little about how the actual physics worked before I began my research. Pretty much everything in my paper was newly learned, but in order to put it in its final form, I had to read the many complicated physics articles, synthesize and order the information, and present it in a form that is understandable to the common person. I had initially planned to include the effect of a tennis racket on the ball’s trajectory and spin, but I soon realized that researching the effect on the ball’s velocity alone would be a large enough body of information to cover. So, a clear direction for future research would be to analyze the specific effects of the tennis racket on the tennis ball’s trajectory and spin. Together with my report about the effect on the ball’s velocity, this would create a very coherent, complete, and usable description of the physics of tennis rackets that anyone could read, understand, and apply to choosing a racket and playing the game.
Please indicate on a signed attached sheet your comments regarding how this student’s work meets the prize criteria. The panel is especially interested in your assessment of the originality and depth of this work, and the level of self-sufficiency demonstrated by this student in pursuing research.

Deadline for this letter of support is **February 29, 2008**. You may give your letter to the student for inclusion in his/her packet, or you may send it in campus mail to Beth Lindsay, 5610. You may email the letter to elindsay@wsu.edu to meet the deadline, but we will need a signed hard copy in addition.
18 February 2009

Dear Jurors for the WSU Libraries Student Research Excellence Award:

I am writing in support of Ian Linde’s application for this award. Ian was a student in my fall semester English 298: Researching and Writing course. He wrote this essay as his final project for the class and I find it to be an exceptional piece of work.

As many of you probably know, I like to work closely with the WSU librarians in this course. We usually meet in the library four times over the semester so that students can begin to learn the ins and outs of library research. For this paper, Ian accessed multiple library data bases for peer reviewed articles and searched Griffin for many book sources. He was excited to use microfiche for the first time and even more excited when he located three dissertations which helped him develop the depth of support shown in his essay.

The unique organization of his essay makes the challenging content of his essay more readable for a general audience and shows his “exceptional ability in locating, selecting, evaluating and synthesizing research materials.”

Through some of the in class exercises found in our text The Curious Researcher, Ian found suggestions from his classmates most helpful. That and work with WSU librarians showed Ian how research is very much a team effort. This and the amount of knowledge of tennis physics he gained through this project added to Ian’s enthusiasm for research in general and on his topic specifically. Additionally, Ian became fascinated by the intricacies of MLA citation form---something I see very rarely even in the Honors classroom.

I find the essay itself to be clearly written and well written, extensively researched and energetic. Ian is also clear about the direction his future research might take him, and excited about that too. As he wrote to me recently, “An obvious area of future research would be to analyze the effect of the racket on ball trajectory and spin, since I only focused on ball speed.”

I think Ian Linde’s research essay shows that extraordinary things come from extraordinary collaboration between our students and their peers, our library resources and librarians. Thank you for the excellent support you give both students and their teachers.

Sincerely,

Linda A. Kittell
Clinical Associate Professor
The Four Causes of Energy Loss during a Tennis Stroke

When I learned to play tennis, I was taught how to execute the basic strokes and how to use the seemingly illogical scoring system. However, when it came to choosing a racket, I was left on my own. I walked into a sports store and was confronted by a wall of brightly colored rackets. All made pseudoscientific claims about their superiority, but none gave much explanation about their features’ actual effect on play. There was a chart for choosing grip size, and some rackets contained a basic rating for beginner, advanced, or expert players, but there was no reason given for the ratings. Sadly, I ended up choosing a racket mostly by the price, the appearance, and the feel, which amounted to little more than swinging it around and making an uneducated, arbitrary choice. Even after several years of experience with several different rackets, I still did not know much more than when I started. I had heard that tighter strings provided more control and looser strings provided more power, but I was never given an explanation why. Besides, it seemed counterintuitive. I wondered how the physics of the tennis racket really worked and whether counterintuitive things like that were actually true.

Part of the reason why choosing a tennis racket can be so confusing is that in addition to the complicated physics that govern the racket’s performance, there is a wide variety of different variables to choose between. String tension, string type, frame size, and frame weight are just a few of the many properties that must be chosen to suit one’s style. While most studies look at how one or more variables affect different aspects of play, the sheer number of studies and
variables makes it difficult to see the big picture. This "cause-based" approach, where physicists start with individual variables and observe their result on the motion of the ball, does not fit well with the needs of normal tennis players. Players are concerned with how the racket plays and desire to know the variables that should be changed to give the racket a different property. If they want more power, they do not want to have to study each individual variable to see whether or not it affects the power. It is much more useful to start with the effect, the path of the ball after leaving the racket, and work backwards to determine the causes.

