Energy Efficiency in Tennis Ball and String Contact

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Contents

1 Abstract

The purpose of this paper is to detail the progress that has been made towards understanding how energy is conserved in tennis racket stringbeds during contact with a tennis ball. The ultimate goal was to determine how string tension and material would impact energy dissipation between input swing energy and output kinetic energy of the ball. The study began with a static analysis and then progressed to a dynamic analysis. The results showed that a racket stringbed exhibits effective energy efficiency during contact when compared to a solid metal surface. However, the extent that tension and string material affected that efficiency could not be well defined. In addition, the ABAQUS/Explicit model used to compare empirical results to showed there were flaws in the assumptions made for the design of the simulation, and also imply that the mechanics of a real stringbed are more complex than the simulation could model.

2 Introduction

Understanding the interaction between a tennis racket and a tennis ball is vital for optimizing a racket configuration to meet the needs of a player. However, the racket strings themselves merit more attention than they receive in the interaction process, as they are the point of direct contact for the ball. Much of this is due to the difficulty of modeling and gathering data on string behavior and material properties, since tennis strings are viscoelastic and susceptible to effects like creep and stress relaxation [1]. In addition, strings are put in a weave configuration in the racket, which makes them particularly complex to model. However, this does not mean their importance should be neglected; they allow the player to adjust the spin and power they create in a more cost-effective manner than by purchasing a new racket, and those effects can be adjusted greatly. In particular, the power that can be generated by a shot depends on the ability of the stringbed to deflect, as it reduces the amount of deformation the ball undergoes as it changes directions, thereby reducing the largest source of energy dissipation in a shot [2]. This deflection can be measured by a variety of factors including, but not limited to, string tension, cross-sectional area, material, and stringing configuration. By understanding how each of these variables affect the stringbed's ability to deflect, players can use this information to optimize the amount of energy efficiency they wish to maintain in their stringbed.

The goal of this study was to quantify how two of the most readily customizable aspects of a racket stringing, the string material and the stringing tension, affect the overall energy loss during contact with a tennis ball. The process for accomplishing this was twofold; first, an ABAQUS finite element analysis was developed to capture the behavior of a tennis ball impacting a stringbed. This was done by initially using ABAQUS/Standard to make sure the string modeling was adequate using T3D2 truss elements without a weave in the strings, as other research models had done previously [3]. By comparing those results to empirical static load testing done in tandem, the validity of the method could be confirmed for the subsequent step of the analysis, using ABAQUS/Explicit for dynamic loading with a tennis ball using Mooney-Rivlin material properties and S4R shell elements. The second portion of the process was to run energy conservation tests using ball drops from specific heights to determine how the racket tension and string material affected the energy dissipation at contact. By comparing the results from the ball drop tests with those from the dynamic analysis, the effect of those variables on energy loss could begin to be quantified as a percentage of the total energy initially in the system. Due to the viscoelasticity of the string materials, the changes in height for the ball drop played an important role in determining whether the increase in the initial energy of the system led to any significant increases in energy loss as a percentage of the total initial system energy. Any increase in that percentage of energy loss would indicate that the velocity at which the ball and strings contact each other plays an important role in the stringbed's ability to deflect. In addition, tensile testing was done on two different string types (synthetic gut and polyester) so that their moduli of elasticity could be applied to the ABAQUS/Explicit simulation and provide the most accurate results possible.

3 Procedure

3.1 Initial ABAQUS/Standard Progress

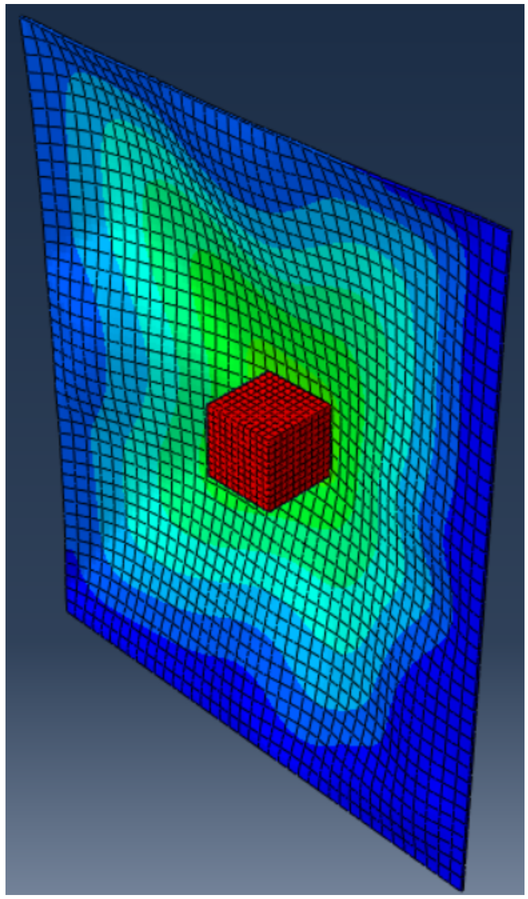


Figure 1: Initial contact model using a rigid cube against a thin metal sheet. Displacement condition was applied to the cube into the sheet to create the deformation seen.

The first step in this process was to develop a better understanding of how a complete model in ABAQUS would work, which would ultimately end up being a ball contacting a stringbed. To begin this process, the models started off fairly simple. Figure 1 shows the first model that was attempted in ABAQUS to mimic the interaction between a ball and a stringbed, which ended up being a rubber cube that was displaced into a thin steel sheet. The colors in the figure indicate the displacement into the z axis, the axis of actuation. The sheet in this model behaved as expected, however the cube displaced uniformly instead of deforming too. This was because the displacement condition on the cube was applied to the entire cube, which removed any reaction response when contacting the sheet. To fix this issue in future models, a partition was created on the part contacting the stringbed on which the displacement condition was applied.

Progressing into the next stage of modeling, the strings needed to be represented by elements with their behavior. This was where some of the most important decisions occurred early in the study, as there were numerous aspects which needed to be considered.

