Peer-Review

Keym, Analise. 2025. “Polymer Microstructure Effects on Impact Response, Frequency Dynamics, and Vibrational Signatures in High-Performance Badminton Racket Strings.” *Journal of High School Science* 9 (4): 262–94. https://doi.org/10.64336/001c.153846

Good experiment. However, I think the paper has significantly more potential than has been realized. For example,

1.I plotted graphs of times of elastic and/or visco-elastic deformation of various string types against distance (only for a center hit), see attached spreadsheet. The graphs are informative in that the ultimax has fast instantaneous relaxation that slows down with time, regardless of distance of hit. The BG80’s deformation increases and then decreases (and eventually stays the same) with increasing hit distance. The BG65’s vibrations dampen with time (except for the 3 feet distance). I am sure you can derive much more information from these graphs if you search the literature for elastic and visco-elastic properties of polymers under tension.

2.The last graph plots initial/delayed and viscous deformation with time for a 3 feet hit for all the strings. the strings transition from a logarithmic to a parabolic to a hyperbolic profile with ultimax,80 and 65 respectively. This roughly means the vibrations start quicker and dampen quicker for ultimax, start a little later and dampen with a longer time for 80 and dampen and then increase for 65.

3.The graphs have several implications:

a] the point at which those vibrations are (period, amplitude) at the NEXT SHOT will determine the rate of decrease of successive smashes. This is where your frequency amplitude Fourier analysis comes in. You will need to approximate the time between sucessive smashes or hits and ‘where the string is with respect to its relaxation status’ during that next shot….and the next….and the next….".

4.Which leads to the interesting question of whether the natural frequency of the string (at a certain tension) should be equal to the time between shots or plays, to gain maximum advantage.

5.You can do the same analysis with your FT curves if you actually deconvolute them to represent the time domain. This way you can plot the amplitude of vibration against time to determine mutiple successive shot advantages for different strings.

I am sure theat a lot more useful information can be derived if you incorporate your top and bottom graphs into this mix as well. I know this is perhaps more than you bargained for when you submitted the paper, but I would hate to see information - that can be processed into knowledge - go to waste. Please therefore add depth to this project by a thorough read of reference 2 at the minimum and incorporate processed information as appropriate.

Good experiment. However, I think the paper has significantly more potential than has been realized. For example,

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October 12, 2025
Reviewer: Dr. Shireesh Apte, Journal of High School Science
Manuscript Title: Optimizing Badminton Racket String Selection: A Multivariable Experimental Analysis of Impact and Vibrational Signatures on Polymer-Based String Microstructure for Offensive Athletes
Submission ID: 2780126
Journal: Journal of High School Science
Author: Analise Keym
Dear Dr. Apte.
Thank you very much for the opportunity to revise and resubmit my manuscript entitled **Optimizing Badminton Racket String Selection: A Multivariable Experimental Analysis of Impact and Vibrational Signatures on Polymer-Based String Microstructure for Offensive Athletes.** I found your comments to be helpful in revising the manuscript and digging deeper into the data and potential meaning of my findings. Your suggestions have been very valuable to me and my findings. Thank you very much for also including some graphs of my data to help me understand the knowledge that could be derived from additional analysis. I have carefully considered each of your comments and have made many changes and updates to my original manuscript.
I am including a detailed response to your comments including where and how each is addressed. You will find your comments are listed by number verbatim (in blue) and in the box below each I list how and where in the revised manuscript I addressed them. Many of the changes are widespread throughout the manuscript in order to integrate my new, deeper understanding of the concepts, information from additional literature reviewed, methods for analysis, results from that analysis, and the discussion of those additional findings. Additional changes are listed at the bottom of the document.
Thank you again for your consideration of this revised manuscript. I believe the revisions have greatly strengthened the depth and practical application of my work. The changes add important material science context. I am grateful for your guidance in helping me realize the full potential of my data. Should there be additional clarifications/revisions, I would be happy to address them.
Sincerely,
Analise Keym
Wantagh High School
Wantagh, NY 11793

analise.keym26@gmail.com

Review:
Good experiment. However, I think the paper has significantly more potential than has been realized. For example,

1. I plotted graphs of times of elastic and/or visco-elastic deformation of various string types against distance (only for a center hit), see attached spreadsheet. The graphs are informative in that the ultimax has fast instantaneous relaxation that slows down with time, regardless of distance of hit. The BG80's deformation increases and then decreases (and eventually stays the same) with increasing hit distance. The BG65's vibrations dampen with time (except for the 3 feet distance). I am sure you can derive much more information from these graphs if you search the literature for elastic and visco-elastic properties of polymers under tension.

Thank you for this excellent suggestion. I have substantially expanded my analysis to include elastic and viscoelastic behavior across distances.

Revision to Original Manuscript:
Section 1.3 - Added new paragraph explaining elastic vs. viscoelastic properties of polymer-based strings, citing Baltussen, Wismans, Snoeijer, and Vaidyanathan
Section 2.5 (NEW SUBSECTION) - "Elastic and Viscoelastic Time-Domain Analysis" - Entire new methodology subsection describing how I analyzed deformation and recovery patterns
Section 3.2 (NEW SUBSECTION) - "Time-domain Elastic and Viscoelastic behavior" - Entire new results subsection with detailed analysis of each string's behavior at 3, 5, and 8 ft
Figures 6 & 7 (NEW) - Added graphs showing vibration amplitude vs. time organized by string type and distance, with polynomial trendlines and R^2 values
Section 4.1 (NEW SUBSECTION) - "Elastic and Viscoelastic Response Patterns Across Impact Distances" - Detailed discussion linking polymer microstructure to observed behavior patterns

To address this comment, I studied elastic and viscoelastic behaviors of polymers to better understand what my methods and results mean. In these areas, as a result, I have added time-domain analysis comparing elastic (BG 66 Ultimax) to viscoelastic (BG 65) to mixed elastic/viscoelastic (BG 80) behavior of each string. I created new graphs showing how each string's vibration pattern changes with distance and connected the findings in my additional literature review of polymer science on tension and relaxation behavior. Lastly, I explained how microfilament vs. multifilament structure of strings influences energy dissipation.

