



Polymer microstructure effects on impact response, frequency dynamics, and vibrational signatures in high-performance badminton racket strings

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Abstract

Despite substantial research on badminton equipment performance, limited quantitative analysis exists linking polymer string microstructure to player-specific performance outcomes. This study investigated the mechanical behavior of three Yonex BG series multifilament strings: BG66-Ultimax, BG65, and nylon/Vectran[®]-core BG80—to evaluate potential suitability for offensive playing styles. High-precision accelerometry was employed to measure impact dynamics across three distances (3, 5, and 8 feet) and three string-bed zones (top, center, bottom). MATLAB-based signal processing characterized acceleration patterns, frequency responses via Fast Fourier Transform, and viscoelastic behavior through Hilbert transform analysis and settling time calculations. Statistical analysis found significant differences in peak acceleration among string types (Kruskal-Wallis $H = 17.15$, $p < 0.001$, $\epsilon^2 = 0.18$). BG66-Ultimax exhibited dominant elastic behavior with mean peak accelerations \sim three times greater than BG65 (17.47 ± 16.55 g vs. 6.04 ± 5.09 g), consistent with rapid energy return, and consistent power generation across impact zones. BG65 demonstrated pronounced viscoelastic damping with gradual decay patterns, providing characteristics associated with control-oriented play at the expense of power efficiency. BG80 displayed balanced intermediate characteristics. While descriptive settling time data showed BG66-Ultimax with shorter mean settling times (0.636 ± 0.632 s) compared to BG65 (0.998 ± 0.753 s), this difference was not statistically significant ($p = 0.298$). These findings establish a quantitative framework that potentially links polymer microstructure to performance metrics and evidence-based string selection for attacking players. The analytical methods developed may be extended to vibration characterization studies in other racket sports.

Keywords

Polymer microstructure, Sports equipment mechanics, Accelerometry, FFT analysis, Viscoelastic materials, Elastic materials, Badminton strings, Racket dynamics, Yonex BG series, Athletic injury prevention

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1. Introduction

Over the past few decades, the main goal of several badminton manufacturers— including Yonex—has been clear: efficiency. This increased priority on efficiency has led to the development of new and increasingly advanced materials that improve player performance. Specifically, the development of high-modulus carbon graphite has produced stronger and more stable racket frames, thereby providing players with more power and control (1).

In conjunction with the aforementioned developments in rackets, recent advancements in string technology, including hybrid strings employing multi-material polymer compositions, aim to boost racket performance by also enhancing power, control, and durability (2). Moreover, new string plane design innovations are revolutionizing badminton, making shots more accurate, powerful, and fast (3). These technological advances have elevated the overall level of badminton play, leading to improved player performance (1). But as badminton equipment develops, athletes hoping to maximize their performance increasingly depend on knowing how these developments affect gameplay.

1.1 Gap

Despite substantial research on general badminton equipment performance, there is limited research surrounding the impact of string material on attacking players' performance. The existing literature on badminton equipment predominantly focuses on racket frame materials and overall player performance (4-6) without considering the

nuanced interactions between string materials and an offensive players' specific needs and preferences (2, 7). Understanding this interaction is crucial for refining equipment recommendations for optimizing play. This study aims to help players and coaches make informed decisions on string selection to enhance speed, precision, and power, while also providing manufacturers with data to refine future string designs for offensive play.

1.2 Literature review: evolution of badminton equipment

Badminton equipment manufacturers' innovations in material optimization were initially on racket material and design. Although rackets were first made of wood, subsequent advancements have resulted in the evolution of composite materials including steel, fiberglass, aluminum, carbon, graphite, and boron (7, 8, 9). As badminton gains popularity globally, manufacturers, such as Yonex, continue to innovate all equipment they manufacture to enable players to perform at unprecedented levels while modernizing the sport.

Technological developments are also evident in badminton string materials. The earliest strings were natural gut as they could maintain strength and durability due to their thickness (10). However, strings have evolved into complex nylon materials made from advanced synthetic polymers, offering greater flexibility (11,12).

These modern synthetic strings are categorized as monofilament and multifilament strings with a structure consisting of three layers: the core, sheath, and coating (Figure 1) (13). The simplest

string is the monofilament string made from a single strand of fiber and is commonly a polyester or polyether material, which may or may not accommodate a sheath and/or coating (14). In contrast, multifilament strings, such as Yonex BG65, Yonex BG80 and Yonex BG66 Ultimax are made from several fibers twisted together, again, with or without a sheath and/or coating (14, 15). Polymer-based badminton

strings exhibit both elastic and viscoelastic properties (16, 17). Elastic responses are instantaneous and reversible, as energy stored during deformation is rapidly returned when the load is released. Viscoelastic responses involve time-dependent recovery where energy dissipates more slowly due to internal friction within polymer chains (18, 19).

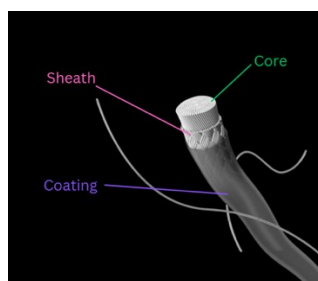


Figure 1. The composition of a badminton string

Beyond instantaneous energy transfer, the temporal characteristics of string vibration decay are critical for successive shot execution. In high-level play, attackers must execute rapid exchanges with minimal time between impacts. The strings' vibration settling time (duration required for string oscillations to decay substantially) directly affects readiness for the next shot. Strings that continue vibrating may interfere with control and energy transfer in subsequent impacts.

1.3 Impact of string material on attacking players' performance

Mechanical characteristics relevant to offensive play, such as power transfer, speed, and accuracy, may be affected by string material during a match (11). Attacking players prefer to play shorter points with control and precision,

while being aggressive on the shuttle and against their opponent (14). Unlike defensive players or beginners, they prioritize speed and aggression, necessitating equipment that improves their ability to generate powerful shots (14). This is important for offensive athletes to generate powerful smashes and flat, hard drives, put pressure on their opponents, end points quickly, disrupt their opponent's rhythm, and control the net with drop shots, pushes, and fast net shots (29).

These performance characteristics emerge from complex mechanical interactions during shuttlecock impact. Factors such as racket design, string characteristics, shuttle properties, impact location, and player technique may influence stress transfer and vibration from racket to player and shuttlecock. Regarding

strings, a study by Takizawa et al. (3) performed a simulation to examine various string configurations, finding that thinner, high-tension strings increased shuttlecock velocity due to better energy transformations. Similarly, Nor Azman and Sanusi (11) analyzed polymer-based string cores and determined that string made from polyphthalamide was superior with regard to overall performance. The physical properties of badminton strings influence the characteristics of strings and, therefore, impact player performance. Informed choice in strings should be a critical decision made by players seeking high-level performance.

Yonex, an industry-leading badminton brand, rates its strings on a 10-point scale for 5

characteristics (see Figure 2) (17). However, they do not recommend specific strings for different playing styles, leaving athletes to make uninformed selection decisions. Polymer-based strings exhibit varying recovery rates after impact, as some recover almost immediately, favoring rapid exchanges and sharper control, while others continue vibrating longer, potentially affecting subsequent shot power and stability (20). Time-domain decay characteristics may be particularly relevant for rapid-exchange scenarios where shot frequency contributes to offensive effectiveness, with the balance between energy return and damping being critical for both performance optimization and potential injury risk mitigation in sporting equipment (20).

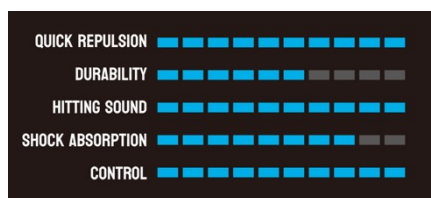


Figure 2. Visual representation of Yonex string characteristics (9)

Previous studies have shown that badminton's demanding postures, repetitive movements, and hand-arm vibration create risk factors for upper limb musculoskeletal disorders including tingling, inflammation, and weakness (24, 26). Additionally, vibration dampers and sweet spot optimization have shown limited success in reducing impact discomfort (27), suggesting string material selection may influence mechanical vibration exposure. Quantitative characterization of string vibration behavior provides a foundation for evidence-based

equipment selection that considers both tactical requirements and vibration exposure.

1.4 Research hypotheses

The fundamental differences in polymer microstructure among monofilament, and multifilament strings; with additional manufacturing-imparted and composition differences; should manifest in measurable performance differences during shuttlecock impact. Drawing from polymer mechanics theory and prior sports equipment studies (2, 17-

19), specific predictions can be derived regarding how these materials will behave under controlled loading conditions.

During the brief shuttlecock-string contact period elastic materials store deformation energy and release it rapidly, maximizing energy transfer to the projectile. In contrast, viscoelastic materials dissipate energy through internal friction, reducing transfer efficiency. The multifilament high-intensity, high molecular weight, nylon multifilament, lowest gauge, BG66-Ultimax, with high elastic modulus and minimal internal damping, should therefore produce the highest peak accelerations. The (relatively) unstretched, low molecular weight, multifilament nylon, BG65, with the greatest gauge and greater fiber-to-fiber friction and viscoelastic damping, should yield the lowest peak accelerations. The medium gauge, combination of (relatively) unstretched nylon and Vectran[®]-based BG80 should exhibit intermediate behavior. These material property differences should translate into statistically significant performance disparities (ANOVA or Kruskal-Wallis H-test; $\alpha = 0.05$), particularly at 3 ft distance where impact energy would be greatest. See Appendix 1 for a comparison of string characteristics and Appendix 2 for a comparison of polymer characteristics.