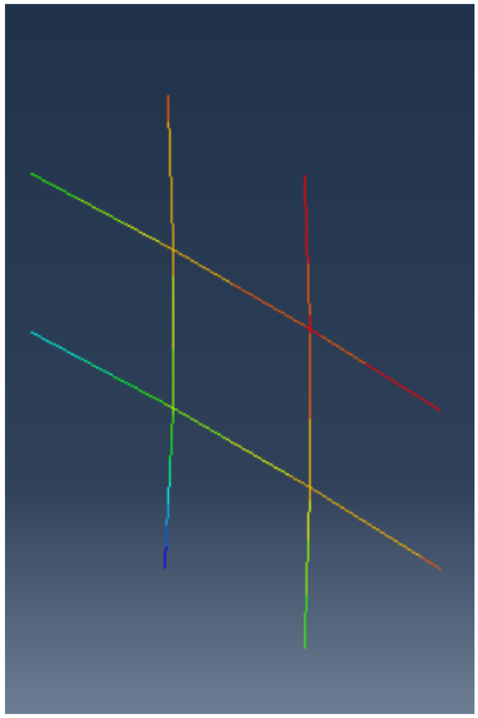


Figure 2: T3D2 truss elements under tension and transverse loading. First step applied a tension load onto the end nodes on the left and top two strings, then the next step applied a load normal to the strings at the four string intersections.

The primary concern was the weave pattern in the strings. Due to technical limitations and shortcomings in ABAQUS understanding, the strings would have to be modeled without a weave. The importance of this cannot be understated, as it becomes an assumption in the comparison between the testing and FEA that the weave itself doesn't play a significant role in the structural integrity of the stringbed. However, by making that assumption, it eliminates the need to create the part in 3D space for analysis with very specific contact conditions between strings. The second decision was which element the strings should be modeled with. The first option was to continue to model the strings using a sheet, but apply orthotropic properties whereby the hybrid material would be string-reinforced air. The other option was to model the strings using 3D truss elements, a method used by the study mentioned earlier. After experimenting with both possibilities, T3D2 elements were selected because of the simplicity required to implement them and the ease with which loading and boundary conditions could be applied to the model. In addition, they are more precisely adjustable, allowing for greater specificity in stringing configuration. The latter point is important for modeling in comparison to experimental testing, as this model was expanded until it matched the racquet stringbed that was used for testing.

The final progression for the FEA modeling was to create a ball which would behave like a tennis ball. The ball ended up using S4R shell elements with the dimensions of a tennis ball and a hyperelastic rubber with Mooney-Rivlin material properties, in addition to an internal pressure. Figure 3 shows a view cut of such a ball after contact with a steel wall, where the colors indicate the total deflection in the axis of actuation (z-axis). As can

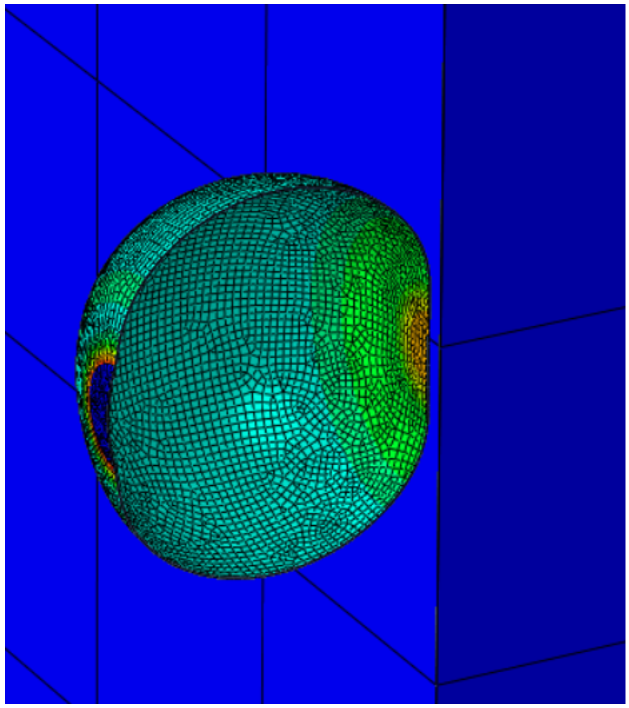


Figure 3: A rubber tennis ball using S4R shell elements contacting a steel wall, cut along the x-axis to show the ball deformation. The displacement condition was applied to the left side of the ball, which is indicated in the blue section on the ball (left side). The simulation ran with non-linear geometry so that it could deform as pictured.

be seen, the ball behaves as expected, expanding parallel to the wall where it can no longer displace into the direction of actuation. By this point the combination of the ball and the T3D2 truss strings could be made into a single contact model, which will be discussed later in this report.

3.2 Static Transverse Loading

To set up a test which could be modeled in ABAQUS, the key was to make sure that the strings were isolated as much as possible. The simplest way to test string deflection was to set up a static loading condition on the stringbed and measure the deflection from the weight. Figure 4 shows a Wilson Six.One 95 racket secured about the frame with a deflection meter placed directly underneath. The racket was strung with a tension of 0 lbf, according to an electronic stringing machine, meaning that the strings were pulled taut but not prestrained before testing. Weights were then applied on top of a small piece designed to reduce the surface area of the load applied to the stringbed as much as possible, but without compromising balance. Each weight would deflect the stringbed further, at which point the meter would be checked (precision of 0.001") to create a load v. deflection plot.

This test was repeated for three scenarios, the first using a polyester string and the second using a synthetic gut material. The last used a racket strung up with mains only, meaning that there was no support in the strings from the crosses. This was done using the polyester string. All of the stringing configurations used a 16 gauge string and were done

Figure 4: Test setup in the machine shop. The racket frame was stabilized with two metal blocks of equal dimensions at the top and another at the handle, with a vice action securing the center of the frame. The deflection meter can be seen positioned directly underneath the center of the stringbed.

using the same model of racket.

3.3 Ball Drop Experiment

Until this point, all of the testing and analysis was completely static and mainly served to determine how well the ABAQUS model could simulate a tennis racket stringbed and a tennis ball. The next step was to move from a static to a dynamic environment, which is where the tennis ball and racket stringbed interaction would occur. Especially due to the viscoelasticity of the strings, it was important to see if those effects became more prominent as velocities at contact increased. As the ultimate goal of this study was to determine how much of an effect the tension and string material played in energy losses during contact, the key to designing a dynamic test was to find a method by which an energy state before and after contact could be easily measured, thus allowing for a quantified energy loss as a percentage of the total energy in the system. The simplest way to do that was to use gravity to capture the potential energy of a tennis ball before and after hitting strings by dropping it from a specified height and then measuring the height it ended up at after reaching its second apex.