2. The last graph plots initial/delayed and viscous deformation with time for a 3 feet hit for all the strings. the strings transition from a logarithmic to a parabolic to a hyperbolic profile with ultimax,80 and 65 respectively. This roughly means the vibrations start quicker and dampen quicker for ultimax, start a little later and dampen with a longer time for 80 and dampen and then increase for 65.

I appreciate this suggestion and seeing how the strings can be described as logarithmic/parabolic/hyperbolic adds depth to the understanding of how the polymers function mechanically for play.

Revision to Original Manuscript:
Section 3.2 - Added descriptions of "rapid initial decay," "gradual amplitude growth," and "quick initial drop followed by prolonged gradual decay"
Figure 6 - Individual string type graphs with polynomial trendlines showing the different curve shapes
Figure 7 - Direct comparison graphs showing the transition from BG 66 Ultimax to BG80 to

BG65
Section 4.1 - Explicitly describes the "logarithmic-type decay" (BG 66 Ultimax), "parabolic-type response" (BG80), and "hyperbolic-type decay" (BG65)
Section 4.2 (NEW SUBSECTION) - "Implications for Successive Shot Execution" - Discusses how settling times relate to rapid play

These changes to my Methods and Discussion sections of the manuscript contain information regarding how each string's decay pattern shape (logarithmic/parabolic/hyperbolic) are characterized. I also explained what these patterns mean mechanically. The BG 66 Ultimax snaps back quickly and stabilizes, the BG 80 has a delayed viscoelastic recovery, and the BG 65 has sustained gradual energy dissipation. Furthermore, I connected the curve shapes to what I learned about polymer chain behavior and the fiber structures. Lastly, I added settling time analysis, or the time to reach 5% of peak amplitude, in order to quantify each string's readiness for the next shot.

3. The graphs have several implications:
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A. Which leads to the interesting question of whether the natural frequency of the string (at a certain tension) should be equal to the time between shots or plays, to gain maximum advantage.
B. You can do the same analysis with your FT curves if you actually deconvolute them to represent the time domain. This way you can plot the amplitude of vibration against time to determine mutiple successive shot advantages for different strings.
C. I am sure theat a lot more useful information can be derived if you incorporate your top and bottom graphs into this mix as well. I know this is perhaps more than you bargained for when you submitted the paper, but I would hate to see information - that can be processed into knowledge - go to waste. Please therefore add depth to this project by a thorough read of reference 2 at the minimum and incorporate processed information as appropriate.

Thank you for showing me the potential implications for my findings for subsequent shots and the rate of successive smashes as well as in analysis of the strings' natural frequencies. I have added comprehensive envelope analysis and settling time calculations throughout the paper and I acknowledge the limitations in expanding this study beyond the original scope and data collection for this study. I am grateful for your comment in showing how this information would be very valuable in additional research. The changes I have made in regards to these comments strengthens the manuscript.

Revision to Original Manuscript:

For Parts A & B:
Section 1.3 - Added new paragraph: "Beyond instantaneous energy transfer, the temporal characteristics of string vibration decay are critical for successive shot execution...Strings that continue vibrating may interfere with control and energy transfer in subsequent impacts."
Section 2.6 (NEW SUBSECTION) - "Time-Domain Envelope Analysis" - Added complete methodology using Hilbert transform to extract amplitude boundaries and define settling time (5% threshold)
Section 3.4 (EXPANDED SUBSECTION) - "Vibration Envelope and Settling Time Analysis" - Quantified settling times at each distance (e.g., 3ft: BG66-Ultimax 0.20s, BG80 0.27s, BG65 0.27s)
Figures 9 & 10 (NEW) - Added vibration envelope decay curves and time-to-settle graphs

showing when each string reaches "quiet" state
Section 4.2 (NEW SUBSECTION) - "Implications for Successive Shot Execution" - Discusses typical rally intervals (0.3-0.6s) and whether strings are mechanically ready for next impact
Section 5 (Conclusion) - Added: "For attacking players, the BG66-Ultimax is optimal for rapid net exchanges where maximum repulsion is prioritized..."

For Part A (specifically):
Section 5.1 (Limitations) - Added substantial new paragraph: "While the envelope analysis in this study quantifies when strings reach 'quiet' states, this information may not be useful in determining timing for multiple successive shots...Also, this study did not measure the natural frequency of the string-racket system..."
Section 5.2 (Future Directions) - Added: "Additionally, measuring the natural frequency of the complete string-racket system under tension would address a key limitation...Modal analysis could show if the string's vibration cycles match up with shot timing..."

To address these comments I performed Hilbert transform envelope analysis in MatLab on my data to show the vibration amplitude boundaries over time. I also calculated specific settling times for each string at each distance to quantify the "readiness" for the next show. In order to better illustrate this information, I created graphs in MatLab. Additionally, I compared settling times to realistic inter-shot intervals in competitive play (0.3-0.6 seconds) and discussed whether residual vibration at typical shot intervals could affect performance.

However, for Part A specifically, I acknowledged that I did not test if natural frequency equals optimal shot timing. I added the perspective that shot timing in actual play is determined by many factors, including shuttlecock flight time, player positioning, offensive gameplay decisions, and many more inter-related factors. Therefore, I identified this as a limitation to my study and suggested additional analysis for future research.

For Part C:
Figure 6 - Organized to show ALL positions (top, center, bottom) for each string type at all distances
Figure 7 - Reorganized to compare all three strings at each position and distance
Section 3.2 - Added analysis: "For the BG66-Ultimax...the top position showed distinct patterns based on distance...Center hits showed relatively consistent parabolic-like shape...bottom hits displayed more erratic and varied patterns"
Section 4 (EXPANDED) - "The wider spread of acceleration values at different string bed positions indicates that string material significantly influences energy transfer and shot precision"

To address this comment, I included a comprehensive position analysis and showed how impact location affects the elastic/viscoelastic response differently for each string. I noted my finding that bottom hits show more variable behavior, especially at the longer distances. Lastly, I integrated the position data into the elastic/viscoelastic characterization.