Beyond immediate energy transfer, the rate at which vibrations decay influences equipment readiness for rapid successive shots. The vibration envelope represents the amplitude boundary of oscillations following impact and shows how quickly each string returns to baseline after contact with the shuttlecock.

Elastic strings should recover quickly as stored energy dissipates efficiently, while viscoelastic strings should exhibit prolonged settling periods. Quantifying this through settling time measurement (the duration required for vibration amplitude to decay to 5% of its peak value) should reveal that BG66-Ultimax recovers fastest, BG65 slowest, with BG80 intermediate.

The wave propagation characteristics within the string-bed, revealed through frequency-domain analysis, provide additional insight into material behavior. The spacing between resonant modes in the frequency spectrum (FFT mode spacing) is expected to differ systematically among strings, with patterns reflecting variations in stiffness and wave velocity. The following sections detail the experimental methods employed to test these hypotheses.

2. Materials and Methods

This quantitative investigation integrated multiple physical assessments to evaluate string material effects on performance. Extending the work of Arianto et al. (30) on string tension, this study examined how specific material properties influenced attacking player efficiency. Clinical validation through future player-centered studies will be necessary to establish direct links between these mechanical findings and gameplay performance or injury outcomes.

2.1 Research design

A controlled experimental design was employed to isolate the effects of string material type by standardizing environmental conditions

(temperature, humidity, air pressure, lighting) across all trials (2, 30) to ensure validity.

2.2 Racket, strings, and shuttlecock selection

The Yonex Astrox 88 S Pro racket was chosen as it features a stiff graphite shaft that improves shot control while the Rotational Generator System shifts weight distribution to enhance swing speed (9). Understanding how different polymer strings interact with its shaft and head-heavy balance can inform playstyle-based equipment recommendations.

The Yonex BG series strings are made from different types of polymer materials and manufactured for specific performance characteristics. The material properties of strings, including thickness and elasticity, play a critical role in determining the performance characteristics of badminton rackets (14). This study focused on three strings from the BG series—Yonex BG80, BG65, and BG66-Ultimax. Their popularity among professional players and distinct polymer compositions made these strings ideal for this study, allowing for a comparison of performance outcomes (9). While they are all made from high-quality polymers, they differ in type and arrangement, which influence their performance.

The BG80 is constructed with a combination of (relatively) unstretched nylon and Vectran[®] as its core material. Vectran[®] is a high-performance liquid crystalline polymer (LCP) manufactured from aromatic polyester (38). LCPs such as Vectran[®], exhibit highly ordered molecular chain structures that align parallel to the fiber axis, resulting in exceptional tensile strength,

low creep, and a high Young's modulus of approximately 60-80 GPa, significantly greater than that of conventional (unstretched) nylon (2-3 GPa) (16, 17, 20, 21, 39, 40). This ordered chain structure provides high repulsion and rapid energy transfer during impact (9).

The BG65 features a high-polymer nylon multifilament core wrapped in a braided nylon outer layer, offering high durability and repulsion through its bundled fiber construction (9, 15).

The BG66-Ultimax is similar in polymeric composition with the BG65 but uses 'high intensity' nylon multifilament fibers. This probably implies that the high molecular weight nylon fibers are stretched during manufacturing so that the polymer chains are aligned and provide greater crystallinity (and hence elasticity) to the drawn, thin gauge, crystalline final core. This 'high intensity' core is then wrapped in a braided nylon outer layer, similar to the BG65. Additionally, the BG66-Ultimax features a uniquely designed polymer coating that further enhances speed, control, and repulsion (9). This aligned, drawn, (relatively) higher molecular weight, crystalline, low gauge architecture, combined with the specialized coating, produces different mechanical behavior despite sharing nylon66 as a core material (Appendix 2)

String tension was set to a constant 24 lbs., as used in other studies (30), ensuring consistency and comparability while isolating the independent variable—string material. Additionally, the racket was strung using a

Wilson Baiardo machine; the same machine used in the U.S. Open. It is guaranteed to be accurate to 1/10 lb. of the desired tension. Furthermore, the same expert stringer was used to string the racket each time.

The Yonex AEROSSENSA 50 shuttlecock was selected for its demonstrated consistency in prior research (2) and widespread use among competitive players. Digital balance scale measurements confirmed minimal weight variability among shuttlecocks, ensuring that performance differences were attributable to string properties rather than projectile inconsistencies (2).

2.3 Test equipment selection

This investigation adapted the methodology of Suwannachote et al. (2), employing accelerometry, automated shuttlecock projection, and FFT analysis to characterize string vibration responses.

The “Time Out Automatic Portable Badminton Pitcher” was used to reliably and consistently serve the Yonex AEROSSENSA 50 shuttlecocks to the experimental racket set up. The Radar Gun feature in the Pitch Counter mobile app on an iPhone 12 Pro was used to test the speed of the shuttlecock launched from the Pitcher. Although shuttle speeds in elite badminton play can exceed 250 mph (≈ 111 m/s) during professional smashes (37), this study used a fixed shuttle release velocity of 15 mph (≈ 6.7 m/s), as consistently measured when released from the Pitcher. Despite this lower than

professional gameplay speeds, mechanical consistency and data fidelity across trials could be maintained for this study. By using a reproducible, moderate-speed input, the study isolated relative differences in vibration and recovery behavior among string materials without additional factors such as impact angle variability or frame deflection. Therefore, the results characterize the intrinsic elastic and viscoelastic responses of the strings under controlled loading conditions, not full-game shuttle dynamics.

Impact-induced vibrations were measured using the Witmotion WT901BLECL5.0, a high-precision 3-axis accelerometer, gyroscope, and magnetometer that provided stable, high-quality data output for repeated measurements under varying conditions (31, 32). This sensor directly captured the mechanical response of string materials during shuttlecock impact, enabling quantitative characterization of performance-relevant vibration behavior. Its compact dimensions ($1.42 \times 0.59 \times 2.02$ inches) and low mass (30 grams) minimized interference with racket dynamics (31).

The accelerometer recorded acceleration along the X, Y, and Z axes in g-units ($1 \text{ g} = 9.81 \text{ m/s}^2$), which were converted to SI units (m/s^2) and combined into total acceleration magnitude using Equation 1. Raw data were transmitted via Bluetooth to the WitMotion application and exported in MATLAB (.mat) format for analysis (33).

$$a_{total} = \sqrt{(a_x)^2 + (a_y)^2 + (a_z)^2}$$

Equation 1. Formula used to compute total acceleration magnitude from 3-axis accelerometer data.

Fast Fourier Transform (FFT) analysis was employed to convert time-domain acceleration data into frequency-domain representations, revealing the dominant oscillation frequencies and energy distribution patterns characteristic of each string type. This approach, validated in prior racket sports studies (2, 24), enabled the identification of vibration modes that influence both performance characteristics and injury risk. Additionally, Hilbert transform analysis extracted vibration envelopes to quantify settling times and characterize elastic versus viscoelastic decay patterns. These computational methods, implemented via MATLAB scripts (2, 34), provided quantitative metrics for polymer relaxation behavior and energy dissipation across impact distances.

$$X[k] = \sum_{n=0}^{N-1} x[n]W_N^{kn}$$

$X[k]$ is the DFT output at index k .

$x[n]$ is the input time-domain signal at index n .

N is the total number of points in the signal.

$W_N = e^{-j\frac{2\pi}{N}}$ is the twiddle factor.

k, n range from 0 to $N - 1$.

j is the imaginary unit ($j^2 = -1$).

Equation 2. Fast Fourier Transform

2.4 Experimental setup

Following instrumentation calibration, the experimental setup was configured to maintain controlled testing conditions. A clamp was used to securely hold the racket in place, preventing unintended movement or additional vibrations that could interfere with the data (2). The WitMotion accelerometer was attached to the lower shaft of the racket by a wire cable tie to measure acceleration/vibration. The racket, strung with one of the three selected string

materials, underwent baseline testing to establish initial performance metrics and verify measurement consistency (30).

The experimental phase involved testing each string at three distances—3 feet (ft), 5 feet, and 8 feet—representing various scenarios in an actual game where shots might be executed from different positions on the court (30). For each string, three trials were conducted at each of 3 selected positions on the racket head, totaling nine trials per string type at each distance. The

Badminton Pitcher was used to launch shuttlecocks at a consistent speed and angle ensuring uniformity across trials.

During each trial, the accelerometer recorded time-series acceleration data (in m/s^2) indicating the dynamics of how the shuttlecock interacted with the strings. This data in .mat format was then analyzed by MatLab software as total acceleration across the X, Y, and Z axes.

The FFT analyzer transformed the accelerometer data (m/s^2 , where $1\text{ g} = 9.81\text{ m/s}^2$) to vibration data in Hertz (Hz) in MatLab to better evaluate the energy transfer efficiency of each shot. This allowed efficient and stable processing of large datasets (35). As noted by Suwannachote et al. (2), measuring energy transfer through racket vibrations is essential to understanding how string material impacts power, generated to the greatest extent during smashes (14).