To set up this ball drop test, the first step was to position a video camera (in this case an iPhone 10) on a tripod as far as possible away from the test itself. The primary reason for doing this was so that the error in measuring the position of the ball due the angle of the camera and where the ball appears on the ruler (a phenomenon known as parallax) could be reduced to the greatest extent feasible. The next step was to clamp the tennis racket being tested to a table to eliminate any energy losses due to the frame itself as opposed to from

Figure 5: Ball drop analysis using Tracker software to analyze the ball speeds and displacement. The racket was constrained to a table using clamps, and the ball was lifted to a specified height using a frame of reference set up behind the racket. The software would then use that reference for calibration to track the displacement of the tennis ball during the drop.

the strings. Then, after positioning the ruler immediately behind the racket, a tennis ball was dropped from three specified heights; 50 cm, 100 cm, and 150 cm. This was done a total of six times for each height, and then repeated for rackets of three different tensions; 40 lbs., 50 lbs., and 60 lbs. of tension. By changing both the heights and the tensions, the effect of an increase in energy (and thus speed) at contact could be observed in the energy losses. Using the Tracker video analysis software, the ball's displacement and momentary velocity could be determined as seen in Figure 5. Then the potential energy in the system could be measured by

$$PE = mgh$$

where m was the mass of the tennis ball in kg, g was the gravity constant $9.81\frac{m}{s^2}$ and h was the height of the ball. The kinetic energy in the system could be measured by

$$KE = \frac{mv^2}{2}$$

where m is the mass of the tennis ball in kg, and v is the velocity of the ball in $\frac{m}{s}$. The percent loss of energy after contact was measured by

$$Perc.Loss = \frac{PE_f}{PE_i} * 100$$

where PE_f and PE_i are the final and initial potential energy states of the system, respectively.

3.4 ABAQUS/Explicit Analysis

In departing from static analysis, the new ABAQUS model for the ball drop scenario would need to be done in ABAQUS/Explicit, an environment specifically suited to dynamic analysis. Where ABAQUS/Standard solves for every increment of a finite element analysis by solving for the displacement of each node in a system by running an inverse matrix solution, ABAQUS/Explicit solves for the same system by using many increments which solve for the displacement of each node only as it relates to the nodes surrounding it. This has some benefits and drawbacks; the primary benefit is that it can run iterations much faster than its Standard counterpart, and thus makes it well suited to dynamic scenarios. However, it is also much more fragile due to the matrix math only accounting for each node by the nodes surrounding it, as opposed to every node in the system. This means if the increments are too large, an inaccuracy from one node could propagate throughout the simulation, thus rendering the results useless. To be sure that Explicit could be used to analyze the ball drop scenario, it was first used to compare results from the Beer and Johnston textbook Mechanics of Materials [4].

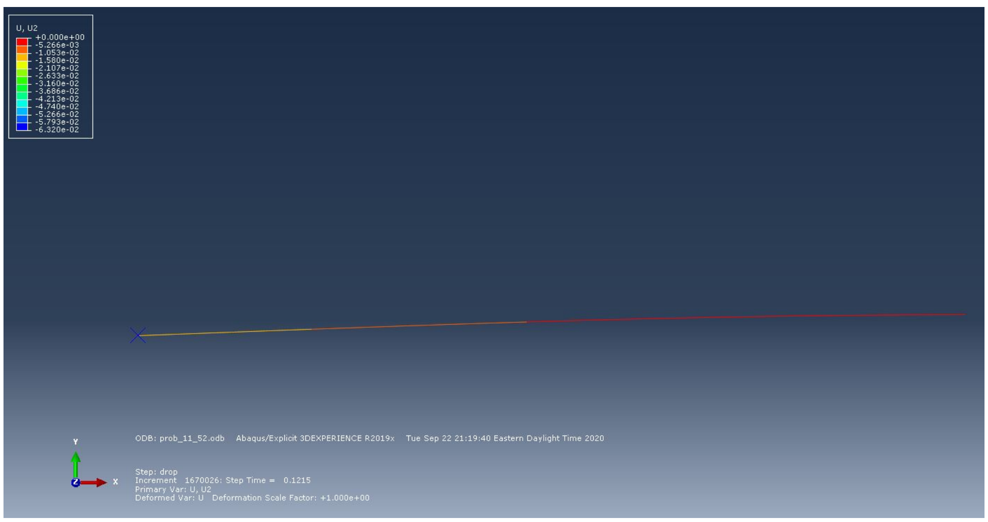


Figure 6: ABAQUS/Explicit model of problem 11.52 in Beer and Johnston. A weight was dropped from a specified height onto the end of a cantilever beam and the maximum deflection of the beam was then measured. The results were compared to established beam energy theory for the same problem to confirm that the ABAQUS/Explicit results were accurate.

After running three different example problems (like that found in Figure 6) and finding the results to be comparable to those found in the book, an Explicit model was created based on the static analysis made previously. It used T3D2 truss elements for the strings and S4R shell elements with Mooney-Rivlin material properties for the tennis ball. The only major departure from previous models was the use of a predefined velocity field to give the ball a velocity towards the stringbed, as well as an output velocity field to measure the velocity of the ball immediately after contact. The tension in the strings was applied using a stress field on the string elements, while the material of the strings was applied using the elastic modulus of the string as found through tensile testing.

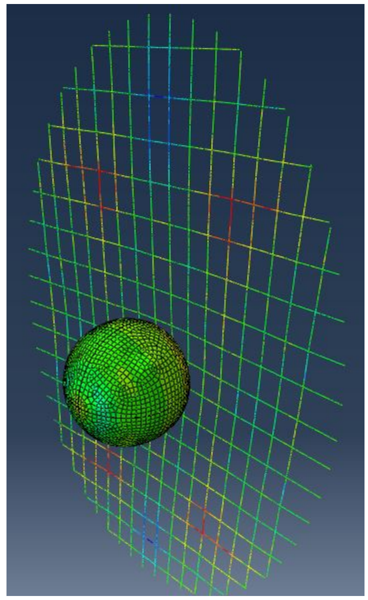


Figure 7: Final ABAQUS/Explicit model, implementing S4R shell elements and Mooney-Rivlin material properties for the ball and T3D2 truss elements for the strings. A predefined velocity field was used for the ball's speed before contact, and a velocity field output measured the velocity of the ball after contact. A stress field was applied to the stringbed.

