Racket Science:

Effect of String Tension and Temperature on Coefficient of Restitution of Badminton Racket Strings

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Abstract

This study aimed to investigate the effect of string tension and heat on the coefficient of restitution (COR) of badminton racket strings. It is widely believed in the badminton community that higher string tensions result in lower rebound velocity of the birdie, but previous literature has been inconclusive. Previous literature regarding temperature and string tension shows that exposure to high temperatures significantly decreases string tension in tennis rackets. Little research has been done to explore this phenomenon in badminton rackets. We aimed to provide insight for badminton players of all levels on appropriate racket storage and determine if an international player traveling to different countries with different temperatures would need to adjust their string tension accordingly. We predicted an inverse linear relationship between string tension and the COR, and an increase in the COR for all string tensions measured after a temperature increase. Our procedure involved measuring the COR of a racket across varying string tensions while at room temperature and after being heated. We planned to use the same racket and string type for all trials. The data showed that there is a statistically significant effect on the COR across certain ranges as string tension increases, as well as when strings are heated across certain tensions. This indicated that leaving a badminton racket outside on a hot summer day will have little impact on racket performance across most tension ranges.

Introduction

Having over 100 million licensed players through the international badminton federation, badminton is one of the most played sports in the world (CKYew, 2022). Requiring only a racket, a net and a birdie, badminton is an accessible game for players of all levels. Professional players spend years honing their skills and finding an optimal racket and string tension. However, it has been seen that string tension in tennis rackets decreases after prolonged exposure to high temperatures (Lindsey, 2016). Assuming the same is true in commercial badminton strings, this could have a drastic influence on how a racket performs, namely, on its COR. The COR is defined as the ratio of the absolute final to absolute initial relative velocity between the birdie and racket after a collision. This value helps determine the efficiency of energy transfer between an object striking a surface, which impacts the speed and trajectory of a birdie launched off of a racket. A higher COR value would lead to an increased efficiency of energy transfer, resulting in higher birdie rebound velocities for the same swing and impact velocity. Understanding the effect of tension on the COR of badminton racket strings is important for players as it allows them to select an appropriate racket and string tension for their playing style and level of expertise. For instance, beginners tend to use rackets with lower string tensions, as it is believed to provide more power and consistency. On the other hand, advanced players, who can already generate sufficient power, tend to prefer a racket with a higher string tension value for greater shot accuracy and control(Yumo, 2021). It is from these descriptions of different string tensions that we hypothesized that lower string tensions have higher COR values. To quote Yumo (2021), a sporting goods store specializing in racket sports, “A softer (looser) string bed means that there is more "bounce/repulsion" from the strings and therefore the player can easily get power even if they lack the proper technique or strength”. Furthermore, it has been found that stiffness in polymers, such as the nylon based polymer of badminton strings, decreases after exposure to high temperatures (Mahieux and Reifsnider, 2001). We hypothesized that heated, less stiff strings at higher tensions would mimic strings at lower string tensions, which meant an increase of string temperature would increase the COR measured at any given string tension. By measuring the COR of a badminton racket across various commonly used tensions and a realistic temperature variation, this study aimed to determine if there was a relationship between string tension and COR and find whether there would be any significant impact on the COR, thus the apparent string tension, after exposure of a badminton racket's strings to high temperatures.

Methodology

Players tend to hit the birdie near the center of the racket and slightly off to one side (Naylor et al., 2020) (Figure 1). Thus, all trials were done at this point on the racket. We used a Li-Ning Airstream NSSIII racket with Black Knight strings (Figure 2). The racket was restrung in between trials to mitigate any potential deformation of strings due to exposure to high temperatures, as there is a permanent effect on tennis string characteristics after heating which may extend to badminton strings (Lindsey, 2016). To test the COR, we dropped a lacrosse ball from 30 cm onto the strings of the racket, which was clamped down between two stable desks. The rebound heights were recorded using an iPhone 10 camera and tripod situated 1m away. Initially, data was collected having the racket directly clamped flat onto a desk, but was recollected with the racket clamped between two desks to ensure there was nothing directly below the string bed. This was done to mitigate the effect on the COR measured in case the string bed rebounded off the table as the ball impacted the racket. Using the data collected, we approximated the effects of drag to be negligible and used the following equation to calculate the COR for each trial (Elert) (1):