2.5 Elastic and viscoelastic time-domain analysis

To examine elastic and viscoelastic string responses in the time domain, acceleration-time data from center impacts at 3, 5, and 8 ft were analyzed to observe deformation and recovery patterns. The overall decay patterns were characterized qualitatively by their envelope shapes, or how the vibration amplitude boundary changed over time. Rapid initial decay followed by quick stabilization suggested predominantly elastic behavior with rapid energy return. Gradual, sustained amplitude growth indicated viscoelastic behavior with slower energy dissipation. These patterns were

examined in relation to polymer relaxation behaviors documented in prior studies (2, 3).

Amplitude–time decay curves, string type and distance were modeled using exponential curves to show how fast each string returned to rest. Strings that snapped back very quickly were described with a single curve, showing mostly elastic behavior. Strings that had a fast rebound followed by a slower settling period were described with two curves, showing a mix of elastic and viscoelastic behavior.

This approach follows methods used in prior polymer creep and stress-relaxation research (21, 22) and in sports-equipment testing (20), where viscoelastic damping and recovery are measured to link material properties with performance and injury prevention.

2.6 Time-domain envelope analysis

To assess the suitability of each string for rapid successive shots, vibration envelope analysis was performed using the Hilbert transform in MATLAB. The envelope function extracts the amplitude boundary of oscillating acceleration data, revealing how vibration intensity decays over time following impact. For each trial, the vibration envelope was computed from the total acceleration signal. The settling time was defined as the duration from peak impact until the envelope amplitude decreased to 5% of its maximum value, a threshold indicating the racket had substantially returned to a quiescent state. This metric quantified how quickly each string "quieted down" and became ready for the next impact, which may be relevant for rapid exchanges, though actual gameplay readiness

depends on additional factors in conjunction with string mechanics.

2.7 Statistical analysis

Data were analyzed using Python (version 3.11) with NumPy, SciPy, and Pandas libraries. For each string type and test condition, three trials were conducted and analyzed, yielding peak acceleration, settling time, and mode spacing metrics across nine total measurements per string type per distance (three positions \times three trials).

Prior to hypothesis testing, statistical assumptions were verified. Normality of distributions was assessed using the Shapiro-Wilk test, and homogeneity of variance was evaluated using Levene's test. When both parametric assumptions were satisfied (normality: $p > 0.05$ for all groups; homoscedasticity: $p > 0.05$), one-way analysis of variance (ANOVA) was performed to compare means across the three string types.

Following significant ANOVA results ($p < 0.05$), Tukey's Honest Significant Difference (HSD) post-hoc test was applied for pairwise comparisons to identify which specific string pairs differed significantly while controlling for family-wise error rate.

When parametric assumptions were violated (non-normal distributions or heterogeneous variances), the non-parametric Kruskal-Wallis H-test was employed as an alternative to ANOVA. For significant Kruskal-Wallis results ($p < 0.05$), Mann-Whitney U tests were conducted for pairwise comparisons with

Bonferroni correction applied to control family-wise error rate ($\alpha_{\text{adjusted}} = \alpha/k$, where k = number of comparisons = 3).

Effect sizes were calculated to quantify the magnitude of differences independent of sample size. For ANOVA, eta-squared (η^2) was calculated, where values of 0.01, 0.06, and 0.14 represent small, medium, and large effects, respectively. For Kruskal-Wallis tests, epsilon-squared (ϵ^2) was calculated using the formula $\epsilon^2 = (H - k + 1)/(n - k)$, where H is the test statistic, k is the number of groups, and n is the total sample size. Statistical significance was set at $\alpha = 0.05$ for all tests. Descriptive statistics are presented as mean \pm standard deviation (SD). For each hypothesis test, the test statistic, degrees of freedom (where applicable), exact p -value, and effect size are reported. Box-and-whisker plots were generated to visualize distributions, with boxes representing the interquartile range (IQR, 25th-75th percentiles), horizontal lines indicating medians, diamonds showing means, whiskers extending to $1.5 \times \text{IQR}$, and circles representing outliers beyond this range.

3. Results

Statistical hypothesis testing and comprehensive vibration characterization were performed on 86 measurements distributed across three string types (BG65: $n=27$; BG80: $n=32$; BG66-Ultimax: $n=27$), three impact distances (3, 5, 8 ft), and three string-bed positions (bottom, center, top). Accelerometer data yielded peak acceleration, from which settling time, and frequency-domain metrics were calculated to evaluate the predictions outlined in Section 1.5.

The Sample sizes varied 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, supplementary trials for BG80 were performed.

3.1 Statistical overview

Summary statistics by string type and distance are presented in Table 1.

Table 1. Summary statistics for peak acceleration, settling time, and mode spacing across three string types (BG65, BG80, BG66-Ultimax) and three distances (3 ft, 5 ft, 8 ft). Values are reported as mean \pm standard deviation. Sample size (n) represents the number of successful measurements for each condition. Mode spacing values have smaller sample sizes due to data quality constraints (many trials did not yield calculable frequency peaks).

String Type	Distance	n	Peak Accel. (g)	Settling Time (s)	Mode Spacing (Hz)
BG65	3ft	10	8.58 \pm 7.31	0.57 \pm 0.77	1.15 \pm 0.24
BG65	5ft	9	5.11 \pm 2.75	1.21 \pm 0.61	1.72 \pm 0.40
BG65	8ft	8	3.90 \pm 2.64	1.30 \pm 0.76	1.70 \pm 0.65
BG80	3ft	9	13.82 \pm 17.49	0.58 \pm 0.71	2.02 \pm 1.51
BG80	5ft	11	12.14 \pm 8.53	0.73 \pm 0.80	1.59 \pm 0.86
BG80	8ft	12	12.68 \pm 9.41	0.82 \pm 0.79	1.45 \pm 0.59
BG66-Ultimax	3ft	9	13.80 \pm 10.62	0.53 \pm 0.57	1.31 \pm 0.39
BG66-Ultimax	5ft	9	14.62 \pm 11.34	0.83 \pm 0.74	1.46 \pm 0.01
BG66-Ultimax	8ft	9	24.01 \pm 24.72	0.55 \pm 0.65	1.42 \pm 0.42

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.

All metrics exhibited substantial within-group variability (coefficients of variation often exceeding 50%), indicating shot-to-shot variability inherent to shuttlecock-string impact dynamics under controlled conditions. Formal hypothesis testing and detailed vibration characterization follow.

3.2 Peak acceleration

Peak acceleration values exhibited non-normal distributions for all string types (Shapiro-Wilk test: BG65, $W=0.71$, $p<0.001$; BG80, $W=0.80$, $p<0.001$; BG66-Ultimax, $W=0.75$, $p<0.001$) and unequal variances (Levene's test: $F=3.69$,

$p=0.029$). Therefore, the non-parametric Kruskal-Wallis H-test was employed.

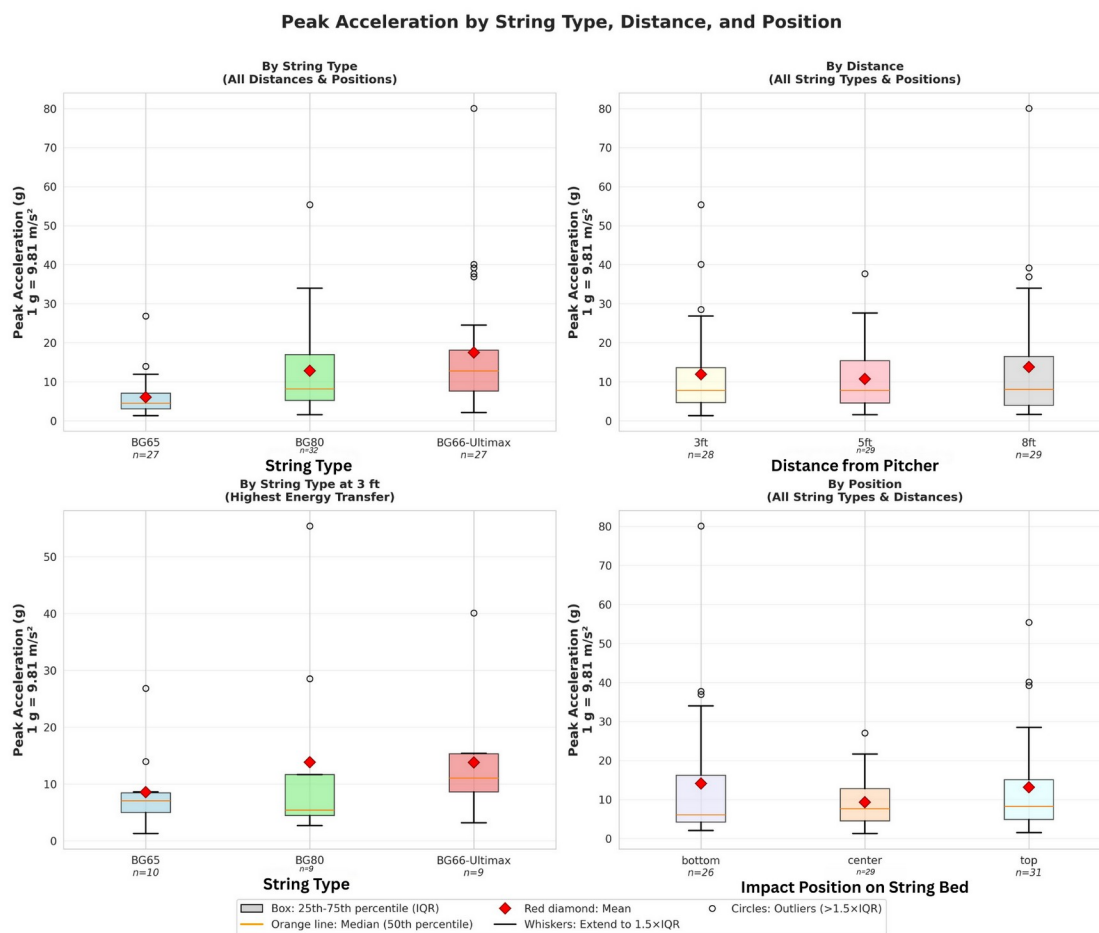


Figure 3. Peak acceleration (g) comparisons among string types. (A) Overall comparison across all conditions. (B) By distance. (C) At 3 ft (highest impact energy). (D) By string-bed position. Boxes show interquartile range (IQR), orange lines indicate medians, red diamonds show means, whiskers extend to $1.5 \times \text{IQR}$, and circles represent outliers. BG66-Ultimax and BG80 produced significantly higher peak acceleration than BG65 ($p < 0.01$).