3.5 Tensile Testing

To determine the elastic modulus for each string material tested, a tensile test was done using the MTS machine in the Union College Mechanical Engineering Department. A strand of each string material was cut and then clamped in the machine, at which point a constant speed was applied to the machine's operation such that the string would not be prone to snapping due to the viscoelasticity. Once the machine surpassed the maximum tension it would be expected to reach (60 lbs.), the machine was stopped and the results were converted to a csv file. The engineering strain was found by

$$\epsilon = \frac{\delta}{L_o}$$

where δ is the final deformed length of the string, and L_o is the original gauge length. The engineering stress was found by

$$\sigma = \frac{P}{A_o}$$

where P is the load and A_o is the cross-sectional area of the string before being axially loaded. Both were calculated applying the data from the MTS machine, and a stress-strain curve was developed for each material. Using a first-order polynomial line of best fit, applied to the part of the plot where the string would be in the range of tensions expected in the stringbed, the slope of the polynomial was used as the elastic modulus of the string material.

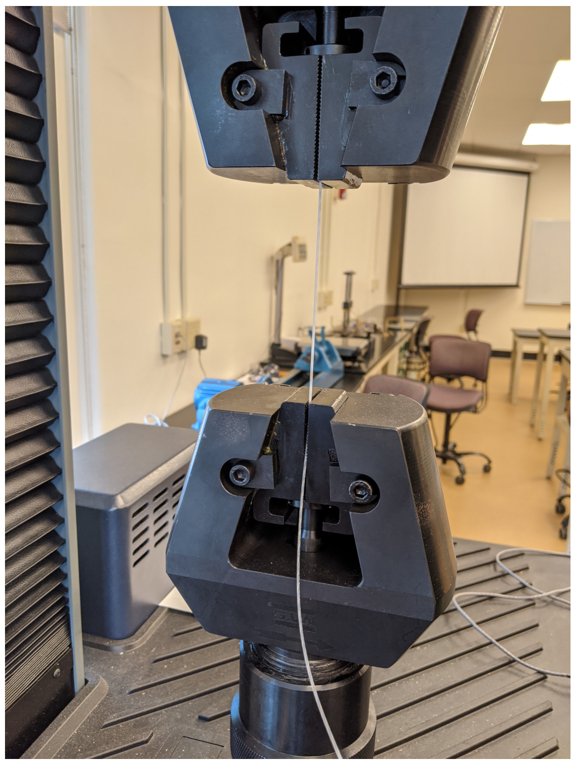


Figure 8: Tensile test done clamping a thread of string on both ends and increasing the force using a constant speed. Displacement of the machine quantified the strain.

4 Results

4.1 Static Analysis

4.1.1 Experiment Results

After completing the deflection testing in the shop, a load v. deflection plot was put together to compare results.

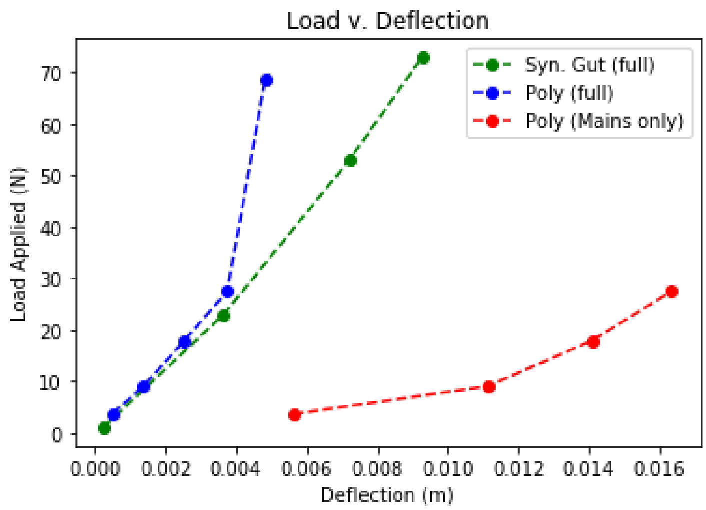


Figure 9: Results from machine shop deflection testing. The fully strung rackets with polyester and synthetic gut string material are shown in blue and green, respectively. The red shows the polyester string in the mains of the racket only (lengthwise).

As can be seen in Figure 9, the fully strung rackets exhibited similar behavior at lower transverse loads, but began to differ greatly in deflection once the loads increased. In contrast to the fully strung rackets, the racket strung with mains only had effectively no resistance to loads, and even in the data that was gathered, the applied loads had to be balanced since the stringbed had no ability to keep the weights upright. This is illustrated by the incredibly high deflection and the respectively low weight applied to the strings for that test before it broke down entirely. For the fully strung polyester stringbed, the maximum weight of 68.83 N yielded a deflection of 4.83 mm, while the synthetic gut stringbed yielded a deflection of 9.02 mm for a maximum weight of 73 N. This shows a higher resilience for the polyester string at higher loads.

4.1.2 ABAQUS/Standard

To complement the experimental testing completed on the racket stringbeds, an ABAQUS quarter symmetry model was created under the same loading conditions as the experiment. Seen in Figure 10, the model sets up conditions in multiple steps, first employing a specified tension, then applying a transverse load. The material properties of the string used linear elastic Nylon with the cross-sectional area of a 16-gauge string (1.5 mm diameter). For the sake of comparison with the experimental results, the tension was initially set to zero.

