Evaluation of Tennis Racket Swing during Impact with a Tennis Ball

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Abstract: *This report analyzes the differences in the ball exit velocity (BEV) when a ball arriving at a given velocity is hit at different points on the string bed of a racket and describes the reaction force on the handle of the racket, though the use of Dynamic Finite Element Simulations. The objective is to prove that the Finite Element Method can be used to determine optimal hitting points for rackets during a tennis match. Optimal hitting points are considered to be the ones producing the fastest BEV and lowest reaction force on the user's hand. Eleven different spots were analyzed. The incoming ball velocity was assumed to be 40m/s and the racket rotational swing speed was assumed to be 0.05 rad/ms. The results show that it is feasible to simulate the impact of a ball with a racket and determine stresses on the racket as well as the BEV and reaction force on the user's hand using Dynamic Finite Elements and Abaqus/Explicit. This work can be very insightful into using Finite Element Simulations to determine optimal racket swing speeds and ball hit positions for a tennis player to create optimal plays during a match.*

Keywords: *tennis, ball, finite element analysis, sweet spot, exit velocity*.

I. INTRODUCTION

The main purpose in a tennis game is to hit the incoming ball in such a way that the opponent is not able to play a good return. To achieve this aim, players need to hit back the ball not only fast, but also with desired angle and placing.

There is a sweet spot in the racket. The sweet spot is known as the location on the racket, when hit by a ball, imparts the greatest amount of forward momentum to the ball (Tennis Warehouse University). A tennis racket has an approximately elliptical head and the professional experienced players have said that the best locations range on the racket to hit the ball is the center of the racket.

Nowadays, the most common material that the tennis racket is made of is carbon fiber composite, while others may be made of aluminum or other alloys. Tennis racket made of carbon fiber composite are firmer while have less mass than other materials, so that it brings players more comfort and better performance.

The main goal in this research is to study the sweet spot on a racket made of carbon fiber composite, consequently finding the location on the racket that will produce the highest BEV as well as lowest reaction force. Additionally, the results can provide more accurate data for tennis companies to manufacture equipment and athletes to improve performance.

To achieve the main goal, the Finite Element Method will be used in this paper, and Abaqus/Explicit is a powerful tool in implementing the explicit procedure, which is well-suited for high-speed problems, such as tennis racket hitting a ball.

2. METHODS

Based on the real dimension of a tennis racket, a model of the tennis racket was built by using the CAD (computer aided design) software SolidWorks and shown in Figure 1. For the convenience of the finite element analysis, the racket is built without a handle. The racket will be controlled by a rigid body, which represents the player's hand. The dimensions were obtained by measuring the Wilson BLX Pro Open 100.

Figure 1. Tennis racket model.

Additionally, the tennis ball will also be analyzed during the impact simulation. Once the racket and the ball were modeled, it was imported into HyperMesh, which helped create the mesh for further finite element analysis.

Both the racket and the ball are hollow, so that they can be defined as shell section elements (Allen, 2010) when meshed with triangular element (Bogale, 2014). The strings are defined as 1-D line elements and are shown in Figure 2.

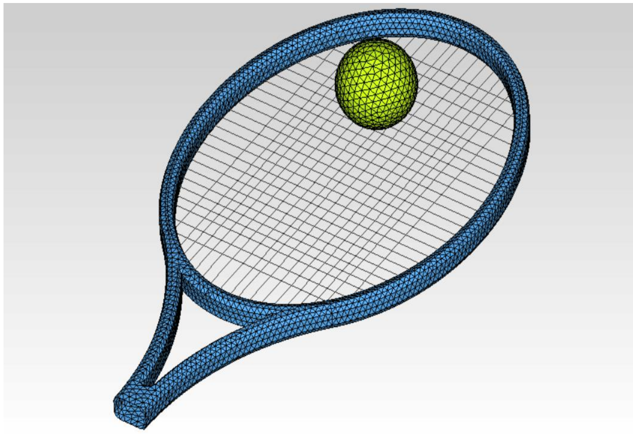

Figure 2. Model of the tennis racket and ball.