Peak acceleration differed significantly among string types ($H = 17.15$, $p < 0.001$, $\varepsilon^2 = 0.18$), representing a medium effect size. Mean peak accelerations were: BG65 = 6.04 ± 5.09 g, BG80 = 12.82 ± 11.41 g, and BG66-Ultimax = 17.47 ± 16.55 g.

Post-hoc Mann-Whitney U tests with Bonferroni correction ($\alpha = 0.0167$) found that BG66-Ultimax produced significantly higher peak acceleration than BG65 (median difference = 8.29 g, $p < 0.001$). BG80 produced significantly higher peak acceleration than BG65 (median difference = 3.67 g, $p = 0.002$).

No significant difference was observed between BG66-Ultimax and BG80 (median difference = 4.61 g, $p = 0.226$). These findings support the first prediction stated in Section 1.5, confirming that strings with higher elastic moduli (BG66-Ultimax and BG80) produce significantly greater peak accelerations than the more viscoelastic BG65.

Table 2. Summary of statistical hypothesis test results for all three predictions: test statistic, p-value, significance determination, effect size, and interpretation (for each hypothesis). Green shading=statistically significant results ($p < 0.05$); pink shading=non-significant results.

Hypothesis	Test Used	Statistic	p-value	Result	Effect Size	Interpretation
H1: Peak Acceleration (Overall)	Kruskal-Wallis	H = 17.15	$p < 0.001^{***}$	SIGNIFICANT	$\epsilon^2 = 0.18$ (Medium)	BG66-Ultimax & BG80 > BG65
H1: Peak Acceleration (at 3ft)	Kruskal-Wallis	H = 2.91	$p = 0.234$	Not Significant	$\epsilon^2 = 0.04$ (Small)	No significant difference at highest energy transfer
H2: Settling Time	Kruskal-Wallis	H = 2.42	$p = 0.298$	Not Significant	$\epsilon^2 = 0.005$ (Very Small)	Trends suggest BG66 fastest, but not statistically significant
H3: FFT Period (at 3ft)	ANOVA	F = 1.15	$p = 0.369$	Not Significant	$\eta^2 = 0.25$ (Large)	Insufficient sample size (n = 2-5 per group)

Table 3. Pairwise comparisons of peak acceleration among string types using Mann-Whitney U tests with Bonferroni correction ($\alpha = 0.0167$). Median differences, p-values, and significance determinations are provided. Checkmarks (✓) indicate statistically significant differences; X marks indicate non-significant differences.

Pairwise Comparison	Median Difference	p-value	Significance	Interpretation
BG66-Ultimax vs BG65	8.29 g	$p < 0.001^{***}$	✓ SIGNIFICANT	BG66-Ultimax produces significantly higher peak acceleration
BG80 vs BG65	3.67 g	$p = 0.002^{**}$	✓ SIGNIFICANT	BG80 produces significantly higher peak acceleration
BG66-Ultimax vs BG80	4.61 g	$p = 0.226$	X Not Significant	No significant difference between these two strings

The temporal patterns of acceleration during shuttlecock impact varied across distances and string-bed positions, providing insight into the dynamics of energy transfer. BG65 across all string-bed positions. This pattern was particularly pronounced at the bottom and top positions where maximum energy transfer occurs. At 5 ft distance, the relative performance ranking remained consistent (BG66-Ultimax \geq BG80 > BG65), though absolute acceleration magnitudes

At the 3 ft distance, BG66-Ultimax and BG80 exhibited higher peak accelerations compared to

decreased due to reduced impact energy. At 8 ft distance, the greatest absolute peak accelerations were observed, likely reflecting optimal impact conditions at this shuttle trajectory.

Impact position on the string-bed influenced

acceleration magnitudes, with bottom and top positions generally producing higher peaks than center impacts. This positional effect was consistent across all string types, suggesting that the tension and geometric characteristics of the string-bed, rather than material properties alone, influenced impact location sensitivity.

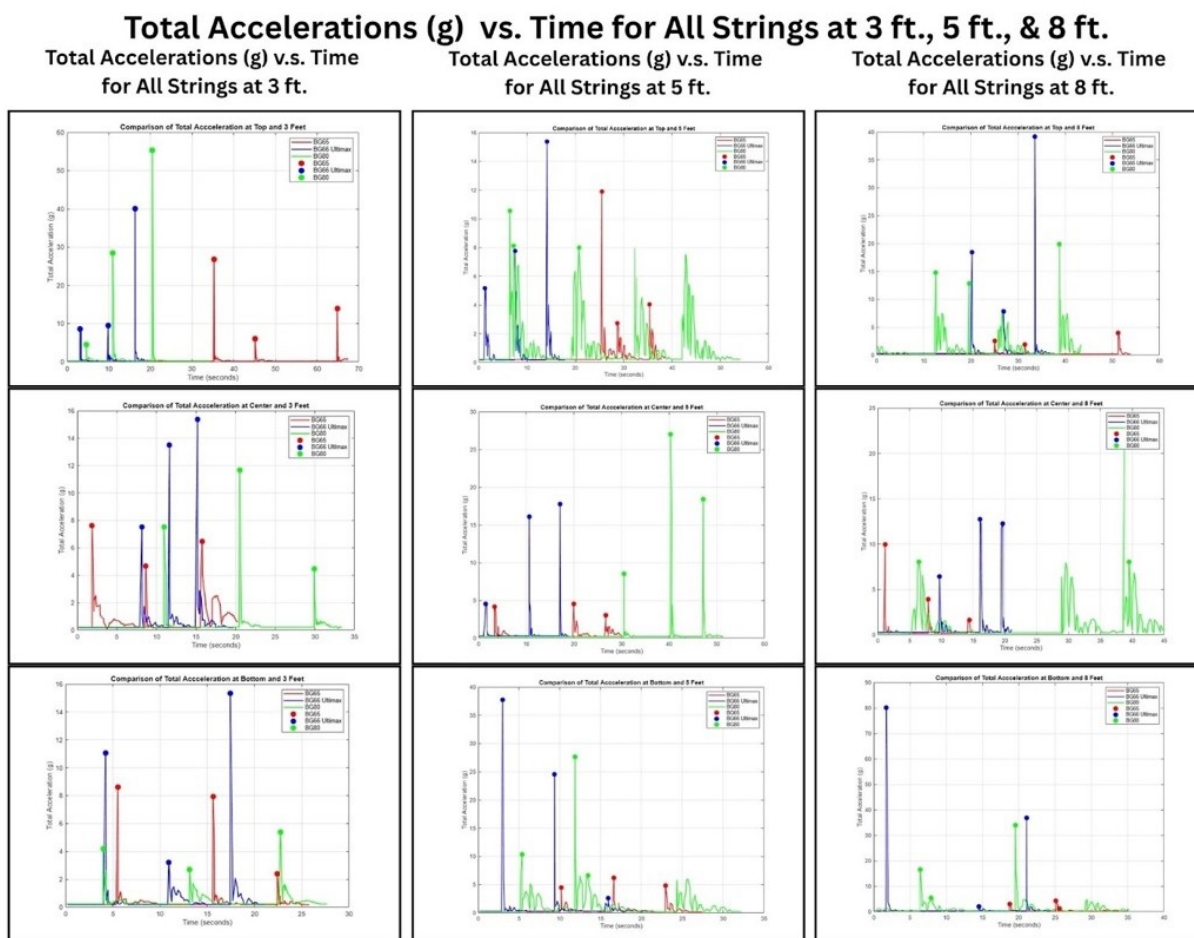


Figure 4. Time-series acceleration measurements (g) during shuttlecock impacts at three distances (3, 5, 8 ft) and three string-bed positions (bottom, center, top). Colored lines represent string types (BG65=red, BG80=green, BG66-Ultimax=blue). Three distinct peaks per condition represent individual trials. BG66-Ultimax and BG80 exhibited higher peak accelerations than BG65 across most conditions. Time labels indicate continuous recording times.