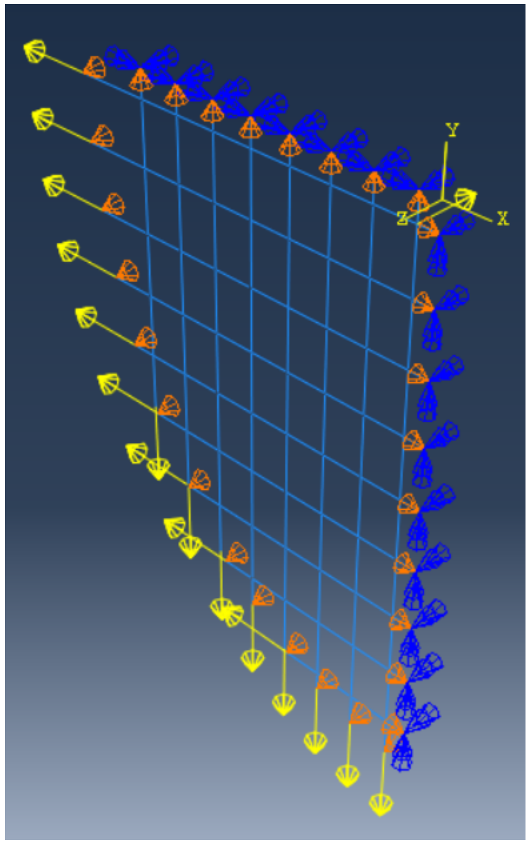
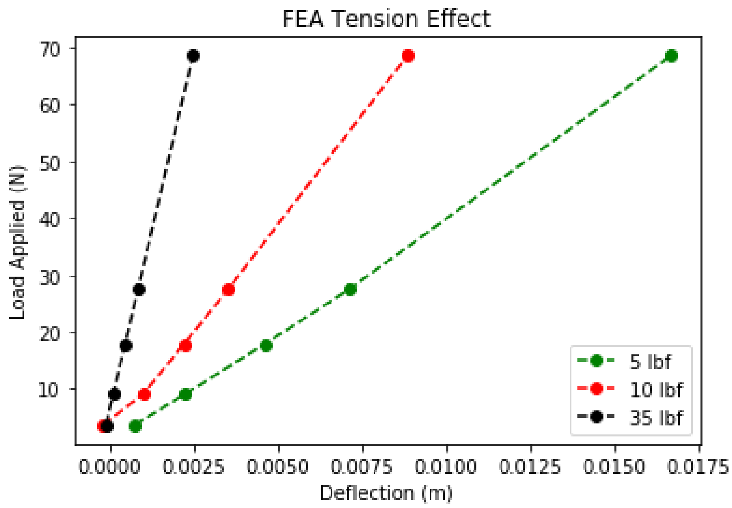
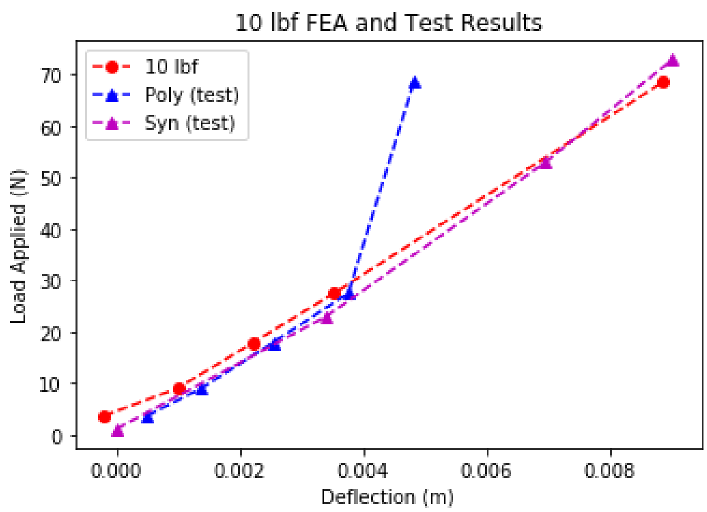


Figure 10: Quarter symmetry model of the experimentally tested stringbed. Symmetry conditions were applied to the top and right of the strings, at which point the same loading conditions and steps were employed for this model as were for Figure 2. The tensions and transverse load were adjustable as needed, with the latter being applied to a single point in the model such that a full representation would show four points of loading. All loads applied were divided by four to compensate for this.

However, due to a practically non-existent deflection resistance, the job failed, so the next job was then run with tensions greater than zero. Using the same loading conditions as the experiment, the simulation showed the effect of tension on the deflection in the model, and showed how tension variations compared to the actual test results.



(a) How tension affected the static loading simulation.



(b) An overlay of a 10 lbf. tension with test results.

Figure 11: Load v. deflection plots showing how different tensions affect the resulting deflection and how the 10 lbf FEA model compared to the test results for fully strung racquets, respectively. Figure (a) shows a clear relationship between string tension and deflection as expected, while Figure (b) suggests that either the FEA model is not accurate or that there was unknowingly tension in the test strings

As can be seen from the preceding figures, changing the tension greatly varies the deflection resistance the strings exhibit. At a maximum load of 68.83 N, the maximum deflection measured was 16.7, 8.86, and 2.48 mm for 5, 10 and 35 lbf tensions, respectively. In Figure 9, the 10 lbf tension job was compared to the test results for the fully strung polyester and synthetic gut strings, and as can be seen, the results for the synthetic gut line up with the FEA results, while they also line up with the polyester string at lower loads.

4.2 Dynamic Analysis

4.2.1 Ball Drop

After completing the ball drop tests, the average heights were calculated and then used to compute the change in potential energy in the system after the ball contacted the racket stringbed. Figure 12 shows the results of that analysis.