Additional changes made to the original manuscript:

- The abstract has been rewritten to emphasize these findings.
- The keywords have been updated to reflect relevant terms related to these findings.
- Additional references have been added and referenced throughout the paper.
- I incorporated Reference 2 into the new sections of the paper and applied their finding that "measuring energy transfer through racket vibrations is essential to understanding how string material impacts power" in Subsection 2.4. I used a similar conception framework of vibration to

performance relationships and extended on their work by adding time-domain and elastic/viscoelastic analysis, which they did not perform in that study.

- Added a discussion of why settling time may not directly predict shot timing in gameplay for the Limitations. The settling times in my research measures at 0.18-0.67 seconds. While they overlap with realistic shot intervals, they don't predict them. Through additional readings, the shot frequency in competitive play, especially offensive play, is determined by many factors, not incorporated into my methods. Also, my methods did not measure the natural frequency of the strings, so I was not able to test the hypothesis on resonance optimization of the strings.
- Added to Future Directions the suggestion for material modeling and modal analysis studies. Additional studies that examine material properties in relation to shot time strategy would also be a good study for future research.

Thank you for addressing my comments. The paper is significantly improved from its previous version. However, you will need to perform statistical testing, graphing with error-bars where appropriate (in figure 8 for the FFT spectrum, you can specify the spectrum as the average of 3 spectra), as well as populating your 'limitations' section with more verbiage. I also recommend changing the subtitle "future directions' to 'perspectives'. Please also rearrange so that the conclusions is the last section of the manuscript.

If you have not taken a statistics class, I recommend taking the help of your AP statistics teacher. I look forward to your next and last iteration.

1.Please specity what model/make this Figure is related to –65, 66, 80 or other.

2.Please delete control of 'wind conditions' since all testing was performed indoors.

3.Cite a reference to the Vectran polymer (wikipedia is fine) and mention that it is a Liquid Crystalline Polymer (LCP). Discuss in brief, its young's modulus due to the ordered chains in the LCP. 66 also contains vectran polymer. What then is the difference between 66 ultimax and 80 vectran?

4.What does an 'excellent hitting sound' have to do with player performance?

5.Figure 3 needs a square-root sign across all arguments. Also, please do not call this a figure. Renumber other figures as a consequence. Acceleration units are not 'g' , rather, distance/time^2. you are not measuring acceleration (or multiples thereof) due to gravity.

6.Badminton shots can reach speeds of 250 mph. Hence, your speed of 15 mph is not at all representative of actual play speeds. Explain why. If you cannot justify, please put this down as a limitation in your manuscript.

7.Explain how the units of 'gravity over time' relate to acceleration. Also, see point 5.

8.Figure 6 needs axes labels (headings) and units for both x and y axes; even though the title states the labels. Emphasize in the text that R^2 values are only shown for empirical prediction; they do not represent or explain the variance or mechanism for any physical phenomenon related to elasticity or visco-elastic behavior. Furthermore, they (R^2 values) are not substitutes for inferential statistics.

9.Mention in limitations: [1] Single racket model, single tension, limited distances and trials, and one accelerometer mounting; no sensitivity analyses was performed to stringer variability, tension drift, feed speed, or mounting conditions. [2] there were no positive/negative controls (e.g., unstrung frame, damped vs. undamped), no baseline noise characterization, and no calibration/control impacts. [3] normalization of amplitude (acceleration spectra) to input (impact) energy was not performed. [4] extrapolations to injury risk and specific tactical recommendations outpace the data (tested to a speed of 15 mph; an order of magnitude lesser than actual shot speed).

10.Please check the manuscript thoroughly for factual reporting errors. For example, you state "….At 8 ft, the BG66-Ultimax recorded its highest acceleration values, with peak acceleration exceeding 80g at the center position where maximum energy is transferred to the shuttlecock…." This is for the bottom position (not center). Again - and also -, "g" is not an accurate unit for acceleration. Please replace with correct units throughout the manuscript.

11.For figure 9, you should have error bars since you performed each test in triplicate.

12.Toward the end of the manuscript, you state "….There is no definitive answer to this study's hypothesis…." Please state the hypothesis at the beginning of the manuscript. Also, in science, there is no such conclusion as a 'non-definitive answer'. A hypothesis is either true or false depending on whether it passes the statistical rigor expected of it (i.e. typically a p value of 0.05). (see point 13)
13.You have performed no statistical testing (No hypothesis tests, CIs, SD/SE, or assumption checks; small n; include ANOVA or nonparametric tests, multiple-comparison corrections, and effect sizes.) For example, your hypothesis point 1 may state " At 15 mph, the greater the energy transferred from the ball to the string (or; the lesser the distance), the faster the vibration decay recovery in the order 66(fastest), 80 and 65(slowest), use ANOVA with post-hoc HSD t-tests at p=0.05) or KW test (if Levine's test for homoskedasticity does not pass at p=0.05). Another hypothesis may state: When a simple sinusoid is fitted to the FFT curves in Figure 8 (there should be three curves for each test since you tested thrice), the parameter "T", the period in the frequency domain (at center) will be longest for 66 and shortest for 80 (intermediate for 65), at the highest energy transfer (3 feet) corresponding to the most narrowly spaced resonant modes for 66 (8-15 seconds) then 65 (2-16 seconds) then 80 (longest(11-30 seconds) in the time domain (figure 5), which is indeed true, Use ANOVA here as well with a p of 0.05. In simpler terms, if you ask chatgpt

The string with a shorter T (more rapid oscillations in the FFT curve) has more widely spaced reflections or resonant modes in the time domain.

→ It could mean the string supports longer vibration travel time or more complex wave interference.

The string with a longer T (slower oscillations in the FFT curve) has closely spaced reflections or shorter wave travel time.

→ It might be slightly shorter, stiffer, or more tightly coupled to its frame.

This aligns with your hypothesis of stiffer, higher elastic modulus 66 and more visco-elastic 65 followed by most viscoelastic 80 at high energy transfer (3 feet) at the center location.