When analyzed separately for the 3 ft condition alone (highest energy transfer), peak accelerations did not show statistically significant differences among string types (Kruskal-Wallis $H = 2.91$, $p = 0.234$, $\varepsilon^2 = 0.04$). This lack of significance likely reflects the high within-distance variability and relatively small sample sizes at this specific distance (BG65: $n=10$; BG80: $n=9$; BG66-Ultimax: $n=9$). Descriptive statistics remained consistent with overall patterns: BG65 = 8.58 ± 6.94 g, BG80 = 13.82 ± 16.49 g, BG66-Ultimax = 13.80 ± 10.01 g.

3.3 Fourier analysis

3.3.1 Frequency-domain analysis

Fast Fourier Transform (FFT) analysis was

performed on acceleration time-series data to characterize the frequency content of string vibrations following shuttlecock impact. FFT analysis found differences in vibration intensity among string types. The BG65 exhibited the highest amplitude peak, the BG80 showed a moderate amplitude peak, and the BG66-Ultimax illustrated the lowest amplitude peak across all distances, with a broader frequency distribution at higher impact heights. At a distance of 3 ft the differences between string sets were clearly defined, at 5 ft the results remained mainly consistent, and at 8 ft the peak amplitude of BG65 increased further. Meanwhile, the BG66-Ultimax continued to demonstrate the lowest vibration, but its frequency response broadened slightly.

FFT Analyzer Results from all Trials and Strings

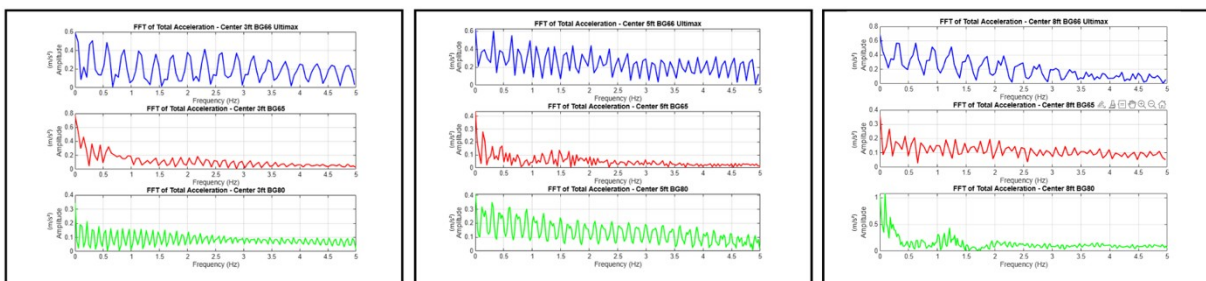


Figure 5. Frequency-domain characteristics from Fast Fourier Transform analysis. Vertical axis shows amplitude (m/s^2), horizontal axis shows frequency (Hz). BG65 exhibited highest amplitude peaks (greatest vibration intensity), BG80 showed moderate peaks, and BG66-Ultimax demonstrated lowest amplitude with broader frequency distribution. Distinct peaks indicate resonant vibration modes reflecting material properties and microstructure.

3.3.2 Mode spacing analysis

Beyond these dominant frequency characteristics, quantitative analysis of mode spacing, or the frequency interval between resonant peaks, was attempted but severely

limited by data quality. Clear frequency peaks suitable for mode spacing calculation were present in only a subset of trials. At 3 ft distance, calculable mode spacing values were obtained

for only BG65 (n=3), BG80 (n=2), and BG66- Ultimax (n=5).

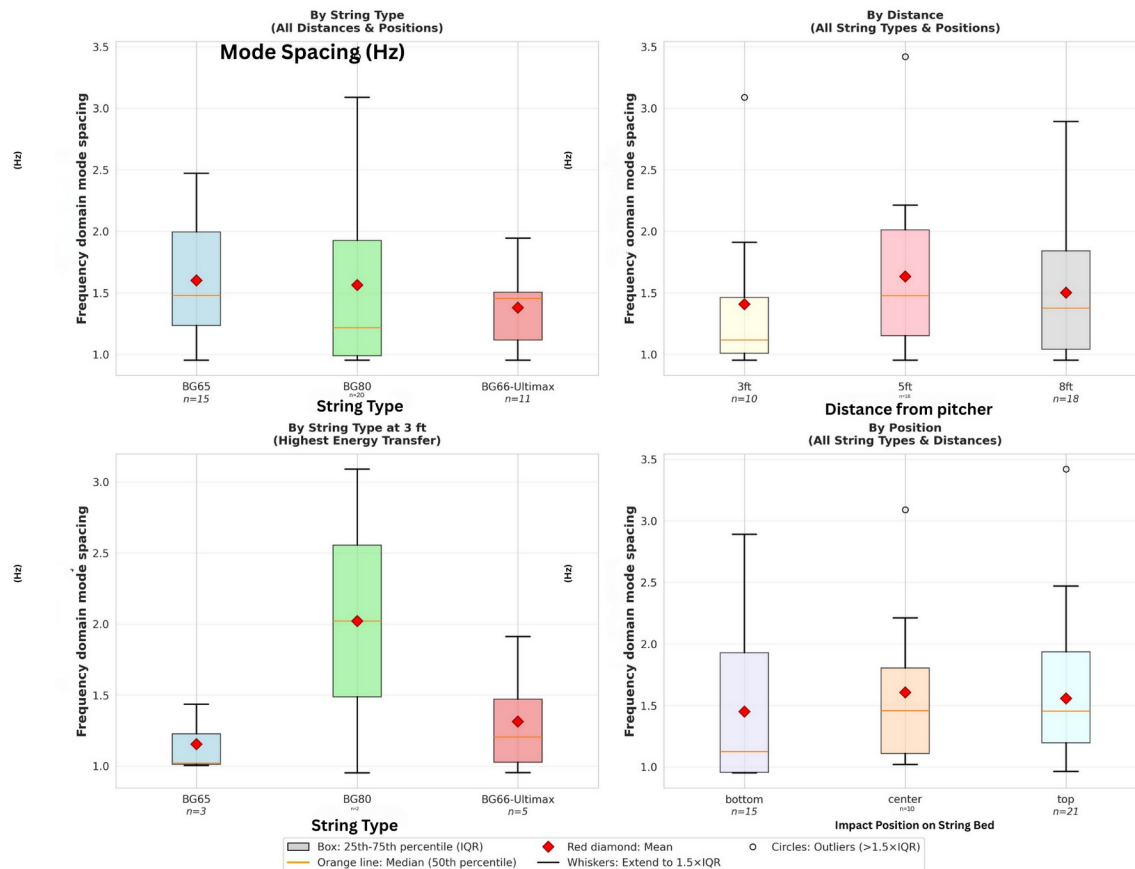


Figure 6. Box-and-whisker plots comparing mode spacing (Hz) among string types. Note: Many trials yielded indeterminate mode spacing values due to insufficient peak clarity, resulting in very small sample sizes (n=2-5 per group at 3 ft distance). Box plot format as described in Figure 3.

For trials with calculable values, the data met parametric assumptions, permitting one-way ANOVA. The analysis revealed no significant difference in mode spacing among string types ($F = 1.15$, $p = 0.369$, $\eta^2 = 0.25$). Mean mode spacing values were: BG65 = 1.15 ± 0.20 Hz, BG80 = 2.02 ± 1.07 Hz, and BG66-Ultimax = 1.31 ± 0.35 Hz. Despite the lack of statistical

significance, the descriptive pattern showed BG80 with the highest mean mode spacing, consistent with theoretical predictions. However, the very small sample sizes preclude definitive conclusions.

3.4 Elastic and viscoelastic behavior

To examine elastic and viscoelastic string responses in the time domain, acceleration-time data from center impacts at 3, 5, and 8 ft were analyzed to observe deformation and recovery patterns.

For the BG66-Ultimax (left column), the top position showed distinct patterns based on distance. At 3 ft, the response exhibited a sharp peak followed by rapid decay ($R^2 = 1.0$ for 3 ft curve), consistent with elastic-dominated behavior. At 5 ft and 8 ft, the curves showed more complex shapes, suggesting delayed viscoelastic behavior becoming greater.