In order to control the racket to impact the ball in the impact simulation, the bottom part of the racket is defined as rigid body (shown in white), as shown in Figure 3. This zone represents the player's hand on the racket.

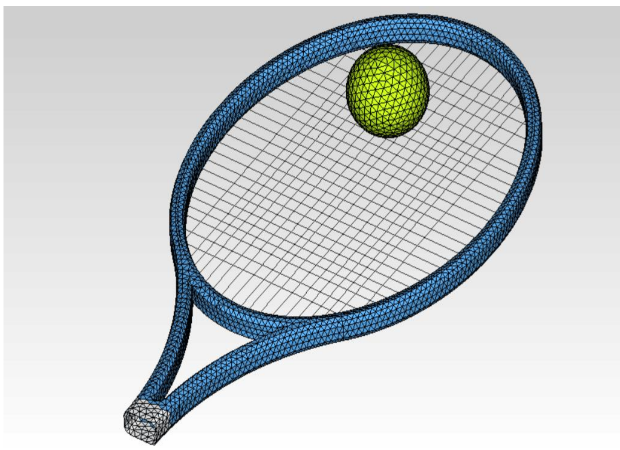

Figure 3. Model with rigid handle.

In order to achieve our research goal of finding the sweet spot, where the ball will have higher BEV as well as lower reaction force when impacting the ball, the tennis ball was simulated to hit different areas on the string bed of the racket. The eleven different hitting locations are shown in Figure 4.

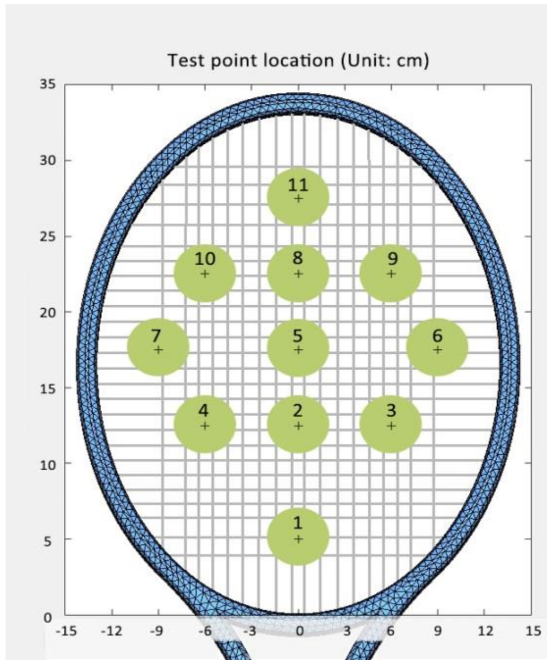

Figure 4. Test point location.

After this, all meshed models are output in the Abaqus input file format so that several essential parameters of the racket and the ball can be defined. These include, the velocity of the ball, rotation and swing angular velocity of the racket, pre-stress of the strings and environmental parameters. In Abaqus, the parameters above can be modified using keywords editing (Abaqus Keywords Reference Guide), so that one single geometric mesh can be analyzed under various conditions.

With different hitting technique and players' preferences, parameters such as velocity of the ball, swing angular velocity and pre-stress of the strings are modifiable. In this paper, all hitting analyses are under the same conditions except hitting position in order to control variables. Since the pre-stress is predefined by using pre-defined filed in ABAQUS, the stress on the strings will vary due to deformation of the frame. However, this variation is small and eligible. So that it will not influence the evaluation of the sweet spot.

The variables for the racket swing simulation that were considered to find which position can provide the better BEV are mainly the location where the ball is to be hit. It is also possible to study the general behavior along the racket and determine where the racket will be undergoing major stresses and where it will generate more effectiveness in a swing. The simulation methodology used has been to include a rigid body with an applied angular velocity and boundary conditions allowing rotation about one single axis, while giving the ball an initial velocity along one single axis.