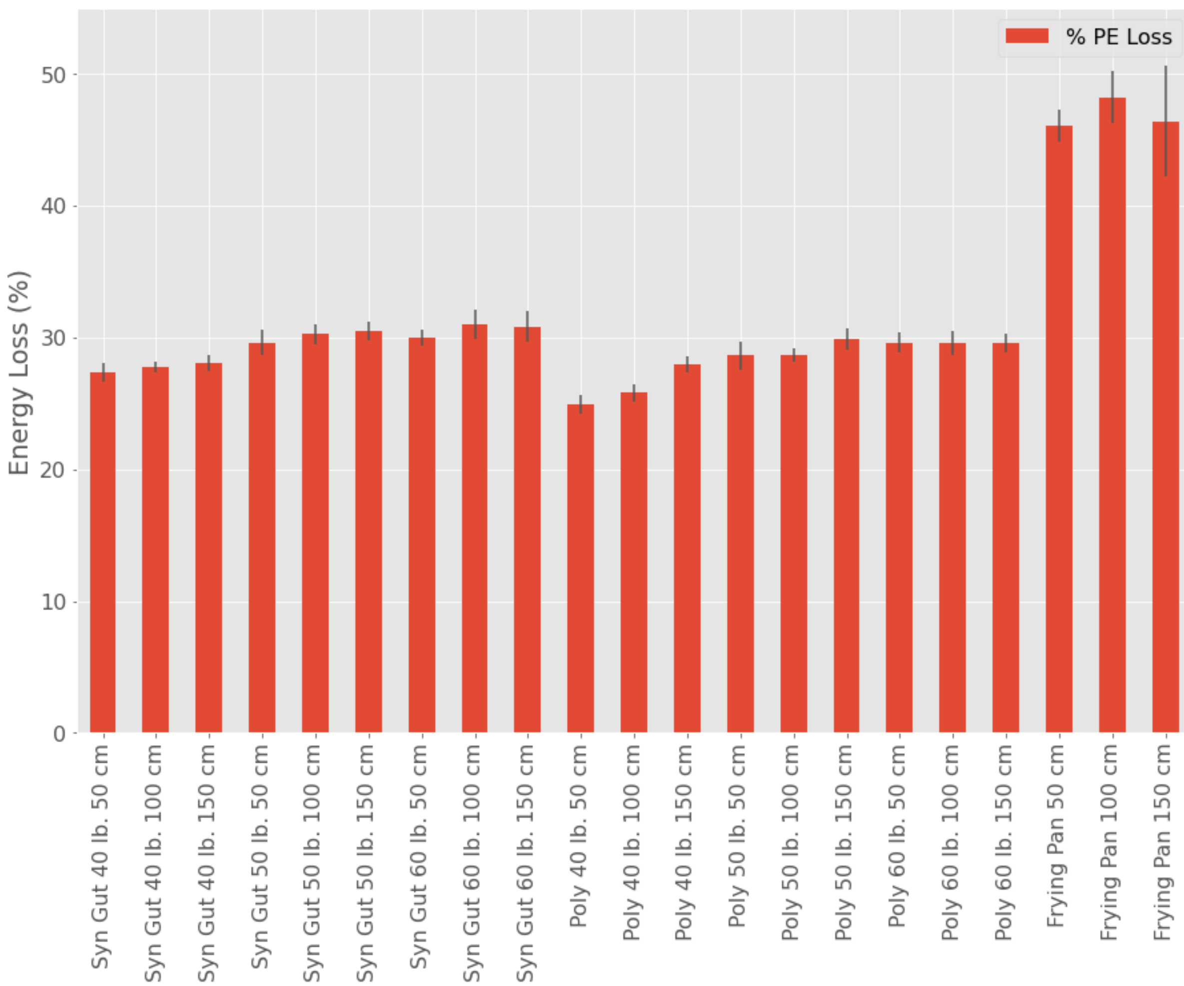


Figure 12: Average energy losses from six trials of each ball drop test as a percentage of the total energy in the system. While the differences between the stringbeds themselves were almost negligible, the large drop in energy from contact with the frying pan by comparison shows that any of the stringbeds will conserve more energy during contact.

As can be seen, the most notable observation to be made from the figure is how the stringbeds differed from the frying pan. Unsurprisingly, while only the synthetic gut 60 lb. tension exceeded an energy loss greater than 30%, the frying pan energy losses for all three initial energy states neared 50%, showing clearly that a conventional racket stringbed consistently exhibits greater energy conservation capacity than a solid metal surface. Surprisingly, although the polyester string had a Young's modulus more than twice that of the synthetic gut, the difference in results between strings (and tensions) was so small that it could be considered statistically insignificant. This suggests that either there was a lack of consistency in the testing, a shortcoming in the assumptions made for the test, or that the effect of tension and material on stringbed energy efficiency are not quantifiable under the test conditions.

4.2.2 Finite Element Analysis

For the ABAQUS/Explicit simulation of the testing scenario, different material types for the stringbed were adjusted based on their elastic modulus measured from the tensile testing. For the synthetic gut and polyester, the elastic modulus values were 2556 MPa and 5585 MPa, respectively. For each simulation, the velocity of each node on the ball was averaged for every step in the simulation, at which point, since there was no acting gravity on the tennis ball after contact, the average velocity for the last nine frames of the simulation was taken and averaged. The resulting average value was then converted into an exit kinetic energy, and thus with the exit and initial kinetic energy, the energy losses for each scenario could be calculated and compared with the testing energy losses, as seen in Figure 13.

The figure is telling primarily in that it suggests there are some major flaws in the assumptions made for the simulation itself, as the Explicit analysis consistently and significantly underestimates the energy losses occurring in every contact scenario. This could be occurring for a variety of factors within the simulation, including the environmental factors left out and how the model itself operates with the lack of a weave and a tennis ball made of shell elements. Later sections will break down the different possible factors.