November 11, 2025

Reviewer: Dr. Shireesh Apte, Journal of High School Science

Manuscript Title: Polymer Microstructure Effects on Impact Response, Frequency Dynamics, and Vibrational Signatures in High-Performance Badminton Racket Strings (New Title)

Submission ID: 2780126

Journal: Journal of High School Science

Author: Analise Keym

Dear Dr. Apte.

Thank you for the opportunity to revise and resubmit my manuscript, now entitled *Polymer Microstructure Effects on Impact Response, Frequency Dynamics, and Vibrational Signatures in High-Performance Badminton Racket Strings*. Please note the revised title, which better reflects the scope and focus of the study following your feedback.

The manuscript has undergone substantial revisions. In addition to addressing each of your specific comments, I have reorganized sections for improved logical flow, added new statistical analyses with corresponding figures and tables, and properly distinguished between equations, tables, and figures throughout. These changes represent a comprehensive strengthening of the work's scientific rigor.

I have prepared a detailed point-by-point response document that describes each change and its location in the revised manuscript. Through this revision process, my understanding of statistical hypothesis testing, polymer science, and precise scientific communication has deepened considerably. The additional analyses have revealed insights in the data that were not evident in the original submission.

Thank you again for your consideration of this revised manuscript. I believe the revised manuscript addresses your concerns comprehensively and represents a substantial improvement in scientific rigor. I remain grateful for your guidance in helping me realize the full potential of my data.

Sincerely,
Analise Keym
Wantagh High School
Wantagh, NY 11793

analise.keym26@gmail.com

Response to Review:
Thank you for addressing my comments. The paper is significantly improved from its previous version. However, you will need to perform statistical testing, graphing with error-bars where appropriate (in figure 8 for the FFT spectrum, you can specify the spectrum as the average of 3 spectra), as well as populating your 'limitations' section with more verbiage. I also recommend changing the subtitle "future directions' to 'perspectives'. Please also rearrange so that the conclusions is the last section of the manuscript.
If you have not taken a statistics class, I recommend taking the help of your AP statistics teacher. I look forward to your next and last iteration.
1. Please specity what model/make this Figure is related to –65, 66, 80 or other.
2. Please delete control of 'wind conditions' since all testing was performed indoors.

Thank you, I have done the following:

#1. I have added figure captions throughout the manuscript that explicitly identify which string type(s) each figure represents. Specifically:
• Figure 1 now includes the caption clarifying it shows the general composition applicable to all badminton strings
• Figures 3-11 now clearly indicate which string types (BG65, BG80, BG66-Ultimax) are being compared in each visualization
• When figures show data for a specific string type, this is stated explicitly in both the caption and the in-text reference

Location: All figure captions throughout Section 3 (Results), pages 12-22.
#2. I have removed all references to wind conditions as a controlled variable. The revised manuscript now accurately reflects that testing was performed in a controlled indoor testing environment where wind was not a factor.

Location: Section 2.2 (Experimental Design), page 8, and Section 4.3 (Limitations), page 29.

3. Cite a reference to the Vectran polymer (wikipedia is fine) and mention that it is a Liquid Crystalline Polymer (LCP). Discuss in brief, its young's modulus due to the ordered chains in the LCP. 66 also contains vectran polymer. What then is the difference between 66 ultimax and 80 vectran?

#3. I have significantly expanded the discussion of Vectran® polymer properties and the distinctions between string types:

1. Added citation to Vectran™ literature identifying it as a Liquid Crystalline Polymer (LCP) with reference to its molecular structure
2. Discussed how the ordered chain alignment in LCPs results in high Young's modulus (approximately 75 GPa for Vectran™), contributing to superior tensile strength and elastic recovery
3. Clarified the key differences between BG66-Ultimax and BG80:
   • BG66-Ultimax: High-polymer nylon multifilament core with Vectran™ braided outer
   • BG80: Pure Vectran™ multifilament construction throughout
   • This structural difference explains why BG66-Ultimax exhibits more elastic behavior (faster

settling) while BG80 shows balanced elastic-viscoelastic properties

Location: Section 1.2 (Literature Review), pages 4-5, and Section 4.1 (Material Property Interpretation), page 24.

4. What does an 'excellent hitting sound' have to do with player performance?

#4. I have removed subjective terminology like "excellent hitting sound" and replaced it with objective, mechanically relevant descriptions. The revised text now focuses on quantifiable performance metrics such as:

- Energy transfer efficiency (measured via peak acceleration)
- Vibration decay characteristics (measured via settling time)
- Frequency response (measured via FFT analysis)
- Impact on successive shot execution timing

The manuscript now focuses exclusively on measurable phenomena that can be tested and validated in regard to string description.

Location: Section 1.3 (Impact of String Material on Performance), page 6, with subjective language removed.

5. Figure 3 needs a square-root sign across all arguments. Also, please do not call this a figure. Renumber other figures as a consequence. Acceleration units are not 'g' , rather, distance/time^2. you are not measuring acceleration (or multiples thereof) due to gravity.

7. Explain how the units of 'gravity over time' relate to acceleration. Also, see point 5

#5. I have made the following changes:

1. Added proper square-root notation across all arguments in the total acceleration formula
2. Changed the equation from "Figure 3" to "Equation 1" and renumbered all subsequent figures accordingly (previous Figures 4-12 are now Figures 3-11)
3. Corrected acceleration units throughout the manuscript:
   • Changed "g" to m/s^2 with the conversion factor stated ($1\ g = 9.81\ m/s^2$) for clarity when discussing magnitude
   • Emphasized that we are measuring linear acceleration in standard SI units, not gravitational acceleration
   • Updated all axes labels, data tables, and text references to use m/s^2 as the primary unit

This correction has reinforced my understanding that precise unit notation is critical in scientific communication, and that "g" should only be used when explicitly comparing to gravitational acceleration, not as a standalone unit.

Location: Equation 1 (previously Figure 3), page 10; all data tables (Tables 1-3), pages 13-15; all figure axes labels, pages 12-22; throughout Results and Discussion sections.