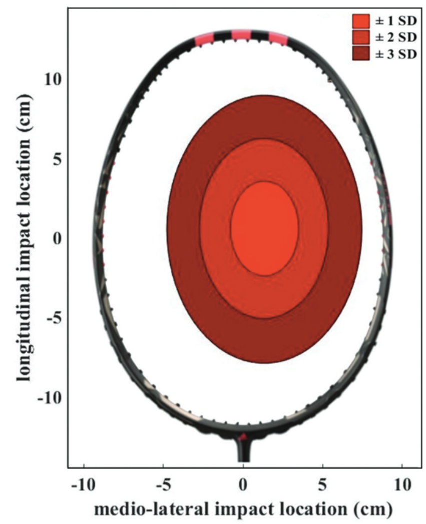


Figure 1: The mean racket-birdie impact locations within one, two, and three standard deviations of the mean (Adapted from Naylor et al., 2020).

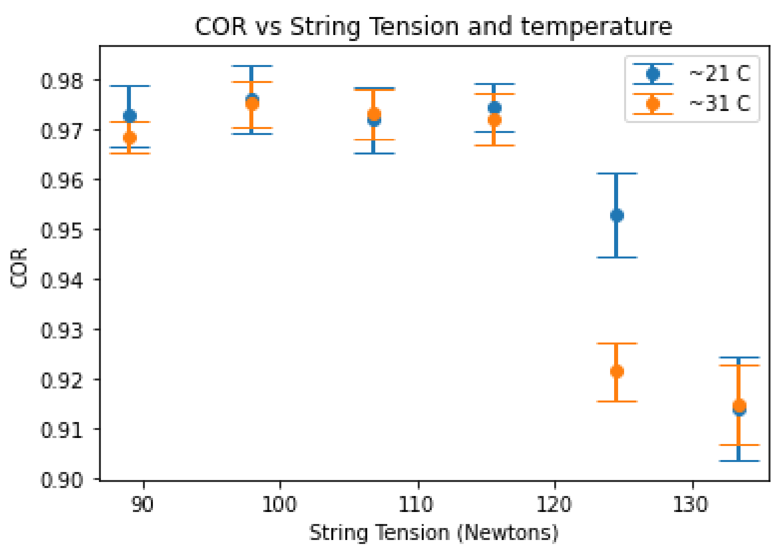
Figure 2: Li-Ning Airstream NSSIII racket used for the experiment strung with Black Knight strings

$$\text{Coefficient of Restitution} = \left|\frac{v_{up}}{v_{down}}\right| = \sqrt{\frac{2gh_{bounce}}{2gh_{drop}}} = \sqrt{\frac{h_{bounce}}{h_{drop}}} \quad (1).$$

We opted against the use of badminton birdies, as their more complex shape and lighter weight would make recording the drop and rebound heights difficult, and introduce more complex drag forces which would be difficult to account for. To test the effect of temperature on the COR, we increased the temperature of the strings by as much as possible using a blow dryer (with our blow dryer at +10º C change was possible), while using an infrared thermal imaging camera to keep track of the temperature of strings. The temperature of the racket frame was disregarded as there is little influence of small temperature changes on a carbon frame (Huang 2019). We then did as many trials as possible while the strings remained at the elevated temperature. Data on rebound heights at room temperature and elevated temperatures were collected in 2-pound (8.9 N) intervals, ranging from 20 to 30 pounds (89.0 N to 133.4 N) of tension. With this data, we determined the relationship between string tension and the COR. We also determined the relationship between temperature and the COR, to see if a temperature change would result in a shift in apparent string tension.