Although the 11 tested positions used the same model of racket and ball, the location of ball are different. The engineering time needed to set-up the run is about half an hour, including moving the ball to the assigned location and modifying the input file. Also, the engineering time needed to run each condition is about 15-20 minutes.

3. RESULTS

Results (Abaqus/CAE) are shown for the Ball Exit Velocity based on different hitting positions as well as the reaction force on the tennis racket rigid handle. The ratio is obtained by dividing the maximum velocity (BEV) by the reaction force. Table 1 below shows the results.

Table 1. Impact position max velocity and reaction force.

Position	Max Velocity (m/s）	Reaction Force (N)	Ratio
1	40.6805	81.0254	0.5021
2	68.5611	127.119	0.5393
3	69.7298	131.596	0.5299
4	68.0761	129.456	0.5259
5	64.5634	63.1448	1.0225
6	55.3465	63.8471	0.8669
7	55.2387	63.3803	0.8715
8	64.4998	62.8661	1.0260
9	57.6936	63.7985	0.9043
10	57.9134	63.9504	0.9056
11	53.121	168.128	0.3160

An animation sequence of the tennis racket to ball impact is shown in Figure 5. One can observe that the racket continues to rotate during impact of the ball and after. The rotation is controlled through the simulation and can be any specific velocity function for the racket handle control point. The intent is to be able to control this velocity function, in order to optimize the impact after we have determined the best location to hit the ball with the racket.

In an ideal case, one can then train the player to achieve the optimized velocity function as determined from a numerical calculation, such as the one portrayed in this paper.

We believe that having this ability and a good measurement system, can help validate different hitting modes and optimize them for the player.

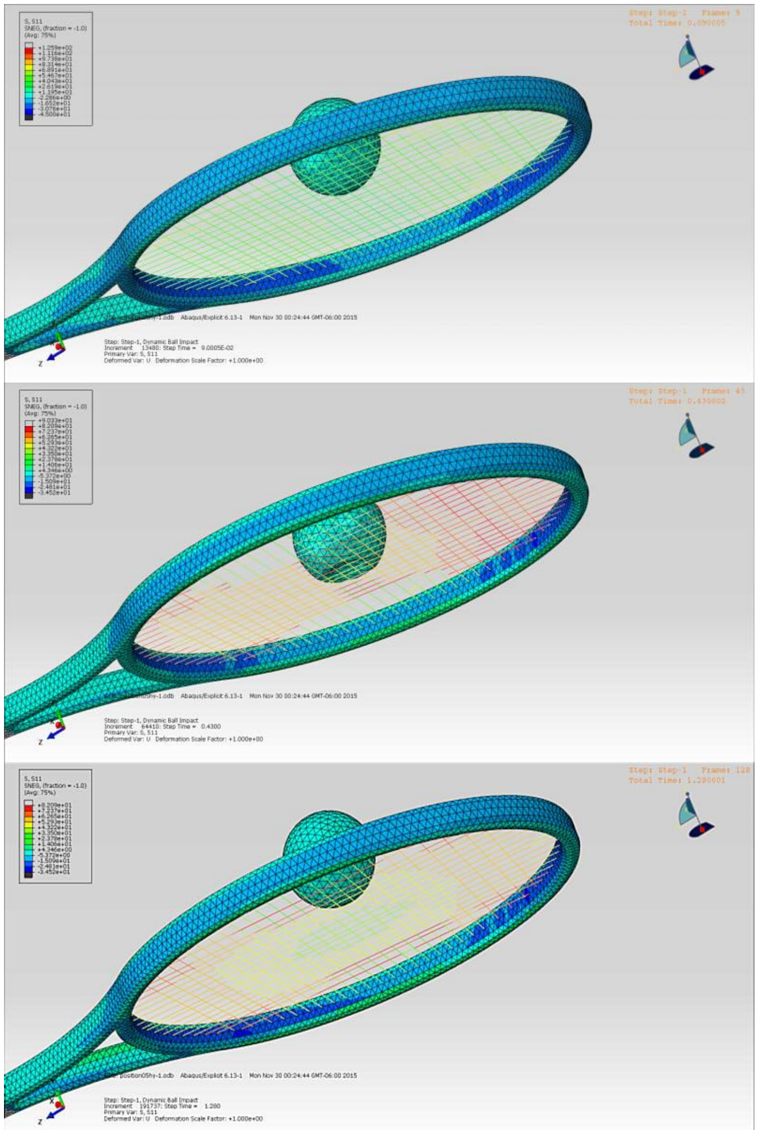

Figure 5. Impact process.