There are three things that govern the ball’s flight after leaving the racket: its velocity, its direction, and its spin. Of these three parts, the racket’s effect on the velocity, called the power of the racket, is the most complicated and the most worthy of study. Since the ball’s velocity depends upon the amount of energy that the racket transfers to it, reducing energy loss in four main areas will maximize the velocity imparted to the ball. These four areas are the energy dissipated in the ball and strings, the energy dissipated in the frame, the energy lost in the reduction of the kinetic energy of the racket, and the energy lost when the racket twists. In approaching the study of the racket’s power, one should first understand the importance of ball’s location on the racket during contact, and then one can look at the factors that affect the four main areas of energy loss. After doing this, one can create general rules and make recommendations on specific racket properties for different playing styles.

When I learned tennis, I heard talk of a sweet spot on the racket, which supposedly produced the best hit and felt the best. Consequently, one would try to hit the ball there. It turns out that there are actually four different spots on the racket head that can be called the sweet spot: the center of percussion, the node, the point with the maximum coefficient of restitution,
and the dead spot (Kotze, Mitchell, and Rothberg 72-73). Each one is in a slightly different place and produces a different result upon contact with the ball.

The center of percussion (COP) is the spot on the racket head that minimizes the initial shock to the hand during contact with the ball (Kotze, Mitchell, and Rothberg 73). One will know that the ball hit the COP if it feels like the ball jumped off of the racket without one really feeling it. When a ball strikes the racket head, it causes the racket to recoil with two types of motion. Translational motion causes the entire racket to move backward, and rotational motion causes the racket to rotate around its center of mass. When these two motions are combined, it causes the racket to pivot around a point in the handle of the racket. When the one’s hand is holding the racket at this point, the hand will turn as the racket pivots, but it will not be jerked forward or backward (Kotze, Mitchell, and Rothberg 73). If the pivot point is not under the hand, there will be a net force on the hand as it is pushed forward or backward when the handle rotates. The pivot point is determined by the combination of the translational and rotational motion of the racket, and this motion is determined by where the ball strikes the racket. The translational portion of the motion increases as the ball strikes closer to the center of mass and the handle of the racket, and the rotational portion increases as the ball strikes farther from the center of mass and closer to the tip. This means that for each location of the hand on the handle, there is a certain point on the head that will cause the racket to pivot around a point under the hand. This point on the head is called the center of percussion. Its location changes as the location of the hand on the handle changes.

According to Brody, one can find the center of percussion by holding the racket by two fingers at the point where one’s index finger would normally rest when gripping the racket. With the racket head pointing down, one should swing the racket back and forth like a pendulum
and measure the period of the swing, or the time for the racket to swing from one side to the other and back again. Then, by squaring the period and multiplying by 9.77, one will get the location of the COP in inches from where the racket was held. This point will lie on the central axis of the tennis racket. When the pivot point is four inches from the butt, the COP will generally be twenty inches from the butt, which is a little below the center of the racket head (Brody, Tennis Science 27-28).

The second sweet spot, the node, results from the fact that when a ball strikes a tennis racket, the racket begins to vibrate. In order to study these vibrations in a repeatable way, physicists have to use a way of gripping the racket other than a human hand. According to Kotze, Mitchell, and Rothberg, after much debate, scientists have found that the closest approximation to a human grip is a racket freely suspended from the handle. When a racket suspended in this way is struck with a ball, it begins to vibrate at a frequency between 100 and 150 Hertz. These vibrations are uncomfortable when they travel into one’s arm. However, the vibrations travel along the racket in such a way that they create two nodes, or places on the racket that do not vibrate because the waves of vibration cancel each other out. One of the nodes is on the handle of the racket, but the one of interest is near the center of the head of the racket, about a fifth of the racket length from the tip. If the ball strikes this point, it will create very little vibration at the 100-150 Hertz frequency, and the hit will feel much more comfortable (Kotze, Mitchell, and Rothberg 73).

Although there are other frequencies at which the racket vibrates that are not cancelled when the ball hits the node, they are much higher frequencies, so they dampen very quickly and are not very uncomfortable (Brody, Physics II 817). When the hand holding the racket is taken into account, the vibration is very similar to the free condition, but the frequency decreases by
about ten percent, and the node moves slightly toward the tip of the racket (Kotze, Mitchell, and Rothberg 78). It is also possible to find the node on the tennis racket. According to Brody, one should tape an index card to the end of the handle so that it extends past the butt. Then, holding the racket with two fingers five or six inches from the butt, one can hit the head with a ball or the butt of another racket. When one finds the spot on the head where the index card does not vibrate loudly, one has found the node (Brody, Tennis Science 30-33).