Data

Figure 3: Blue points and error bars represent the means and standard deviations of the CORs of string tensions at room temperature. Orange points and error bars represent the means and standard deviations when temperature of the strings has been increased. Each point is a mean of around 10-20 values. Both the blue and orange points are relatively constant from 20-26 pounds, but decrease significantly afterwards



The data shows that the COR is relatively constant at around 0.973 until 26 pounds (115.6 N) of tension, at which point it decreased significantly, to 0.953 at 28 pounds (124.6 N) and 0.914 at 30 pounds (133.4 N). Something to note is that the 0 of the y-axis has been suppressed in this graph, and the percent difference between 26 pounds and 30 pounds of tension is 6.4%. The COR measured at ~31^{o} C only showed a statistically significant difference from the COR measured at ~21^{o} C, at 28 pounds.

It was confirmed through a two-way ANOVA test (see appendix) that there was a statistically significant impact of varying string tension on the COR, but there was no significant impact of temperature change on the COR. A set of t-tests (see appendix) also confirms that there was a statistically significant decrease in the COR from 26 to 28 pounds of tension, as well as from 28 to 30 pounds of tension.

Discussion

The threshold p-value, usually 0.05, is the chance (5% for 0.05) that the difference in results could have resulted from random chance. A lower value indicates a more statistically significant difference, since there would be a less than 5% chance that the differences could have resulted from random chance or uncontrollable variables.

From the two-way ANOVA, we can conclude that there is a significant impact from string tension on COR, since the p-value, 0.004718, is less than the threshold value of 0.05. From visual analysis, this is only the case at higher tensions, which we theorize is due to slight differences in experimental procedure, as in the lower tensions (20-24 pounds or 89.0-97.9 N), experiments were performed without clamps and manually held down due to location constraints. Additionally, the test reveals that there is no significant impact of temperature on the COR of badminton strings. From a visual analysis of the plotted data the COR is relatively constant until 26 pounds, at which point it decreases significantly going from 26 to 28 pounds, and again from 28 to 30 pounds. The significance of the decrease was confirmed with t-tests (see Figure 7 in the appendix).

We predict that the higher the string tension, the more akin to a concrete floor the string bed is like, therefore a lower COR would be found at higher tensions. We also predict that at very low string tensions, there would be no rebound of the ball, as strings would absorb all of the ball's kinetic and potential energy. For this reason, we theorize there may be a peak in the COR in a range below 26 pounds of tension, and that it tapers off to a lower value as the tension increases past 26 pounds of tension. To see the peak, we would need to take data at lower string tensions below 20 pounds. At 28 pounds of tension, we saw an increase in temperature have the opposite effect on string tension from what we expected, which was a decrease in COR. This may have been an outlier, as the COR of every other string tension remained constant even after the temperature was increased. This difference should be the subject of further experimentation.

Seeing how temperature has no significant impact on the COR of a racket across most string tensions suggests that small temperature changes will not influence racket performance. The lack of statistically significant differences in COR across temperatures suggests that storing a racket in warm temperatures has no apparent effect on racket performance. However, we were only able to increase the strings' temperature by 10º C, while the temperature in a car left in the sun can reach up to 70º C (Dadour et al., 2011). Whether the COR of each trial was solely a function of changing string tension and temperature and not of any variable associated with the racket frame is not entirely known, however, it can be assumed that the increase in temperature did not affect the carbon fibre badminton racket frame, as carbon fibre is heat resistant and is seen to be unaffected after being exposed to temperatures exceeding 400º Celsius (Yang et al., 2019). An error that may have affected the results includes data collection methods, as the ball did not bounce in the exact same spot every time, increasing uncertainty in the measured COR. The positioning of the recording device may have also increased uncertainties, as due to parallax, the line of sight with the bottom of the ball and the lines on the ruler and the phone camera are often not parallel to the ground, which meant the height measurements taken above and below the horizontal plane of the camera have increasingly higher uncertainties. We attempted to negate this effect as much as possible by placing the recording device as far away from the trial area as possible.