#7. I have corrected this fundamental error in unit interpretation. The phrase "gravity over time" was incorrect and has been completely removed. The manuscript now correctly states:

• Acceleration is measured in m/s^2 (meters per second squared), representing the rate of change of velocity
• The conversion factor "$1\ g = 9.81\ m/s^2$" is provided only for readers familiar with expressing acceleration magnitude as multiples of Earth's gravitational acceleration
• All data analysis uses m/s^2 as the standard unit
• The accelerometer measures linear acceleration along three axes (X, Y, Z), not gravitational effects

This correction, combined with the changes in Comment 5, has eliminated the conceptual confusion between measuring acceleration and referencing Earth's gravity.

Location: Section 2.3 (Data Collection and Analysis), page 9; throughout Results section.

6. Badminton shots can reach speeds of 250 mph. Hence, your speed of 15 mph is not at all representative of actual play speeds. Explain why. If you cannot justify, please put this down as a limitation in your manuscript.

I have added a comprehensive explanation of the 15 mph experimental speed in the Limitations section:

"The experimental shuttle speed of 15 mph was substantially lower than those observed in competitive play, where smashes may exceed 250 mph (Towler et al., 2023). This lower velocity was intentionally chosen to: (1) prevent excessive deformation that would damage equipment and compromise measurement fidelity, (2) maintain consistency and repeatability with the available Badminton Pitcher apparatus, and (3) work within the accelerometer's optimal measurement range for accurate data capture. However, this speed limitation means the vibration characteristics measured here may not directly extrapolate to high-energy impacts in elite play. The tested impact speed (15 mph) is roughly an order of magnitude lower than actual shot speeds, and extrapolations to real gameplay dynamics must be made cautiously."

I have also added a citation to Towler et al. (2023) for the 250 mph reference and emphasized throughout that results should be validated at higher impact energies in future work.

Location: Section 4.3 (Limitations), pages 29-30.

8. Figure 6 needs axes labels (headings) and units for both x and y axes; even though the title states the labels. Emphasize in the text that R^2 values are only shown for empirical prediction; they do not represent or explain the variance or mechanism for any physical phenomenon related to elasticity or visco-elastic behavior. Furthermore, they (R^2 values) are not substitutes for inferential statistics.

#8. I have made comprehensive improvements to Figure 6 (now Figure 5 after renumbering):

1. Added complete axis labels with units:
   - X-axis: "Frequency (Hz)"
   - Y-axis: "Amplitude (m/s^2)"
2. Added a clarifying note in the figure caption and surrounding text:

"R^2 values shown in polynomial curve fits represent empirical prediction quality only and are not inferential statistics. These coefficients describe how well the fitted curve matches observed data points within this specific dataset but do not explain underlying physical mechanisms of elasticity or viscoelastic behavior. R^2 values should not be interpreted as measures of statistical significance or as substitutes for hypothesis testing."

This revision has deepened my understanding that descriptive statistics (like R^2) and inferential statistics (like p-values from ANOVA) serve fundamentally different purposes in scientific analysis.

Location: Figure 5 caption and surrounding text, page 17; Section 4.3 (Limitations - Data normalization subsection), page 30.

9. Mention in limitations: [1] Single racket model, single tension, limited distances and trials, and one accelerometer mounting; no sensitivity analyses was performed to stringer variability, tension drift, feed speed, or mounting conditions. [2] there were no positive/negative controls (e.g.,

unstrung frame, damped vs. undamped), no baseline noise characterization, and no calibration/control impacts. [3] normalization of amplitude (acceleration spectra) to input (impact) energy was not performed. [4] extrapolations to injury risk and specific tactical recommendations outpace the data (tested to a speed of 15 mph; an order of magnitude lesser than actual shot speed).

#9. I have incorporated all four limitation points into a comprehensive Limitations section with dedicated subsections:

4.3

Design and Instrumentation:

"The study employed a single racket model (Yonex Astrox 88 S Pro), one string tension (24 lbs.), three distances (3, 5, 8 ft), and a single accelerometer mounting position without sensitivity analyses for stringer variability, tension drift, feed speed, or clamping conditions. These fixed parameters simplified comparison but may constrain generalizability. In addition, there were no positive or negative controls (e.g., unstrung frame, damped vs. undamped), no baseline noise characterization, and no calibration or control impacts to benchmark instrument response."

Data Normalization and Statistical Scope:

"Acceleration amplitudes and frequency spectra were not normalized to input (impact) energy, meaning that absolute amplitude differences cannot be directly compared across strings. Furthermore, polynomial R^2 coefficients were included only to demonstrate empirical curve-fit quality; they were not intended as inferential statistics or as explanations of physical mechanisms for elasticity or viscoelasticity."

Interpretation Boundaries:

"Extrapolations from the present data to injury risk or tactical gameplay recommendations exceed the scope of the measurements. The tested impact speed (15 mph) is roughly an order of magnitude lower than actual shot speeds in elite play, and the present setup cannot model the complex kinetic chain of human motion, neuromuscular response, or multi-impact fatigue dynamics."

These additions have helped me recognize the importance of explicitly stating the boundaries of what can and cannot be concluded from experimental data and organize it logically.

Location: Section 4.3 (Limitations), pages 29-31, with four distinct subsections addressing each limitation category.

10. Please check the manuscript thoroughly for factual reporting errors. For example, you state "….At 8 ft, the BG66-Ultimax recorded its highest acceleration values, with peak acceleration exceeding 80g at the center position where maximum energy is transferred to the shuttlecock…." This is for the bottom position (not center). Again - and also -, "g" is not an accurate unit for acceleration. Please replace with correct units throughout the manuscript.

#10. I have conducted a complete review of the manuscript and corrected all factual reporting errors:

1. Position Correction: Changed "center position" to "bottom position" in the description of 8 ft BG66-Ultimax data (page 14). I verified this correction against the raw data files and Figure 4.

2. Unit Corrections: Systematically replaced all instances of "g" with "m/s²" throughout:
- All text descriptions (Results and Discussion sections)
- All table entries (Tables 1-3)
- All figure axes and legends (Figures 3-11)
- Where magnitude comparisons are helpful, I now state values as "X m/s² (Y× gravitational acceleration)" for context

3. Additional Factual Checks: I also cross-referenced:

• All statistical test results with the actual analysis outputs
• All figure references with the correct renumbered figures
• All data values cited in text with the source tables
• All methodological descriptions with the actual procedures performed

This thorough review process has taught me the critical importance of verification and the dangers of working from memory or assumptions rather than returning to source data.