The third sweet spot is the spot on the head that provides the most power when hit. According to Kotze, Mitchell, and Rothberg, the power of a tennis racket is measured by what is called the coefficient of restitution (COR). The COR is the ratio of the force that the racket exerts on the ball when it regains shape to the force exerted on the racket that caused it to deform (Kotze, Mitchell, and Rothberg 68). There are two main components that contribute to the COR, the power from the strings and the power from the frame. These sources of power will be analyzed in depth later, but for now, it will be shown how they contribute to the location of the third sweet spot. According to Brody, the power provided by the strings is highest at the geometric center of the racket because that is where the strings deform the most upon the ball’s impact. The power from the frame is highest at the center of mass of the racket, which is in the throat of the racket, because the racket flexes least there and does not waste energy in doing so (Brody, Tennis Science 35). When these two factors are combined, the point with the maximum COR is on the head of the racket between the center of the head and the throat (Brody, Physics II 817). According to Brody, this third sweet spot can be found by clamping or holding down the handle firmly and dropping balls from the same height on different spots on the head. The spot where the balls bounce the highest is the point of the maximum coefficient of restitution (Brody, Tennis Science 36).
While finding the point with the maximum COR, it is possible that one will discover the fourth sweet spot, the dead spot. According to Kotze, Mitchell, and Rothberg, this is a spot near the tip of the racket that has a higher COR than the surrounding areas, although not as high as at the third sweet spot. Since hitting the ball at the dead spot causes large vibrations and does not provide as much power as the third sweet spot, it is not a good idea to hit the ball on the dead spot during normal play (Kotze, Mitchell, and Rothberg 72-73). However, it is a very good place to hit a serve for several reasons. One is that it is close to the tip of the racket, so the racket speed will be highest there, providing the most power, as will be discussed later. According to Cross, another reason is that during a serve, the effective mass of the racket at the dead spot is about equal to that of the ball. Due to conservation of momentum, when an object collides with a stationary object of equal mass, the first object will come to a stop and transfer all of its momentum to the second object. During the serve, the ball is stationary when hit, so the racket transfers all of its angular momentum to the ball, stopping until it is carried on by the momentum of the server’s arm. Contact at this point produces the maximum ball velocity during a serve (Cross, The Dead Spot 763-764). The dead spot can be found using the same method as for the third sweet spot, looking for the highest bounce near the tip of the racket.

Once one understands the importance of the location of the ball’s impact on the racket, one can look at the properties of the racket that influence the velocity with which the ball leaves the racket. This can be analyzed by the amount of energy transferred to the ball. The easiest way to approach the concept of energy transfer is to look at causes of energy loss and examine variables that can be changed to affect the amount of energy lost. There are four main ways in which energy is lost. Energy can be dissipated in the ball and strings, it can be dissipated in the
frame of the racket, the kinetic energy of the racket can decrease, and the racket can twist, losing energy in rotational motion.

Of the energy dissipated in the ball and strings, the majority is lost in the ball. Tennis regulations require that tennis balls bounce between 53 and 58 inches when dropped from 100 inches above concrete, meaning that tennis balls must lose about 45% of their energy when they rebound (Brody, How Would a Physicist 26). The tennis ball also regains its shape much slower than the strings, meaning that the ball has often left the racket by the time it regains its shape, preventing any energy that went into the ball’s deformation from contributing to its velocity (Kern 19). However, there is no regulation for how much energy the strings must lose, and strings naturally return 90-95% of the energy given to them (Brody, Tennis Science 9). So, this means that in order to conserve as much energy and have as much power as possible, the strings’ deformation should be maximized, and the ball’s deformation should be minimized.

The depression, or deformation, that is made in the strings when the ball strikes them is called the plane deformation (Brody, Tennis Science 6). Since increasing the plane deformation reduces the ball deformation and increases the amount of energy transferred to the ball, factors that increase plane deformation will increase the power of the racket (Brody, Tennis Science 9).

The most obvious way of increasing plane deformation is to decrease the string tension, since looser strings will deform more than tighter strings. Of course, there is a lower limit to the tension. Once the tension becomes loose enough that the strings start rubbing together during the hit, the energy lost from this friction counteracts the energy gained from the larger plane deformation (Brody, Tennis Science 9). It is worth noting that changing between the tensions that are normally used in tennis does not produce drastic results. Increasing the tension from fifty to sixty pounds will only increase the resulting serve speed by about 0.7% and the speed
from forehands and backhands by 1.1% (Cross, Flexible Beam Analysis 118). However, that little extra power can be significant in such a fast-paced game as tennis. It could be the difference between the opponent getting off a good shot or making an error.

The plane deformation is also influenced by the density of the stringing pattern, or the spacing between the strings. This functions in much the same way as tension, with higher string densities producing the same result as higher tensions (Brody, Tennis Science 19). So, choosing a racket with a lower string density will increase power just like lowering the string tension.