Experimental limitations and improvements

One limitation of our study is that we are using a ball instead of a birdie. The impulse imparted on a lacrosse ball dropped at 30 cm is much less than the impulse imparted on a birdie struck at almost 500 km/h. Additionally, using a blow dryer, we were only able to increase the temperature of the strings by a maximum of 10º C to around 31º C, while the temperature of a car cabin in the sun can reach up to 70º C (Dadour et al., 2011). Another source of error may come from the stringing machine and the stringing process, which may not string the racket with the exact amount of force wanted. We also only took data in the 20-30 pounds range of string tension, but we should take more data below and above this range to see if any trends are missing from the current set of data. To better represent the impulse imparted on a birdie by the racket strings during a badminton match, future experiments should involve dropping a ball from greater heights. To heat the strings to higher temperatures, future experiments could also make use of heat guns instead of a blow dryer. Finally, the string tension and temperature are only few of many factors affecting how a racket may feel when playing badminton in real life. Thus, other variables and their effects on COR should be tested, such as string material, string diameter, and the number of filaments in a string.

Concluding Remarks

The results from the data show that in our lower range of string tensions (20-26 pounds), there is no statistical difference in the COR as a function of string tension. At higher string tensions (28-30 pounds), the COR decreases significantly. Finally, the impact of temperature on the COR across all string tensions was statistically insignificant, except at 28 pounds, where increasing temperature decreased the COR, thus mimicking higher string tension. The data indicates that a player who prefers a string tension of 20 to 26 pounds does not need to adjust their string tension to accommodate for hot temperatures. Further data collection across wider ranges of string tensions and greater temperature variations will be required to propose a concrete model for the effect of string tension and temperature on the coefficient of restitution of badminton racket strings.

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Appendix:

Figure 5: Results of two way ANOVA test. It shows that there is a significant impact of string tension on the COR (p-value < 0.05), there is no significant impact of temperature on the COR (p-value > 0.05), and there is no significant impact from the interaction between string tension and temperature (p-value > 0.05).

Source of variation	**P-value**
String tension	0.004718
Temperature increase	0.552906
Interaction between string tension and temperature increase	0.747726

Figure 7: Results of t-tests. In all comparisons, there is a significant impact of string tension (p-values > 0.05).

	26 vs 28 pounds	28 vs 30 pounds	26 vs 30 pounds
P-values	0.926	0.858	1.00

April 2, 2023

Dear Science One Instructors,

We have carefully reviewed all of the comments from my peers and mentor, and have revised the manuscript accordingly. Our responses are given below.

Reviewer 1: This reviewer suggested including experimental limitations as well as comparisons of our data to literature values.

Response: We added comparisons of our results to literature values. We also expanded on our experimental limitations to include more specific concepts.

Reviewer 2 and 3: These reviewers suggested that we watch our use of commas to ensure they are correct. Also pointed out run-on sentences, as well as suggested that we use consistent citation styles. Also suggested that we elaborate upon the methodology.

Response: We fixed our grammatical errors, and provided justifications for our methods in the methodology.

Reviewer 4 and 5: These reviewers suggested that we watch our use of commas to ensure they are correct. Also pointed out run-on sentences, as well as suggested that we use consistent citation styles. They also suggested that we elaborate upon the methodology and make our figures more clear, as well as discuss how the blow dryer may not be an accurate heat source.

Response: We fixed our grammatical errors, and provided justifications for our methods in the methodology. We also converted pounds to newtons on our figures as they suggested, as well as added how heat being added by means of blow dryer may not be a reliable heat source.

Sincerely,

Mudassir and Dayton.

Author Contributions:

Work was divided in the following way:

Dayton and Mudassir both designed the project together. Majority of data collection and statistical analysis was done by Dayton. Each section of the paper was written and edited together.