Location: Throughout manuscript, with major corrections in Results section (pages 12-22) and Discussion section (pages 23-28).

11. For figure 9, you should have error bars since you performed each test in triplicate.
12. Toward the end of the manuscript, you state "….There is no definitive answer to this study's hypothesis…." Please state the hypothesis at the beginning of the manuscript. Also, in science, there is no such conclusion as a 'non-definitive answer'. A hypothesis is either true or false depending on whether it passes the statistical rigor expected of it (i.e. typically a p value of 0.05). (see point 13)
13. You have performed no statistical testing (No hypothesis tests, CIs, SD/SE, or assumption checks; small n; include ANOVA or nonparametric tests, multiple-comparison corrections, and effect sizes.) For example, your hypothesis point 1 may state " At 15 mph, the greater the energy transferred from the ball to the string (or; the lesser the distance), the faster the vibration decay recovery in the order 66(fastest), 80 and 65(slowest), use ANOVA with post-hoc HSD t-tests at p=0.05) or KW test (if Levine's test for homoskedasticity does not pass at p=0.05). Another hypothesis may state: When a simple sinusoid is fitted to the FFT curves in Figure 8 (there should be three curves for each test since you tested thrice), the parameter "T", the period in the frequency domain (at center) will be longest for 66 and shortest for 80 (intermediate for 65), at the highest energy transfer (3 feet) corresponding to the most narrowly spaced resonant modes for 66 (8-15 seconds) then 65 (2-16 seconds) then 80 (longest(11-30 seconds) in the time domain (figure 5), which is indeed true, Use ANOVA here as well with a p of 0.05. In simpler terms, if you ask chatgpt

The string with a shorter T (more rapid oscillations in the FFT curve) has more widely spaced reflections or resonant modes in the time domain.
→ It could mean the string supports longer vibration travel time or more complex wave interference.
The string with a longer T (slower oscillations in the FFT curve) has closely spaced reflections or shorter wave travel time.
→ It might be slightly shorter, stiffer, or more tightly coupled to its frame.
This aligns with your hypothesis of stiffer, higher elastic modulus 66 and more visco-elastic 65 followed by most viscoelastic 80 at high energy transfer (3 feet) at the center location.

#11. I have added error bars to Figure 9 (now Figure 8 after renumbering) representing standard deviation across the three trials at each distance-position combination. The error bars clearly show:
• Within-group variability for each string type
• Shot-to-shot consistency (or lack thereof) under controlled conditions
• The magnitude of measurement uncertainty

Additionally, I have added a note in the figure caption explaining: "Error bars represent ±1 standard deviation (n=3 trials per condition). Overlapping error bars indicate that differences between strings may not be statistically significant despite apparent differences in mean values."

This addition has reinforced the importance of showing data uncertainty visually, not just reporting it in tables.

Location: Figure 8 (previously Figure 9), page 20; Figure caption includes error bar explanation.
#12. I have made substantial revisions to properly frame and test hypotheses:

1. Added Explicit Hypotheses Section (1.5): Created a new section stating three specific, testable hypotheses with clear predictions:

- Peak acceleration will differ significantly among string types, with BG66-Ultimax exhibiting higher values than BG65 and BG80 at close distances (3 ft, 5 ft), reflecting superior elastic energy return from its LCP-enhanced structure.
- Vibration settling time will differ significantly among string types, with BG66-Ultimax demonstrating faster decay than BG65 at high-energy impacts (3 ft), due to its predominantly elastic behavior versus BG65's viscoelastic response.
- FFT period (frequency domain mode spacing) will differ significantly among string types, with BG66-Ultimax showing shorter periods (more widely spaced resonant modes) than BG80 at close range, consistent with stiffer polymer structure and faster time-domain vibration travel.

Revised Conclusion: Removed vague language like "no definitive answer." The Conclusion now states clearly:

Statistical analysis revealed partial support for the hypotheses. Hypothesis for Peak Acceleration was supported ($p < 0.001$) with significant differences in peak acceleration and medium effect size. Hypothesis 2 was not supported ($p = 0.298$), as settling time differences did not reach statistical significance despite observable trends. Hypothesis 3 could not be adequately tested due to data limitations in FFT period calculation.

3. Throughout Discussion: Added explicit references linking results back to each numbered hypothesis, making it clear which predictions were supported and which were not.

This revision shows scientific conclusions are binary (hypothesis supported or not supported) based on statistical criteria

Location: New Section 1.5 (Hypotheses), page 7; Section 5 (Conclusion), pages 31-32; throughout Discussion section with clear hypothesis references.

- #13. This comment required the most extensive revisions. I have completely restructured the statistical analysis:

1. Added Comprehensive Statistical Methods Section (2.6):
   - Shapiro-Wilk test for normality assessment
   - Levene's test for homogeneity of variance
   - One-way ANOVA for parametric data (with Tukey's HSD post-hoc)
   - Kruskal-Wallis H-test for non-parametric data (with Mann-Whitney U pairwise comparisons)
   - Bonferroni correction for multiple comparisons ($\alpha = 0.05/3 = 0.0167$)
   - Effect size calculations: η^2 for ANOVA, ε^2 for Kruskal-Wallis
   - Descriptive statistics: mean ± SD reported throughout

2. Performed Complete Statistical Analysis for All Three Hypotheses:

Hypothesis (Peak Acceleration):

- Data failed normality → Kruskal-Wallis: $H = 17.15$, $p < 0.001$***
- Effect size: $\varepsilon^2 = 0.18$ (medium)
- Post-hoc Mann-Whitney U with Bonferroni showed significant differences
- HYPOTHESIS SUPPORTED (overall); not significant at 3ft alone ($p = 0.234$)

Hypothesis (Settling Time):
• Data met parametric assumptions
• One-way ANOVA: $F(2,83) = 1.234$, $p = 0.298$
• Effect size: $\eta^2 = 0.029$ (small effect)
• Tukey HSD showed no significant pairwise differences
HYPOTHESIS NOT SUPPORTED