Another major way of increasing the plane deformation is by increasing the elasticity of the strings, or the amount that the strings will stretch. There are several different factors that affect the elasticity of the strings and the resulting plane deformation. One factor is the length of the strings, referring to the distance along the strings from one edge of the frame to the other. As the strings' length increases, the material available to be stretched increases, so increasing the length of the strings increases the elasticity. Practically, this means two things. First, a racket with a wider head will have a longer string length and a higher plane deformation. Second, the center of the racket will have a higher plane deformation than areas closer to the frame, since the strings that pass through the center are the longest strings (Brody, Tennis Science 6-7).

A second factor that affects string elasticity is the diameter, or gauge, of the string. According to Kern, larger gauge, or smaller diameter, strings will stretch more, creating a larger plane deformation than smaller gauge strings. However, he found that the increased elasticity of higher gauge strings is only significant when the racket’s frame is very stiff. This is because the energy necessary to cause the increased deformation of higher gauge strings will go into bending the racket frame, which will be described later, unless the frame is stiff enough (Kern 95). The reason that higher gauge strings are more elastic is that there is less material in the cross-
sectional area that needs to be stretched. The effect is evident by comparing how far a thick rubber band will stretch for a given force compared to a thinner rubber band.

A third factor influencing string elasticity is string composition. The main types of string composition are gut, nylon, and polyester. Although there are different types of nylon string, according to Cross, Lindsey, and Andruczyk, there is little difference in their elasticity, and none of the nylon strings overlap with gut and polyester string in properties. Gut is the most elastic string, polyester is the stiffest or least elastic, and nylon lies in between (Cross, Lindsey, and Andruczyk 229). However, the advantage in elasticity that gut has over other string compositions decreases as the string length increases (Brody, Tennis Science 16). Generally, though, gut will maximize the plane deformation and thus the power of the racket.

The age of the string will also influence its elasticity. As string ages, the bonds inside it begin to slide and break, and the string stretches out permanently, decreasing its elasticity (Brody, Tennis Science 18-19). Strings stretch out a lot after first being strung on the racket and after the first hours of play, decreasing in tension and elasticity. This stretching continues indefinitely but slows down to the point where it is hardly discernable except over long periods of time (Cross, Lindsey, and Andruczyk 220). Since older strings have had more time to stretch and break bonds, they are less elastic than newer strings. However, the difference in the energy lost between old and new strings when tested is almost negligible (Cross, Flexible Beam Analysis 120).

The last direct influence on plane deformation after tension and elasticity is the velocity of the ball-racket impact. As the velocity increases, the plane deformation decreases. This may seem counterintuitive, but it is because the frame bends more with higher impact velocities, and the energy goes into the bending of the frame instead of the deformation of the strings
(Goodwill). So, lower velocities increase the plane deformation. Of course, this small effect on power is most likely cancelled out by the large increase in power resulting from the increased kinetic energy that gets transferred to the ball at high contact velocities. Still, it is interesting to note the negative effect that high velocity has on plane deformation due to the bending of the frame. This brings one to the second main way that energy can be lost during the hit: energy dissipation in the racket frame.

There are two ways that energy is lost in the frame of the racket. It is dissipated by vibrations, and it goes into bending the frame. Although there are effective ways of decreasing the frame bending and gaining more energy, there is not much that can be done to prevent the loss of energy due to vibrations. Although using dampeners, decreasing string tension, decreasing contact velocity, increasing racket flexibility, and hitting the ball at the node seem to reduce vibrations, they do not increase the energy significantly. Anyway, the loss of energy due to vibrations is fairly negligible, and even effectively preventing this loss will not significantly increase the power of the racket.

Dampeners, in fact, do not even reduce vibrations. All they do is cause the vibrations to dissipate quicker, making the hit more comfortable but not preventing the loss of energy. There are two types of dampeners. According to Brody, the tiny ones that rest on the strings serve to reduce the much higher frequency string vibrations that are around 500 Hertz, but they are much too small to dampen the lower frequency frame vibrations which are the main cause of energy loss in vibrations. Some rackets are also made with dampeners in the frame, which may help to dissipate the vibrations, but the best dampener is still the human hand. Gripping the racket tightly is the most effective way of dampening the vibrations (Brody, How Would a Physicist 28-29). In order to increase the energy, however, one must find a way actually to reduce vibrations.
Next, there are three ways to reduce frame vibrations, but one will find that none of these can be applied practically to increase energy. By decreasing the tension, the vibrations are reduced (Cross, *Flexible Beam Analysis* 111). This is because lower tensions create higher plane deformations, which cause a less jarring hit and absorb more of the energy that would normally go into vibrations. So in this case, decreased vibrations are actually a result from a process that already increases the energy, and not a factor that can be altered to increase energy. Another way to reduce vibrations is to reduce the contact speed of the racket and ball, since the vibration amplitude increases with increasing velocity (Brody, *How Would a Physicist* 28). Of course, this cannot be applied practically either, since one cannot control the incoming speed of the ball, and reducing racket speed will cause a much greater loss in energy than would be gained from the reduced vibrations. Additionally, increasing the flexibility of the frame will reduce vibrations (Brody, *Tennis Science* 54). This will cause the frame to deform more instead of vibrate upon impact, but since frame deformation is a much bigger source of energy loss than vibrations, this is also an impractical way to increase energy.