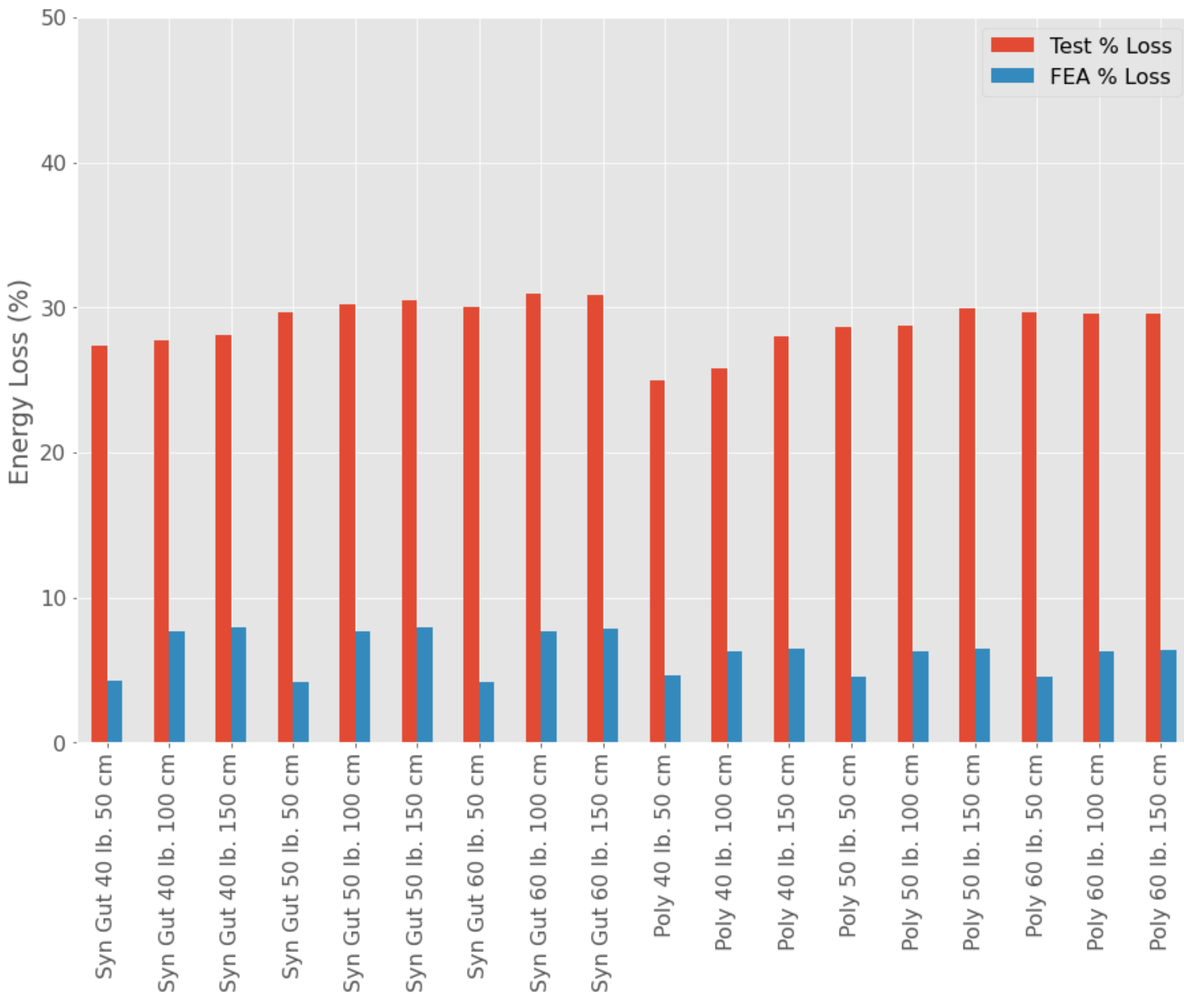


Figure 13: Comparison of FEA and Ball Drop test results for each test scenario run. The disparity between the FEA (blue) and the test results (red) suggest some major flaws in the FEA model design which would lend themselves to underestimating the energy lost during contact.

5 Discussion

In analyzing the results, the first step was to differentiate between what could be determined from the results vs. what could not be determined. A separate limitation analysis was done to determine what factors may explain the lack of definitive answers to certain questions posed regarding the study.

5.1 The Importance of the Trampoline Effect

The first expected outcome from the results was that a generic stringbed has energy conservation properties well suited to contact with a tennis ball compared to a solid surface. This outcome was based on the theory that ball deformation is the greatest source of energy dissipation during contact. By comparing the racket stringbeds to a frying pan in the ball drop test, the hypothesis is unsurprisingly supported by the test results.

The best explanation for this phenomenon is that the frying pan would have the least of a "trampoline" effect; this is where the deflection of the acting stringbed at contact would determine how well the tennis ball's shape is maintained during the interaction. The greater the deflection in the stringbed, the better retention of shape the ball maintains. Since the frying pan (a solid metal surface) would exhibit much less deflection during the contact than a stringbed, the ball would have a larger degree of deformation, thus resulting in a higher energy loss. With the disparity seen in Figure 12, this is undoubtedly the most reasonable explanation for the nearly 20% increase in energy loss for the frying pan in comparison to the racket stringbeds. From that conclusion, it would then follow that any factor within the stringbed itself which may affect the degree of trampoline effect the stringbed has would define how well the stringbed conserves energy at contact. This leads to the second expected outcome of the study.

5.2 Viscoelastic String Properties

The second expected outcome was that the viscoelastic properties of the tennis strings would play a greater effect on energy losses as the initial energy of the system increased. The theory behind this is that as the velocity of the ball immediately before contact increased, the resistance to the force applied would increase on the part of the strings, and thus create less of a trampoline effect to conserve energy in contact. In particular, the hypothesis was that the lower the elastic modulus of the string material used, the greater that effect would be, since initially the energy conservation would be greater at low speeds due to the theoretically better trampoline effect. Thus, that same string would also see greater potential for energy losses as the speed of the ball before contact increased.

While the viscoelasticity may have had some effect on the results, they mostly refuted the hypothesis initially posed due to the lack of significant difference in energy losses between testing scenarios. Since the results only fail to support the original hypothesis, it remains uncertain what could explain how the results actually turned out. What was most surprising was that the lower elastic modulus found in the synthetic gut did not seem to make much of a difference from an energy conservation aspect. It is very possible that for the velocities and tensions the test was run at, any viscoelastic effects occurring from the string may not have been pronounced enough to impact the results. This will be explored in the limitations section, however under these conditions it appears a reduction in trampoline effect due to viscoelasticity cannot be confirmed.

5.3 FEA Modeling Accuracy

The last outcome expected was that a T3D2 truss structure (effectively a net) would be adequate to model a stringbed interacting with a tennis ball, but that the effect of viscoelasticity would inhibit the accuracy of those results. This theory was definitely the least likely to hold, although initially during the static testing it seemed as though the model was accurate enough to work for future analysis. It was only when the jump was made to using a tennis ball contact in a dynamic environment that the results clearly refuted the possibility.

There is still plenty to take away from the lack of accuracy in the results, as they still provide some interesting insights into how it is certain that particular aspects of the simulation do not work. Considering that the trampoline effect is the determining factor in how well a stringbed conserves energy, it follows that the most likely cause of such a dichotomy in results is the way in which the stringbed itself was modeled in the simulation. There are two aspects to this in particular which stand out; one is the elements used for the strings, in this case T3D2 truss elements. While they exist in 3-D space, they can only act as two-force members and therefore can only handle loads in that way. It may be possible that the strings are not actually acting as two-force members, and that modeling them as such is reducing their capacity to handle loading conditions. The second is the lack of a 3-D weave pattern used for the stringbed model. The truss elements are modeled as intersecting lines which all exist on the same plane, thus they do not possess any weave which is customary in tennis rackets. By having all the strings intersecting on the same plane, they behave as though for every intersection where normally a weave would exist, instead there is essentially a weld. While initially it was thought that a single plane truss network would manage to model the racket close enough, the results from the Explicit simulation suggest otherwise.