Vibration amplitude vs. time by string type at each distance and position

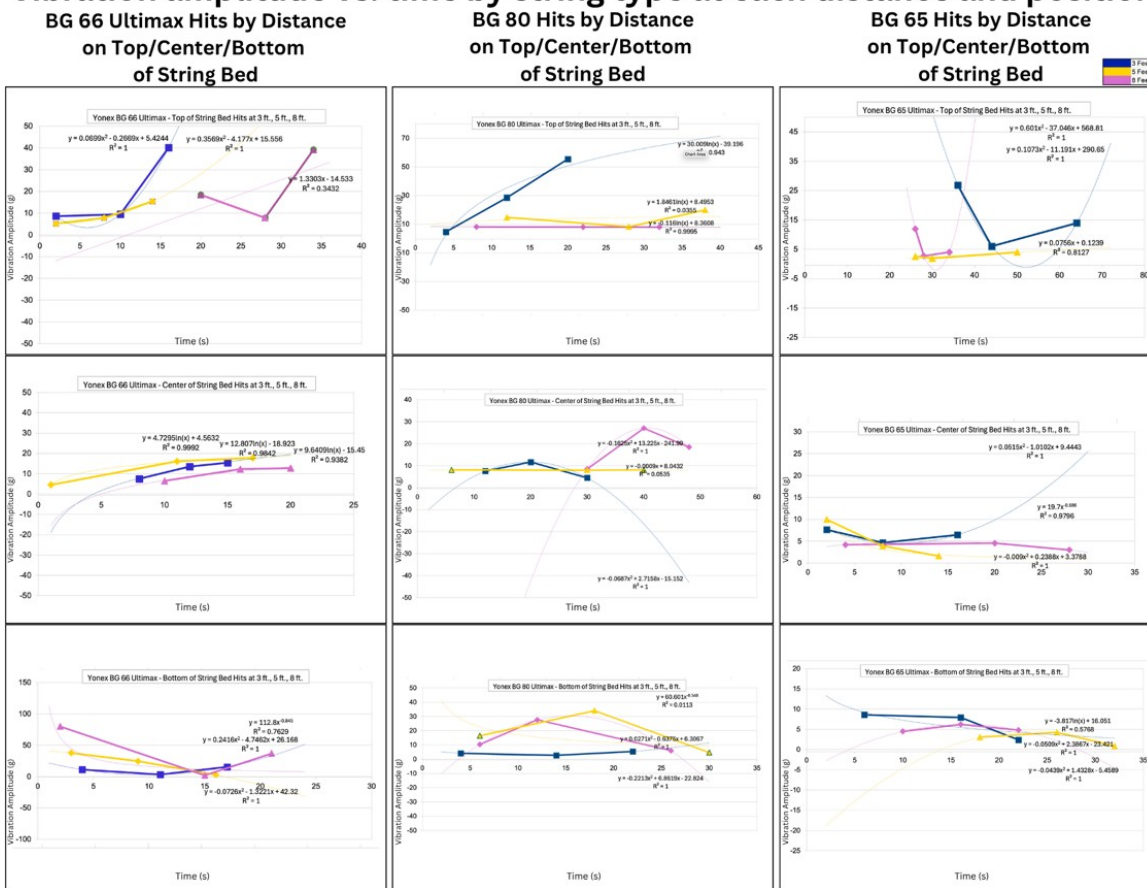


Figure 7. Vibration amplitude (g) vs. time (s) for Yonex BG66 Ultimax, BG80, and BG65 strings at top, center, bottom string-bed positions at 3 ft (yellow), 5 ft (blue), and 8 ft (pink) distances. Polynomial trendlines were fitted to the amplitude–time data to describe envelope shapes, with corresponding R^2 values shown for empirical curve-fit quality and not for inferential statistics. Axes represent time and vibration amplitude in g ($1g = 9.81 \text{ m/s}^2$).

The BG80 (middle column) demonstrated more variable behavior across positions. Center hits showed relatively consistent parabolic-like shape across all distances, with moderate R^2 values (0.38-0.99), while bottom hits displayed more erratic and varied patterns, especially at longer distances.

The BG65 (right column) exhibited the most consistent trendlines across trials, with many curves showing $R^2 > 0.8$. The gradual, sustained

amplitude changes show the viscoelastic character of the multifilament nylon structure.

At 3 ft in the center position, all three strings showed similar behavior at first, but changed in their decay patterns. The BG66-Ultimax dropped sharply while BG65 maintained a more gradual progression. At 8 ft, the difference between string responses became easier to see, with BG66-Ultimax showing the highest peak amplitudes and most noticeable amplitude changes over the time window.

Vibration amplitude vs. time at each distance and position-string comparison

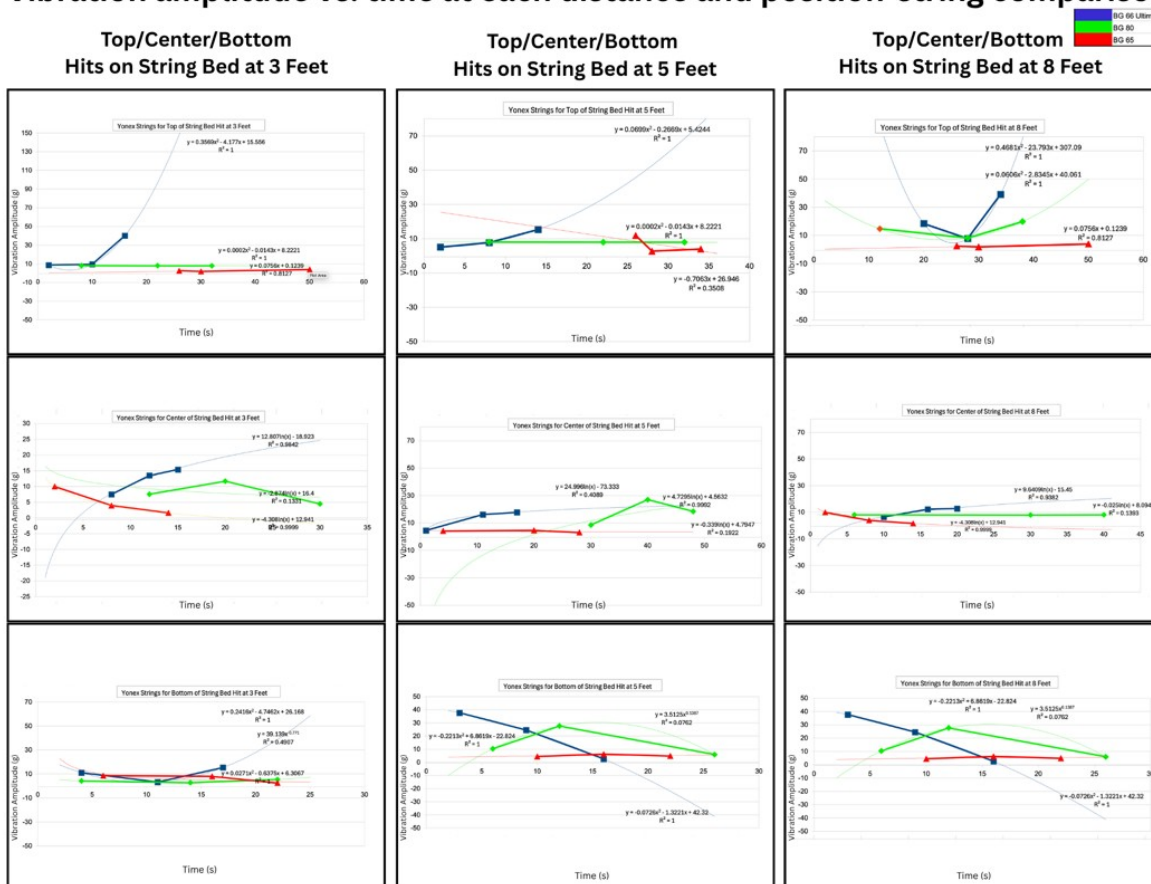


Figure 8. Vibration amplitude (g)vs. time (s) for all three string types at each distance (3, 5, and 8 ft) and position (top, center, bottom). Colors represent strings: blue (BG66-Ultimax), green (BG80), red (BG65).

3.5 Vibration settling time

Time-domain envelope analysis revealed specific decay characteristics among the three

string types. Settling time was defined as the duration to reach 5% of peak amplitude.

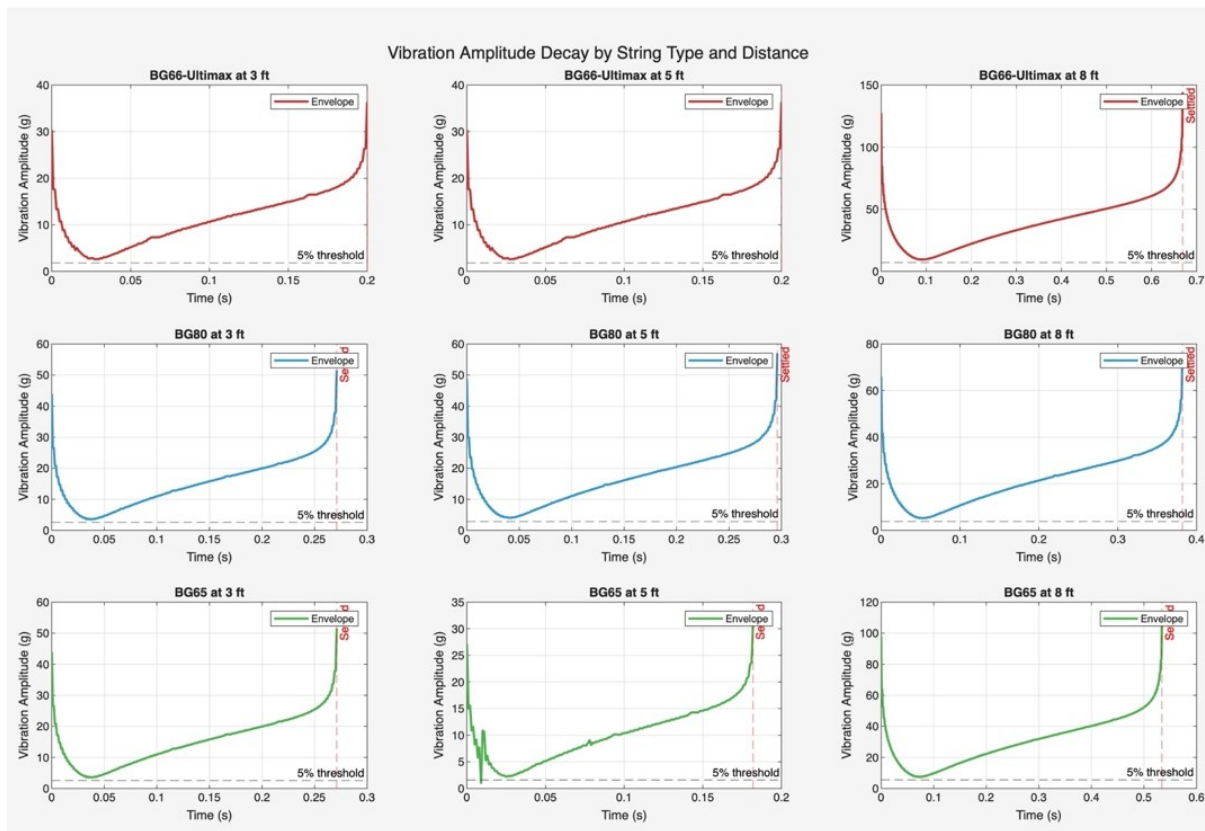


Figure 9. Vibration Amplitude (g) Decay Comparison Across String Types (BG66-Ultimax, BG80, BG65) and Impact Distances (3, 5, 8 ft)

Figure 10 shows envelope comparisons at each distance, with all three strings overlaid. At 3 ft, the BG66-Ultimax exhibited rapid initial decay followed by gradual amplitude increase, reaching peak envelope values of approximately 353 m/s^2 (36g). The BG80 demonstrated moderate initial settling with pronounced late-stage amplitude escalation, particularly evident at the impact endpoint. The BG65 showed the

most gradual amplitude change throughout the time window.