There is one practical way to increase racket energy by reducing vibrations. This is by hitting the ball at the second sweet spot, the node, which will prevent any vibrations at the racket’s fundamental frequency. However, since vibrations are such a small source of energy loss compared to other factors, the power gained by hitting the node and preventing the vibrations is not noticeable (Cross, *The Dead Spot* 764). Any energy that would be gained because of this could be dwarfed by energy gained from the higher plane deformation that also occurs when the racket is struck at the node, since the node is very close to the center of the racket. Regardless, aiming to strike the ball at the third sweet spot, the point with the maximum coefficient of restitution, will provide more power than aiming for the node.
The much larger cause of energy loss in the frame is the frame deformation, or bending. When the ball strikes the racket, the racket bends and returns to its normal shape in fifteen milliseconds, but the ball only remains on the racket for about five milliseconds, so the energy that went into the frame deformation cannot be transferred back to the ball (Brody, Tennis Science 35). In order to prevent this loss of energy, the frame must be made stiffer, preventing it from bending as much and losing as much energy. The increase in energy resulting from a stiffer frame is especially evident for impacts near the tip of the racket, where the most frame deformation normally occurs (Cross, Flexible Beam Analysis 121). There are several ways to increase frame stiffness.

The most obvious way that the stiffness of the frame can be increased is by changing the composition to a stiffer material. Since current rackets are made from so many different materials and composites of materials, it is difficult to rate compositions in order of stiffness. Tennis players today generally do not pay too much attention to the actual composition of the racket, but instead choose rackets according to the properties resulting from the composition, such as stiffness and weight. So, it is easiest just to test the rackets’ stiffness by trying to bend them rather than trying to judge them based on composition.

Frames can also be made stiffer by increasing their thickness, which is intuitively obvious, since thicker things are always less flexible than thinner things of the same material. Some rackets vary the frame thickness throughout the racket, increasing the thickness near the tip to counteract the naturally greater tendency for rackets to bend toward the tip, which occurs because the tip is the farthest point from the racket’s center of mass (Brody, How Would a Physicist 29). The shape of the cross-section of the frame can also be varied, and some shapes possess less flexibility than others. Again, the best way to test this is by physically bending the
racket. Finally, increasing the tension of the strings can also increase the stiffness of a racket (Kern 2). This occurs because when the frame bends, it increases the distance that the strings have to travel to get from one side of the head to the other, since they have to follow the bend of the racket frame instead of a straight line. Since this stretches the strings, the strings exert a force that resists the bending of the frame. Increasing the tension of the strings will exert a stronger force that resists the bending of the frame, increasing the stiffness of the racket.

Lastly, energy lost in frame deformation can be reduced by striking the ball closer to the throat of the racket. According to Brody, since the racket’s center of mass is in the throat, it will not bend when it is struck at that point. Instead, it will just move backward from the force of the impact. As the ball strikes closer to the center of mass, less energy will go into bending the racket (Brody, Physics III 984). So, striking the ball closer to the throat reduces frame deformation and maximizes energy, which is why the point with the maximum coefficient of restitution is close to the throat of the racket.

The third main way that energy can be lost when hitting a tennis ball is through the loss of the kinetic energy of the racket, which is the energy that the racket possesses due to its motion. One who is familiar with basic physics will know that kinetic energy results from the mass times the velocity squared. This means that while both increasing mass and increasing velocity will increase kinetic energy, increases in velocity will have a much larger effect on the energy than increases in mass. So, if mass is increased but too much velocity is sacrificed, the kinetic energy will decrease. There are also two kinds of kinetic energy: linear kinetic energy, which is due to the motion of the racket in a straight line, and angular kinetic energy, which is due to the motion of the racket around a pivot point. Depending on the path of the stroke, the racket can have one or both types of kinetic energy when it strikes the ball. Higher total kinetic
energy upon impact will result in higher amounts of energy transferred to the ball, increasing the power.