6 Limitations

This section will carefully break down each of the aspects of this study in which limitations may have affected the final results.

6.1 ABAQUS Limitations

6.1.1 Absence of Viscoelastic Modeling

While the ball drop test was not able to definitively determine whether the viscoelasticity caused a reduction in the trampoline effect, it is still possible that it did play some role in the energy efficiency of a stringbed. If that is the case, that same effect would not be present in the ABAQUS/Explicit model since the material properties used for the strings only contained information on the mass density of the string, the elastic modulus, and the Poisson's ratio for each string. Due to this, any increase in velocity in the simulation would cause no change in behavior on the part of the string.

This could be a very important aspect of future studies in the field, as a confirmation on the part of a simulation that increased accuracy in the results are related to the introduction of viscoelastic behavior in the string would provide a more concrete conclusion that the viscoelasticity of the string material does reduce the energy efficiency of the stringbed as the ball velocity at contact increases.

6.1.2 Lack of Weave in Stringbed

One of the most significant limitations from the ABAQUS model was the lack of a weave present in the stringbed. Without the weave, there was an inherent assumption that it would not have a significant impact on the results in comparison to a real stringbed. Considering just how different the results ended up being, it is very likely that not only was that assumption incorrect, but also that the weave itself probably accounts for most of the reduction in trampoline effect in the stringbed. Looking back to Figure 9, the racket strung with mains only deflected far more than the rackets with a weave present in the stringbed.

What this suggests is that there is a mechanical property about the weave which provides a notable increase in stringbed resistance. While having intersecting string elements may have managed to mitigate the deflection that would have otherwise occurred if the model only used mains for strings, it is quite clear that using a properly modeled weave is paramount to any future research regarding tennis racket stringbeds (or rackets in general).

6.1.3 Ball Model

Lastly, in regards to modeling limitations, while the trampoline effect was the determining factor for the energy efficiency of the stringbeds, it only conserves energy by reducing the deformation of the ball. It is very possible that the way in which the tennis ball was modeled in the simulation was not effective in exhibiting energy dissipation the same way that a real tennis ball would. If that is the case, then it would also lend itself to characterizing the notably low energy losses shown in the ABAQUS results. Any combination of those three aspects would explain where the disparity in the result comparisons may be coming from.

6.2 Testing Limitations

6.2.1 Consistency

One of the biggest issues with the ball drop test was consistency. This showed itself in many facets of the test, starting with how the ball was dropped by hand. By requiring the video camera operator to inform the person dropping the ball to adjust to the proper height of dropping, there was inherent risk that the height was off or that the ball was not fully let go until it was slightly lower or higher than the point at which it was supposed to drop. In addition, the ball could have missed the exact center of the racket, which could have had a greater impact on the final results than initially anticipated. Having more time to develop an adjustable frame by which a mechanism would drop the ball would have allowed for much more consistent trial runs and better results, as the ball would drop from the same point every time, and would also hit the center of the stringbed each time. This would also lend itself well to increasing the number of trials run.

With regards to video work, the equipment used was also a limiting factor in the accuracy of the results. While the iPhone 10 possesses a good camera for filming, better film equipment designed for sports film would have been ideal for this test, as a high frame rate and an ability to shoot film from further away would have increased the accuracy of the results for two reasons. First, the further away you can film, the less of a factor parallax becomes, which improves the ability of tracker to determine the exact displacement of the ball during a given trial. Second, by improving the frame rate the film would get closer to capturing the exact frame at which the ball comes to a complete stop in the air, in turn improving the accuracy of the final recorded height. It would also allow for a comparison of the kinetic energy of the ball before and after contact with the potential energies measured to see if they are similar, and more importantly determine what portion of the energy losses occurring are happening at contact.

Lastly, an improved mechanism for securing the racket frame would have improved the result accuracy as well. Making sure that all the energy loss in the system is occurring in the stringbed is a vital aspect of this study, as any additional energy loss from frame vibration would compromise the results obtained.

6.2.2 Means

The other major limitation surrounding the ball drop test was the means at the disposal of the study. For example, the highest drop height was 150 cm, but the velocities a ball and stringbed contact would be subjected to would typically be higher than that. Being able to accurately measure the energy losses in the stringbed at greater ball speeds would potentially avail more information about the stringbeds, specifically regarding the viscoelasticity of the materials used. Being able to use a wider range of tensions and materials would have also increased the scope of the research to see if those effects became more pronounced for more unorthodox tensions or string materials.

7 Conclusion

The tennis stringbed is deceiving in its apparent simplicity, as the results have shown how it hides a significant degree of complexity in its operation that could not be fully explained in this study. While many basic hypotheses were confirmed regarding what makes a tennis stringbed efficient at conserving energy in contact with a tennis ball, there needs to be more in-depth testing and analysis to draw more concrete conclusions about how different factors within the stringbed impact its energy efficiency. However, one result that can be confirmed from this study is that the stringbed alone proved to conserve energy quite well in comparison to a metal object which could arguably be used to strike a tennis ball as well.

Since the results failed to draw solid conclusions about how various factors play into the stringbed energy efficiency, there is room for improvement in future studies on the subject. The first step would be to develop a well-modeled ABAQUS/Explicit simulation that employs a stringbed with a weave pattern and beam elements for the strings. The hope is that this would provide a large step in the right direction in terms of establishing a reliable model to compare empirical dynamic testing results to. This would also allow for more material properties to come into play with regards to the assigned material of the string and may provide a better insight as to whether what's happening within the strings is affecting the overall energy losses the stringbed exhibits. In that light, an improved material analysis would be beneficial to determine whether the composite nature of certain strings is playing more of an impact rather than just the elastic modulus measured in a simple tensile test. Combining these two next steps could lead to a much more accurate simulation with a greater ability to quantify more subtle nuances within the structure that could be affecting the overall stringbed energy efficiency. The other major step that could be made to improve on the results of this study would be to drastically overhaul the ball drop test to increase the scope, depth, and consistency of the test as previously stated in the limitations. In short, there is a solid groundwork for a group with greater means and expertise in the field to explore the complexity of how a tennis stringbed actually works.

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