Settling time analysis shows the duration needed for each string to reach 5% of peak amplitude. At 3 ft distance, the BG66-Ultimax settled fastest (0.20s), followed by BG80 (0.27s) and BG65 (0.27s). At 5 ft, the BG65 demonstrated the shortest settling time (0.18s), while BG66-

Ultimax (0.20s) and BG80 (0.30s) required longer durations. At 8 ft, the longest distance tested, BG80 exhibited the fastest settling (0.38s), followed by BG65 (0.53s) and BG66-Ultimax (0.67s). These results indicate that settling time is both string-dependent and distance-dependent, with no single string demonstrating consistently the fastest decay across all impact conditions.

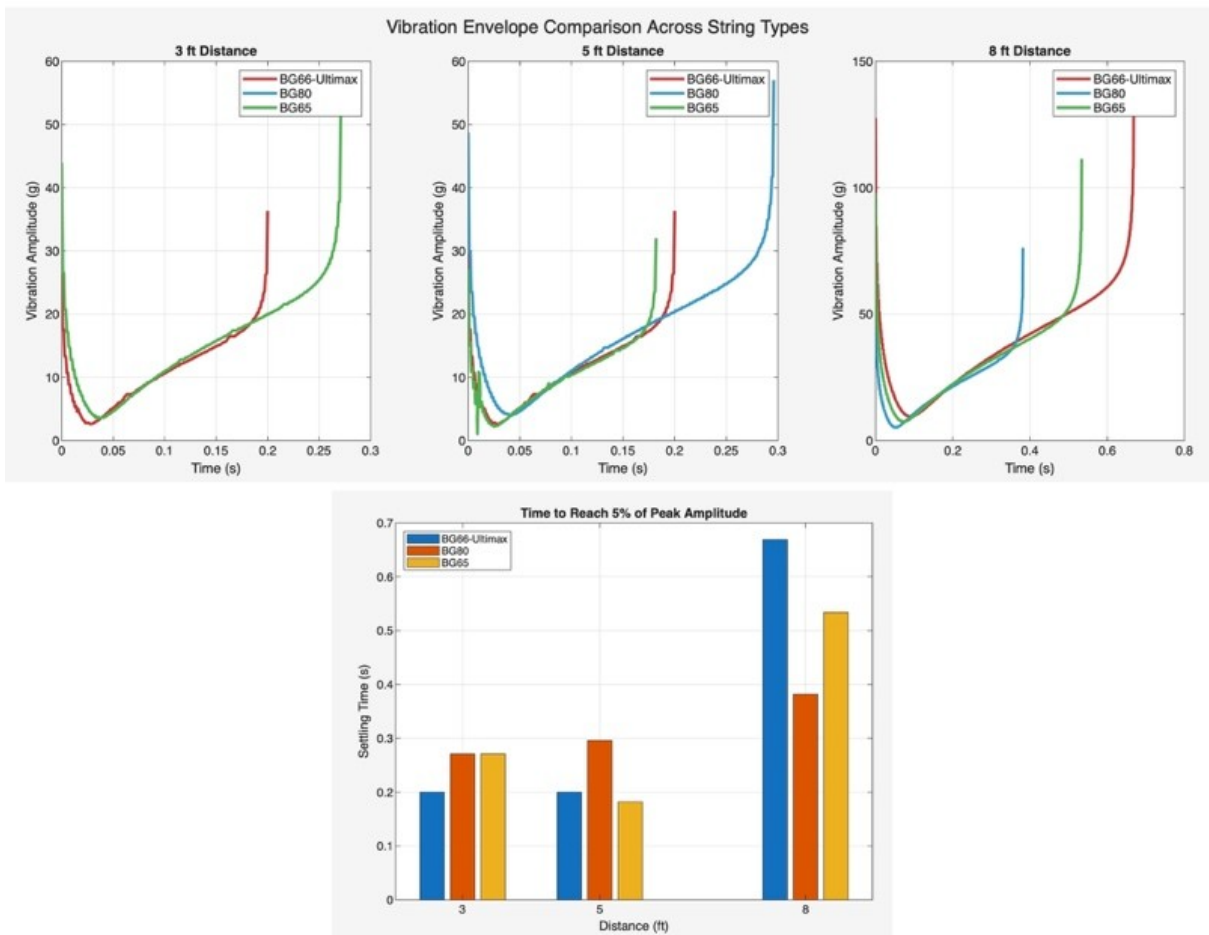


Figure 10. Vibration Envelope Comparison Across Strings and Time to Reach 5% of Peak Amplitude (g). Individual decay curves for each string-distance combination with the 5% settling threshold marked. These curves show the vibration amplitude decay over time (s) and indicate when each string returns to near-baseline conditions.

To rigorously test whether observed settling time differences were statistically significant, settling times were compared among string types using the Kruskal-Wallis H-test. Settling time did not differ significantly among string types ($H = 2.42$, $p = 0.298$, $\epsilon^2 = 0.005$). Mean settling times were: BG65 = 0.998 ± 0.753 s, BG80 = 0.723 ± 0.742 s, and BG66-Ultimax = 0.636 ± 0.632 s.

While the second prediction stated in Section 1.5 was not statistically supported, descriptive statistics showed: BG66-Ultimax mean = 0.636 ± 0.632 s, BG80 mean = 0.723 ± 0.742 s, BG65

mean = 0.998 ± 0.753 s. High within-group variability was observed (coefficients of variation > 50%).

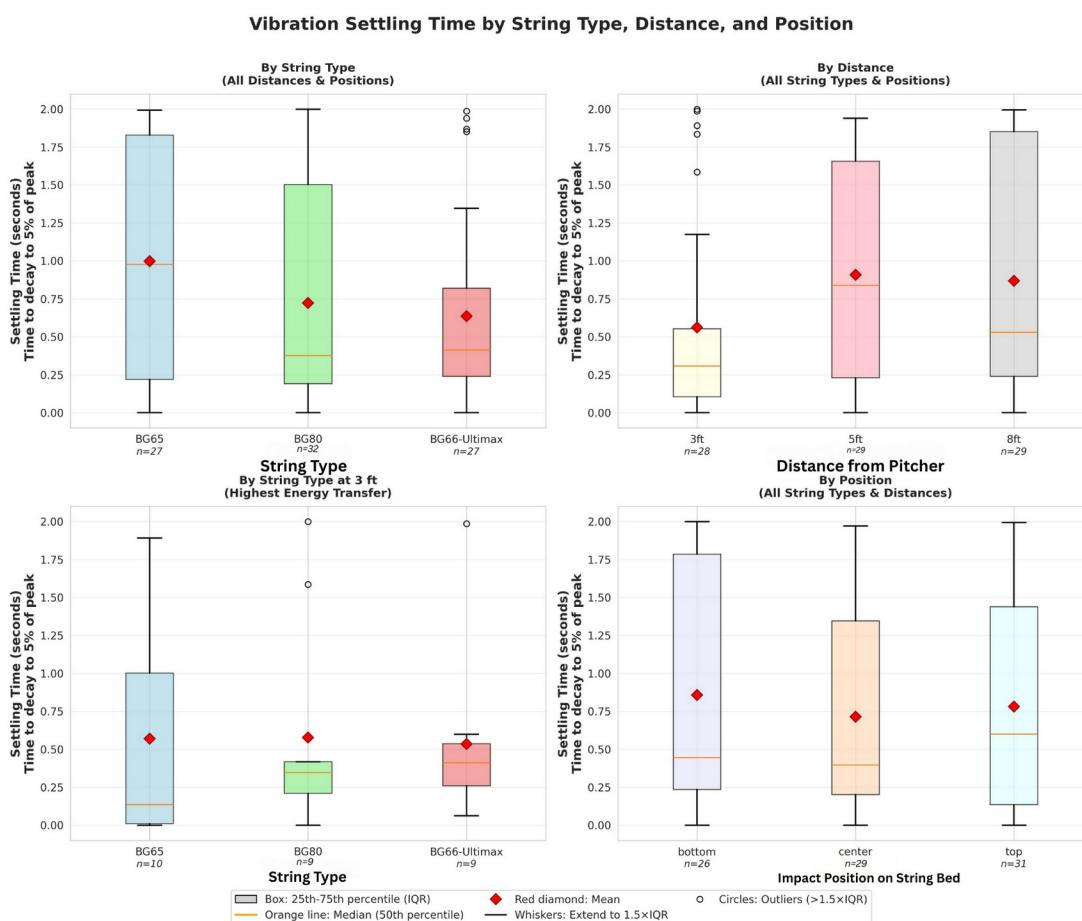


Figure 11. Box-and-whisker plots comparing vibration settling time (seconds, defined as time to decay to 5% of peak amplitude) among three string types. While BG66-Ultimax exhibited a shorter median settling time compared to BG65, these differences were not statistically significant ($p = 0.298$), likely due to high within-group variability. Box plot format as described in Figure 3.