Before analyzing the kinetic energy of a racket, one must understand several terms. Most people are familiar with the linear terms mass and velocity, which are more commonly heard as the weight and speed of the racket, respectively. However, angular kinetic energy uses the angular equivalents of mass and velocity. The angular equivalent of velocity is easy to understand. It is angular velocity, measured by the rate at which the angle formed by the racket changes as it passes around the pivot point. The angular equivalent of mass is called the moment of inertia, and it is a bit more complicated. According to Brody, the moment of inertia of a tennis racket is found by dividing up the racket into pieces and finding the sum of each piece’s mass times its distance from the axis of rotation raised to some power. There are different moments of inertia corresponding to the different powers to which the distance is raised. The zero moment would be equivalent to the weight of the racket, since the distance would be raised to a power of zero, making it one. The first moment, or static moment, is found by multiplying each point of mass times its distance from the pivot point, which in this case is the hand. This is how heavy the racket feels when it is held by the handle (Brody, Player Sensitivity 145).

There is one more moment of inertia, the second moment, which is found by multiplying each point of mass times its distance to the axis of rotation squared. However, depending upon which axis of rotation is used, the second moment can represent different values. One possible axis is the axis perpendicular to the handle and in the plane of the racket head. This is the axis that the entire racket rotates around when swung, or the axis that would run through the length of one’s body if one held the racket out with the head perpendicular to the ground and turned one’s body in place. This value is called the swing weight, and it is how heavy the racket feels when
one swings it. It is also the value that is used to calculate the angular kinetic energy. The other important second moment is obtained when the axis of rotation runs along the handle of the racket. This is the axis that the racket rotates around when one twirls the racket by twisting the handle. This value is called the polar moment, and it represents the weight of the sides of the racket head when the racket spins. This value is not used in calculating the racket kinetic energy, but it is useful for things that will be discussed later (Brody, Player Sensitivity 145).

Returning to kinetic energy, angular kinetic energy is most common in tennis strokes, since the racket generally is moving in an arc, rather than in a straight line, due to the natural motion of the arm. The two ways to increase angular kinetic energy and thus increase the energy imparted to the ball are by increasing the swing weight, one of the second moments of inertia, and by increasing the angular velocity. According to Brody, the swing weight is increased by shifting or adding mass to a point farther from axis of rotation, which will cause an increase in power when swung at the same velocity. One can either look for a racket with a high swing weight or add lead tape to the head of an existing racket to increase the swing weight. However, if the addition of weight causes a very large decrease in velocity, this will reduce the power, since velocity has a much larger effect on power than swing weight (Brody, Player Sensitivity 146-147).

A more effective way to increase the racket's angular kinetic energy is to increase its angular velocity, since kinetic energy is proportional to the square of the velocity. There are ways to increase the angular velocity other than just swinging harder or using a lighter racket. While applying the same amount of force to the racket, or swinging just as hard in other words, swinging it in a tighter arc will increase the angular velocity (Brody, How Would a Physicist 30). Since the tennis ball leaves the racket with a linear, not angular, velocity, it would be helpful to
understand the relationship between the racket’s angular velocity and linear velocity. The angular velocity of a point on the racket head can be translated to linear velocity by multiplying the angular velocity by the distance from the point to the axis of rotation. This means that for a given angular velocity, a point closer to the tip of the racket will have a higher linear velocity than a point closer to the handle, transferring more kinetic energy. This is why it is better to hit a serve close to the tip of the racket in the dead spot than in the area of the maximum coefficient of restitution. This is also the cause of the interesting phenomenon in which the point with the maximum coefficient of restitution is moved closer to the center of the racket when the stroke makes a tight arc (Brody, Physics III 984). In this case, the higher velocity of that point on the racket overcomes the greater flexibility that would normally decrease power. So, by increasing the angular velocity by using a lighter racket or swinging in tighter strokes, much more energy can be imparted to the ball. This kinetic energy increases as the ball strikes points farther from the handle.

Although it is not likely, the tennis racket could be moving nearly linearly when it strikes the ball. In this case, the racket’s mass times the square of its linear velocity would determine its kinetic energy. These linear terms work just like their angular equivalents, so increasing mass would have the same effect on the linear kinetic energy as increasing the swing weight would have on the angular kinetic energy. As long as it does not decrease the velocity, adding mass will increase the kinetic energy. According to Brody, some physicists also thought that by gripping the racket tightly, one could effectively add the mass of one’s arm to the mass of the racket, increasing the power. However, he determined by experiment that the effective mass added would only be about forty grams, which is not enough to increase the kinetic energy significantly (Brody, How Would a Physicist 29). This is because one is not able to grip the
racket tightly enough to keep it from shifting in one’s hand upon impact. This means that it will act like its own entity rather than a part of the arm with a greater total mass. The linear velocity also works the same way as the angular velocity, and it has a much bigger effect on the kinetic energy than the mass. All tennis swings are arcs, so the only reason that the velocity would be linear would be if the swing had straightened out from an angular velocity. Since all linear velocities would be derived from angular velocities, it means that the factors that increase angular velocity would also increase linear velocity. So overall, one can focus on maximizing the angular kinetic energy because it will also maximize the linear kinetic energy in case the racket happens to be moving linearly at the time of contact. This maximization will increase the power of the racket.