To better illustrate the data, we use a gradient plot. As shown in Figure 6, the deeper orange means higher ratio and the higher ratio represents that the ball will have a higher BEV as well as lower reaction force on player's hand. This plot is extremely useful in determining the optimal place to hit the ball with the racket (the ellipse represents the face of racket and little crosses represent the 11 tested positions).

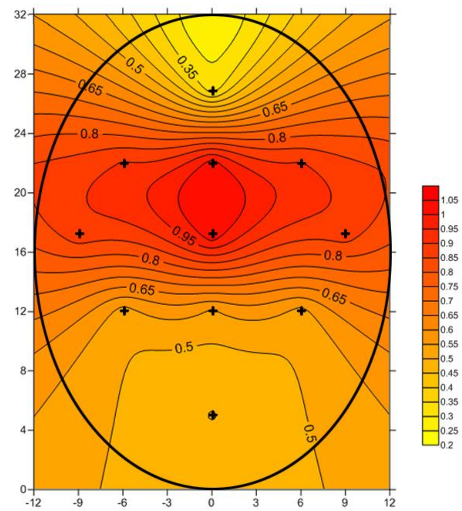

Figure 6. Ratio Gradient Distribution.

Besides the BEV and reaction force, the stresses in the racket are also analyzed in this research. The same approach was used in Figure 7 to show the resulting high stress on the racket vs. the ball impact location. By comparing the stresses (MPa) on the handle when ball hits the sweet spot and other spots, it shows that the stresses are relatively lower when ball hits the sweet spot. Figure 7 below shows the distribution, in which deeper orange means higher stresses in racket handle.

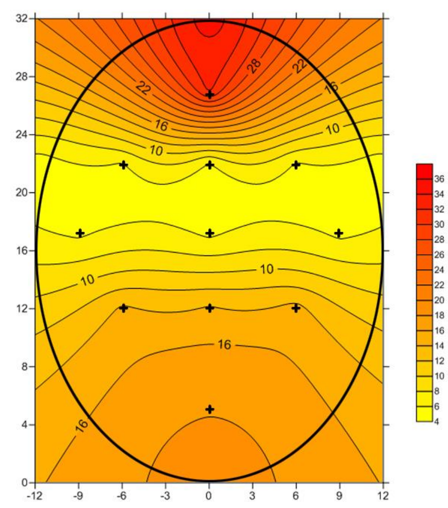

Figure 7. Stress Gradient Distribution.

4. DISCUSSION

In this research the material used for the tennis racket was carbon fiber. Hence, the other materials used for different tennis rackets were not analyzed. The study was focused in finding the sweet spot.

According to the results, the sweet spot was found by simulating a racket swing hitting a ball at several locations on the face of the racket. The location from 10 to 15 cm from the top end of the racket is deemed the sweet spot.

Abaqus/Explicit lends itself very well in allowing these types of simulations to be run, given its versatility in applying prescribed rotation angle over time functions to the racket. This is normally data that can be measured experimentally, allowing to further use this work in conjunction with experimentation. This may lead to improved swing analysis for players, as well as a tool to predict variations in BEV from a player's modification of swing characteristics.

5. CONCLUSION

By combining the results of higher ball velocity and lower reaction force on the handle, we concluded that the sweet spot on the racket can be obtained through dynamic finite element simulations. The best hitting spot is between position 5 and position 8, which is the location from 10 to 15 cm from the top end of the racket around the centerline.

In addition, stresses on the racket can also be determined to understand the effect of the swing and the impact of the ball to the racket's structural performance.

6. REFERNCES

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