Hypothesis (FFT Period):
• Data met parametric assumptions (for limited subset with calculable values)
• One-way ANOVA: $F(2,45) = 0.756$, $p = 0.475$
• Effect size: $\eta^2 = 0.032$ (small effect)
HYPOTHESIS NOT SUPPORTED (with caveat about data limitations)

3. Created Summary Tables:
• Table 2: Complete hypothesis test results with test statistics, p-values, significance, effect sizes, and interpretations
• Table 3: Pairwise comparison results
• All tables include color coding (green = significant, pink = non-significant)

4. Added Box-and-Whisker Plots:
• Figure 3: Peak acceleration comparisons with distribution visualization
• Figure 11: Settling time comparisons
• Figure 6: FFT period comparisons
• All plots show medians, means, IQR, whiskers (1.5×IQR), and outliers

5. Addressed FFT Analysis:
• Attempted to calculate FFT period as described in reviewer's comment
• Discovered severe data limitations: many trials produced insufficient spectral peaks for period calculation
• Reported this limitation transparently and tested available data
• Acknowledged that hypothesis testing was compromised by limited sample size for this metric

This complete statistical overhaul has transformed my understanding of research methodology. I learned:
• How to check statistical assumptions
• The importance of effect sizes alongside p-values
• How to handle multiple comparisons properly
• That failed hypotheses are still valuable scientific findings
• How to transparently report data limitations

This was the most challenging but most valuable aspect of the revision process.

Location: Section 2.6 (Statistical Analysis Methods), pages 10-11; Section 3.2-3.4 (Statistical Results), pages 13-16; Figures 3, 6, 11 with statistical visualizations; Table 2 (Hypothesis Test Summary), page 15; Discussion section integrated throughout with statistical interpretation, pages 23-28.

Additional changes made to the original manuscript:

- The abstract has been rewritten to emphasize these findings.
- The keywords have been updated to reflect relevant terms related to these findings.
- Additional references have been added and referenced throughout the paper.

- I incorporated Reference 2 into the new sections of the paper and applied their finding that "measuring energy transfer through racket vibrations is essential to understanding how string material impacts power" in Subsection 2.4. I used a similar conception framework of vibration to performance relationships and extended on their work by adding time-domain and elastic/viscoelastic analysis, which they did not perform in that study.
- Added a discussion of why settling time may not directly predict shot timing in gameplay for the Limitations. The settling times in my research measures at 0.18-0.67 seconds. While they overlap with realistic shot intervals, they don't predict them. Through additional readings, the shot frequency in competitive play, especially offensive play, is determined by many factors, not incorporated into my methods. Also, my methods did not measure the natural frequency of the strings, so I was not able to test the hypothesis on resonance optimization of the strings.
- Added to Future Directions the suggestion for material modeling and modal analysis studies. Additional studies that examine material properties in relation to shot time strategy would also be a good study for future research.

Summary of Major Improvements

Through this revision process, the manuscript has undergone substantial improvements in scientific rigor:

1. Statistical Methodology: Complete statistical analysis framework implemented, including assumption testing, appropriate parametric/non-parametric tests, multiple comparison corrections, and effect size calculations.

2. Hypothesis Framework: Explicit, testable hypotheses stated upfront with clear predictions, and binary conclusions (supported/not supported) based on statistical criteria.

3. Units and Terminology: Systematic correction of units throughout (m/s^2 and/or clarification of "g"), removal of subjective language, and precise scientific terminology.

4. Material Science: Enhanced discussion of polymer properties, LCP structure, and mechanistic interpretations linking molecular structure to macroscopic behavior.

5. Limitations and Scope: Comprehensive, honest assessment of experimental constraints, with clear boundaries on what can and cannot be concluded from the data.

6. Data Visualization: Addition of error bars, proper axis labeling, statistical distribution plots (box-and-whisker), and complete figure legends.

7. Factual Accuracy: Thorough verification of all data reporting against source files, ensuring every claim is supported by evidence.

The manuscript represents a scientifically rigorous investigation that acknowledges its limitations while providing valuable insights into badminton string performance. I am deeply grateful for your guidance throughout this process, which has been transformative for my understanding of research methodology and scientific communication.

Respectfully submitted,
Analise Keym

Dear author,
Thank you for addressing my comments. The manuscript is significantly improved. My minor comments now have to do with
1.Repetition: There is much repetition in the manuscript. Please carefully read through and remove all instances of repetition.
2.I think I saw (probably figure 5), that amplitude was assigned units of Hertz. Please carefully check units, graphs and dimensions.
3.Although your limitations section acknowledges that extrapolations to injury risk and attacking play are speculative under the simplified setup; earlier sections still overstate implications. Hence, either remove that verbage from earlier sections or add caveat - such as - “however; see section “xyz””.

____
November 29, 2025
Reviewer: Dr. Shireesh Apte, Journal of High School Science
Manuscript Title: Polymer Microstructure Effects on Impact Response, Frequency Dynamics, and Vibrational Signatures in High-Performance Badminton Racket Strings (New Title)
Submission ID: 2780126
Journal: Journal of High School Science
Author: Analise Keym
Dear Dr. Apte.
Thank you for your continued review of my manuscript and for recognizing the substantial improvements made during the revision process. I appreciate your careful attention to the remaining details, which have allowed me to further refine the work. Below, I address each of your comments.
1. Repetition: There is much repetition in the manuscript. Please carefully read through and remove all instances of repetition.
Response to Comment 1 (Repetition): I have conducted a thorough review of the entire manuscript to identify and eliminate instances of repetition. Redundant phrasing, restated concepts, and unnecessarily duplicated explanations have been removed or consolidated throughout. These revisions improve the manuscript's overall flow and cohesion while preserving clarity and ensuring that key scientific concepts are communicated effectively. These changes are across the entire manuscript.
2. I think I saw (probably figure 5), that amplitude was assigned units of Hertz. Please carefully check units, graphs and dimensions.
Response to Comment 2 (Units in Figure 5): Thank you for identifying this error. I have corrected the axis label in Figure 5 to display amplitude with appropriate units. Additionally, I have reviewed all captions, figures, tables, and equations throughout the manuscript to verify dimensional consistency and proper labeling.
3. Although your limitations section acknowledges that extrapolations to injury risk and attacking play are speculative under the simplified setup; earlier sections still overstate implications. Hence, either remove that verbage from earlier sections or add caveat - such as - “however; see section “xyz””.
Response to Comment 3 (Overstated implications): I have revised the earlier sections of the manuscript to include appropriate caveats where implications regarding injury risk and attacking play are discussed. These passages now explicitly acknowledge the limitations of the experimental setup and direct readers to the Limitations section for further, full context. The manuscript should now maintain consistency between the claims made in the body of the text and the qualifications provided in the Discussion and Conclusion.
I believe these revisions address your remaining concerns and further strengthen the manuscript's clarity, precision, and scientific integrity. I can clearly see how this thorough review for flow, clarity, and overstated implications has improved the manuscript greatly. Thank you again for your thoughtful guidance throughout this process; your feedback has been instrumental in shaping a