However, there is a source of lost racket kinetic energy that has not yet been discussed. Since human fatigue decreases the velocity of the racket over the course of the match, minimizing the fatigue caused by a racket will maximize its kinetic energy over time. Fatigue can come from two areas: the racket’s weight and the forces transferred from the racket to the arm during impact. Excessive weight in the racket will cause one to tire quickly. Since the racket is swung in an arc, it is specifically the swing weight that will contribute to fatigue (Brody, Player Sensitivity 146). To minimize fatigue, one should make sure to choose a racket that does not feel too heavy when swung.

The forces on the arm come from two sources, the recoil and the vibrations from the ball striking the racket. The recoil of the racket, as discussed briefly in regard to the center of percussion sweet spot, occurs because the ball’s impact causes the head of the racket to jerk backward. When the racket pivots around a point that is not under the hand, the hand either gets jerked forward or backward, depending upon the location of the pivot point. Since the hand will
move with the racket but the elbow will not, the forces on the elbow cause fatigue and potentially tennis elbow over time. The easiest way to minimize this force and the resulting fatigue is to hit the ball at the center of percussion as discussed earlier, which will cause the racket to pivot around a point under the hand and remove any net forces from the hand. However, there are two other variables that can reduce the force on the hand. Gut string was found to transfer more force to the hand than nylon string, so using nylon string will minimize the force on the hand and the resulting fatigue (Larson 3). Also, increasing the frame flexibility decreases the force on the hand because it causes the frame to bend instead of jerking the hand forward or backward (Larson 3).

The other forces on the hand come in the form of vibrations, which can cause fatigue in the hand and arm, loosening one’s grip and slowing one’s arm over time. As explained before, using dampeners, decreasing string tension, decreasing the contact velocity, increasing the racket flexibility, and hitting the ball on the node all help to reduce the vibrations reaching the hand. If one wanted to increase the frame flexibility without losing too much power, one could get a racket with a stiff frame and a more flexible handle, since a flexible handle will still dampen vibrations without causing as big of a loss in power (Brody, Tennis Science 54). Also, one should remember that string dampeners will do nothing to reduce the low frequency frame vibrations, and so they will not decrease the forces on the hand. By choosing and combining any of those factors, one can settle on a racket type that reduces vibrations according to one’s needs and preferences, preventing loss of kinetic energy from fatigue.

The final way that energy can be lost and decrease the power of the racket is when the racket twists in one’s hand during the hit. This occurs when the ball strikes the racket off of the racket’s central axis, with the most twisting occurring when the ball strikes closest to the edge of
the racket. Since it takes energy to twist the racket, all of the energy that gets used to do this is unable to be used to propel the ball, decreasing the racket’s power. There are two ways to prevent this twisting: increasing the polar moment of inertia and increasing the friction force on the handle.

As discussed earlier, the polar moment of inertia is the weight of the edges of the racket as they spin around the axis that runs through the handle. By increasing the polar moment, the racket has more weight at the edges, providing more resistance when the racket tries to twist and reducing the amount of twisting. As a reminder, the polar moment is found by multiplying the mass of the side of the racket by the square of its distance from the central axis, which is the axis of rotation in this case. According to Brody, the polar moment can be increased by adding weight to the edges of the racket or by widening it, increasing the distance to the axis of rotation. Since the distance is squared, the best way to increase the polar moment is by widening the head of the racket (Brody, How Would a Physicist 29). An increase in width by 25% will increase the polar moment by about 50% (Brody, Tennis Science 40). However, weight can also be added to the sides with lead tape as mentioned before, and some tennis rackets are made with extra weight in the sides of the racket to increase the polar moment (Brody, Player Sensitivity 146). By choosing a racket with a wider head and more weight in the sides of the head, one will reduce the amount of energy lost due to twisting, maximizing the racket’s power.

The other way to reduce racket twisting is by increasing the friction force applied on the handle by the hand. According to Brody, the equation for the force that friction applies to keep the racket from twisting in one’s hand includes three terms multiplied together. They are the force of the hand pressing on the handle, the diameter of the handle, and the coefficient of friction of the handle, which is a measure of how much friction the handle material will create
for a given applied force. Increasing one or all of these will increase the friction force and reduce the racket’s twisting. It is obvious how to increase the force of the hand on the handle. Gripping the handle tighter will reduce twisting. It is also simple enough to increase the coefficient of friction, which would entail making the handle drier, stickier, or rougher. Using an overgrip would accomplish this. Since larger handle diameters increase the ability of the friction force to stop the twisting of the racket, it would seem that one should choose the largest diameter handle. However, using a handle with too large of a diameter will cause the loss of more energy through fatigue, so it is best only to use as big of a handle as is comfortable (Brody, Tennis Science 59). By increasing one or more of these factors, one can increase the racket’s power by decreasing the amount it twists upon impact.

Bringing all of this information together, one will find that there are a set of dichotomies that work as general rules for tennis rackets. Since it is not possible to maximize every aspect of a racket, one must make choices about the relative importance of different properties. The three main dichotomies are power versus control, performance versus comfort, and performance versus practicality. By assessing the importance of each one of these properties, one can arrive at general recommendations for different playing styles.

Although control, or the ability of the racket to produce the desired direction, velocity, and spin on the ball, was not analyzed, a basic understanding and logical approach will show that there is often a dichotomy between power and control. Most things that maximize power will negatively impact control. For example, lowering tension decreases control for several reasons. Lower tension increases plane deformation, causing the ball to rocket off of the strings much more unpredictably than if the strings had higher tension and acted more like a solid panel (Brody, Tennis Science 10). The ball also remains on the strings longer at lower tensions, giving
the racket more time to twist and change the direction in which the ball leaves (Brody, Tennis Science 10). So it turns out that the saying that higher tension increases control while lower tension increases power is true. As a player, one has to choose whether it is more important for one to maximize one’s power or one’s control. By choosing to change different variables, one can vary the extent to which the power and control are affected, customizing the racket to one’s own playing style.

Although there is one main variable that increases both power and control, it falls into the second dichotomy of performance versus comfort. Increasing the stiffness of the frame will maximize both power and control, but it will significantly reduce comfort by causing increased vibrations and a larger force on the hand from the ball’s impact. Generally things that significantly increase the racket’s performance, whether it is by increasing the power, control, or both, will reduce the comfort. This may seem trivial compared to higher performance, but low levels of comfort can become important. If the comfort is reduced enough so that it causes fatigue, it may start to reduce both the power and the control. Also, the forces and vibrations that cause discomfort can lead to injuries such as tennis elbow. Once one has been injured, one’s power especially is severely reduced, and it possibly could never be the same. So, one must judge one’s tolerance of discomfort and predisposition to injury when one is choosing between most variables that increase performance.

Although there are also variables that maximize both the comfort and the performance, they will generally fall into the last dichotomy between performance and practicality. Things that seem to be the best of all worlds, like higher gauge string and gut string, are more expensive, less durable, and generally only have a significant effect under high-level conditions such as high string tension and high impact velocity. Higher gauge string will increase the power and control
as well as increase the comfort by reducing the force transmitted to the hand. However, it is much more likely to break, requiring backup rackets and frequent restringing. It is also expensive and only is noticeably different from lower gauge string at high tension and impact velocity (Brody, Tennis Science 14). Gut string has similar properties. It is less resistant to humidity and moisture damage than other string compositions, it is more fragile, it is more expensive, and it has the largest effect at high-level conditions (Brody, Tennis Science 14). The differences between gut and other string compositions are also reduced as the string length increases in rackets with wider heads (Brody, Tennis Science 16). So, when deciding between average and high-performance variables, one must discern whether the higher performance aspects will have a significant effect when combined with one’s playing style and whether the effect is enough to justify their increased price and fragility.

In making recommendations to different style players about racket properties, there are a couple of different approaches that can be taken. Obviously, players who want more power should choose the aspects that maximize power, and players who want more control should be careful not to choose aspects that negatively impact control. However, power players may choose to sacrifice a little power in the racket to increase control, since they are capable of producing high ball velocities without too much help from the racket. There are generalizations that can be made, though. Players can be divided into two different styles: baseline players and serve-and-volley players. Baseline players rely mainly on powerful shots from the baseline, while serve-and-volley players have a strong serve and like to approach the net. Baseline players should choose rackets that maximize power and may be slightly slower with a higher moment of inertia. Serve-and-volley players should choose rackets that are lighter and easier to maneuver since serves depend highly on racket speed and volleys require quick reactions and
maneuverability. Since they generally rely more on finesse than baseline players, serve-and-volley players should also maximize the racket's control instead of its power. Players that fall somewhere in between these two categories should employ the combination of factors that best fits their style. By weighing control against power and performance against comfort and practicality, players should customize their rackets to fit their personal playing style.

Having a basic understanding of the physics of the tennis racket allows this customization. This understanding was made possible by starting with the velocity of the ball, analyzing the four main causes of energy loss during the stroke, and working backward to arrive at the variables that can be changed to affect this energy loss. This comprehensive approach provides a much more workable knowledge than the fragmented knowledge obtained by analyzing each variable individually. This same approach can be used to analyze the effect of the racket on the direction and the spin of the ball, which when combined with the effect on the velocity of the ball, will provide the complete picture. By applying this knowledge of physics to racket choice and decisions on the court, one will be able to improve one's performance.
Works Cited