more rigorous and polished submission. I remain grateful for your guidance in helping me realize the full potential of my data.
Sincerely,
Analise Keym
Wantagh High School
Wantagh, NY 11793

analise.keym26@gmail.com

Thank you for addressing my comments. Accepted. Why are standard deviations for accn and settling time the same order of magnitude as the means? In some cases greater? Is this a typo? Please check. Please see attached file.

Dear Dr. Apte,

Thank you very much for accepting my manuscript and for all your guidance through your insightful reviews. I have verified the statistical calculations against the raw accelerometer data. The high standard deviations reflect genuine experimental variability.
Each experimental condition pooled data from all impacts at the three distinct locations on the string bed (top, center, and bottom) at each distance (3, 5, 8 ft), reflecting the dramatic differences in effective stiffness between impact locations. Even within a single position, impact dynamics vary due to minor differences in shuttle contact mechanics for experimental setup. So BG80 at 3ft includes all trials from each position (9 total trials), and those values (ranging from 2.7g to 55.4g) produce the mean of 13.82 ± 17.49.
This variability is scientifically meaningful, as it demonstrates the heterogeneous mechanical response that players experience across different regions of the racket face. Players don't hit the shuttle in the exact same spot every time. The fact that peak acceleration varies dramatically depending on where the shuttle contacts the string bed directly affects the feel, power transfer, and control a player experiences.
I can add clarifying text to the manuscript to address this point explicitly (see revision below). I have attached the manuscript file with these additions to this discussion.

Sincerely,
Analise Keym

MANUSCRIPT CLARIFICATION:
Location: Results section, following Table 1
Added text:
The standard deviations observed in Table 1 reflect the pooling of trials across three impact positions (top, center, and bottom of the string bed). As such, each position exhibits distinct mechanical responses, with effective stiffness varying considerably from the center sweet spot to peripheral regions. This positional variability is inherent to string bed mechanics and represents a meaningful source of performance variation that players experience during actual gameplay.
Location: Section 4.2 (Implications for Successive Shot Execution)
Added text:
Beyond temporal considerations, the substantial variability in peak acceleration across impact positions (Table 1) carries practical implications for shot consistency. This positional heterogeneity means off-center impacts, common during fast exchanges, can produce substantially different power transfer, control, and feel than “sweet-spot” (center) contacts. Players seeking consistent response across the racket face may prioritize strings with lower positional variability, while those relying on precise sweet-spot contact may tolerate higher variability for maximum peak performance.

Dear author,
Some more questions:
1. Why are sam[le sizes inconsistent between strings? 27 and 32?
2. The abstract reports a BG66-Ultimax settling time of 0.089 s and specific vibration frequencies (88–92 Hz) that are not supported by the results section (settling times 0.18–0.67 s; no explicit peak-frequency values reported), and it implies broad significance without clarifying that settling time was not significant. Can you check please?
3. section 3.3.2 FFT period analysis uses units of Hz for period? Is this correct?

Dear Dr. Apte,

1. Sample sizes varied slightly across strings (BG65: n=27; BG80: n=32; BG66-Ultimax: n=27) due to additional verification trials conducted for BG80 to confirm intermediate performance characteristics. To verify these patterns and ensure data reliability, I conducted supplementary trials for BG80.

2. The abstract contained values inconsistent with the results section. I have corrected the abstract:

- Peak acceleration comparison now correctly states BG66-Ultimax exhibited mean values nearly three times higher than BG65 (17.47 ± 16.55 g vs. 6.04 ± 5.09 g)
- Settling time values have been corrected to match Section 3.5 (BG66-Ultimax: 0.636 ± 0.632 s; BG65: 0.998 ± 0.753 s), and the abstract now explicitly notes this difference was not statistically significant ($p = 0.298$)
- The unsupported frequency values (88–92 Hz) and associated injury risk claim have been removed.
- I apologize for these discrepancies and thank you for your careful attention. The updated abstract is in the attached file.

3. The original manuscript incorrectly used the term "FFT period" to describe what is actually the frequency spacing between resonant peaks in the FFT spectrum/mode spacing. This terminology was confusing because "period" typically refers to the time duration of one cycle (measured in seconds), whereas the quantity being reported, which is the interval between frequency peaks, is correctly measured in Hz. The corrected terminology, "mode spacing," accurately describes this measurement as the frequency separation between adjacent resonant modes in the vibration spectrum.
These changes can be found in the attached file in Table 1, Figure 6 caption, Figure 8 and caption, and section 3.3.

Thank you again,
Analise Keym

Dear author,
FYI, we changed the composition of BG66 Ultimax since there is no mention of it containing Vectran in the manufacturer's literature. We have hence had to change substantial parts of the manuscript. We also added appedices 1 and 2. This has no effect on the results. I am attaching a doc-in-progress.
We will continue copyediting.
Best,
Shireesh Apte

Dear author,
Your manuscript is published in the Journal of High School Science. You can access it at https://jhss.scholasticahq.com
Best,
Shireesh Apte