4. Discussion

Statistical analysis of 86 controlled impacts revealed significant differences in acceleration magnitude and vibration frequency across string

types ($p < 0.05$), providing quantitative evidence that polymer microstructure influenced mechanical performance characteristics. The BG66-Ultimax consistently demonstrated the

highest acceleration magnitudes, displaying elastic rebound properties characteristic of power-focused equipment (2). The BG80 offered balanced energy return with intermediate acceleration values, while the BG65 exhibited lower acceleration outputs consistent with unstretched, (relatively) low molecular weight nylon's energy dissipation characteristics (11), making it more appropriate for control-oriented players.

At 3 and 5 ft, the BG66-Ultimax absorbed and released greater energy during impact as it consistently recorded higher acceleration peaks (2). This is notable for players generating powerful smashes and flat drives. The BG80's acceleration readings at these distances suggest that the intrinsic nonlinear stiffness of polymer strings affects energy transfer differently based on shot power (3). The BG65 remained consistent in lower acceleration values, reinforcing that softer strings exhibit more energy loss during impact (11).

At 8 ft, the BG66-Ultimax recorded its highest acceleration values, with peak acceleration at the bottom position where maximum energy was transferred to the shuttlecock (2). This shows the BG66-Ultimax exhibits excellent ability to complement attacking players when controlled for distance and hitting location. The wider spread of acceleration values at different string-bed positions may indicate that string material properties influence aspects of energy transfer and impact behavior, as Suwannachote et al. (2) also found.

4.1 Elastic and viscoelastic response patterns across impact distances

Time-domain decay analysis confirmed the predicted distinction between elastic-dominated and viscoelastic-dominated polymer behavior across string types. At 3 ft, the BG66-Ultimax exhibited logarithmic-type decay with rapid initial recovery followed by rapid stabilization, consistent with elastic behavior where the (stretched) crystalline, high molecular weight, low gauge nylon polymer enabled rapid energy return with minimal viscous dissipation (17). This elastic dominance resulted in the string returning to near-baseline in approximately 0.20s, making it mechanically ready for subsequent impacts.

The BG80 demonstrated a parabolic-type response at 3 ft with gradual amplitude increase through the mid-portion of the time window, reflecting balanced elastic and viscous properties. The Vectran[®] polymer component of the nylon-Vectran[®] combination contributed both immediate elastic rebound and delayed viscoelastic recovery, resulting in intermediate settling behavior (16, 18). At 8 ft, the BG80's faster settling (0.38s) compared to other strings suggested that higher impact energies reduced viscous energy loss.

The BG65 displayed hyperbolic-type decay characterized by rapid initial drop followed by prolonged gradual decrease, reflecting sustained viscoelastic behavior. The multifilament (unstretched) low molecular weight, lesser crystallinity nylon polymer structure allowed greater inter-fiber friction, causing energy dissipation over extended periods (11, 13). This

viscoelastic character remained consistent across all distances tested.

4.2 Implications for successive shot execution

Building on the material properties described in Section 4.1, the settling time data sought to address a tactical question: when is the string mechanically optimal for the next impact? The measurements attained revealed distance-dependent patterns that were relevant. In fast-paced play, successive shots may be executed with intervals as brief as 0.3-0.6 seconds during net exchanges or rapid drives (29). The vibration state of the string during this interval could theoretically influence energy transfer efficiency (2) and hence, the power of successive shots.

At 3 ft, the settling times for BG66-Ultimax (0.20s), BG80 (0.27s), and BG65 (0.27s) fell within typical rally intervals, suggesting mechanical readiness for net play. At 5 ft, BG65 exhibited the fastest settling (0.18s), while at 8 ft, BG66-Ultimax required the longest recovery (0.67s). The distance-dependent variation suggested that string mechanical state varied with court position during rapid exchanges.

However, whether residual vibration meaningfully impacts energy transfer efficiency depends on factors beyond string mechanics, including player technique, shuttlecock trajectory, and opponent positioning, which dominate rally dynamics in actual gameplay (14).

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.

4.3 Statistical interpretation of settling time results

While theoretical predictions suggested that the BG66-Ultimax would demonstrate significantly faster settling times than BG65, statistical analysis did not support this hypothesis ($p = 0.298$). However, descriptive trends were consistent with polymer theory: the BG66-Ultimax exhibited the shortest mean settling time (0.636s) and BG65 the longest (0.998s). Several factors may explain the lack of statistical significance. 1] High within-group variability ($CV > 50\%$) suggests that factors beyond string material, including impact location, shuttle angle, and measurement conditions, substantially influenced settling dynamics. 2] The 5% amplitude threshold, while mechanically meaningful, may not capture the full complexity of "mechanical readiness" for successive impacts. 3] Sample size limitations, particularly at individual distances, reduced statistical power to detect material-dependent differences.

4.4 String selection implications for attacking players

The following performance implications are based on controlled mechanical testing at controlled speeds. Direct extrapolation to competitive gameplay and injury outcomes requires validation in future research (see Section 4.5, Interpretation boundaries).

Integrating the findings from peak acceleration (Section 3.2), material response patterns (Section 4.1), and settling time analysis (Section 4.2), three distinct string profiles emerge: The BG66-Ultimax delivered maximum peak accelerations across distances with rapid elastic recovery, providing the highest power transfer but producing stronger oscillations. While higher vibration amplitudes have been

associated with injury risk factors in occupational settings, direct validation of injury outcomes in badminton was beyond this study's scope. The BG80 exhibited intermediate performance across all metrics, balancing power with moderate vibration characteristics and consistent settling behavior across distances. The BG65 produced the most dampened response with lowest peak accelerations, prioritizing control over power transfer. String selection depends on individual performance priorities. Athletes, such as offensive players, prioritizing maximum power may accept potentially higher vibration exposure; those prioritizing control and potentially lower vibration exposure trade power for precision; balanced profiles suit varied playstyles.

Table 4. Performance implications of string type based on mechanical testing

String Type	Impact on Fast Gameplay	Effects on Attacking Power	Impact on Control and Precision	Potential Injury Risk from Vibrations
BG66-Ultimax	Quick energy transfer, best for rapid exchanges	Generates the most power, ideal for aggressive players	Harder to control due to extreme energy returns	Highest potential injury risk due to elevated accelerations/vibrations
BG80	Balanced energy transfer, satisfactory for fast attacks	Strong power with better control than the BG66-Ultimax, good at distance	Balance of control and power, suitable for aggressive but precise play	Moderate potential injury risk resulting from more balanced force distribution
BG65	Better for controlled rallies, not ideal for fast, offensive play	Requires more effort to generate power, not very suitable for attacking players	Superior for control-based offensive players, with less power output	Least potential risk of injury but could cause discomfort from prolonged exposure

4.5 Limitations

Despite the strong results of this study, several limitations must be acknowledged.

4.5.1 Experimental conditions

The experimental shuttle speed of 15 mph was significantly lower than that observed in competitive play, where smashes may exceed 250 mph (37). This lower velocity was

chosen to prevent excessive deformation, maintain measurement repeatability within this laboratory setup; however, it limits generalization to real-game conditions. Future research should examine whether similar material response trends occur at higher energy transfer and/or dissipation levels under player-driven impacts.

4.5.2 *Design and instrumentation*

This 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 subsequent studies, positive or negative controls (e.g., unstrung frame, damped vs. undamped), baseline noise characterization, and calibration or control impacts should be employed to benchmark instrument response.

4.5.3 *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. R^2 values therefore should be interpreted solely as descriptive indicators of fit accuracy within the observed data window.

4.5.4 *Scope of materials and fatigue testing*

The fatigue life of the strings was not tested, leaving an important gap in understanding the time over which different materials maintain their mechanical properties under repeated use. Although this study provides insight into immediate vibration characteristics, it does not represent long-term gameplay where tension loss and polymer degradation may alter

vibration behavior. Additionally, the limited number of materials analyzed (three string types) constrains comprehensive understanding of relationships between string composition and vibration behavior, as different racket types, shuttlecocks, or accessories (such as dampers) could alter performance outcomes. Future research should incorporate fatigue testing and compare multiple string tensions, racket models, string materials, and mounting geometries to assess their combined influence on vibration response.

4.5.5 *Interpretation boundaries*

Extrapolations from the present data to injury risk and/or tactical gameplay recommendations exceed the scope of the measurements. The tested impact speed (15 mph) is ~ 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, thus requiring validation in future player-centered research. While envelope analysis quantified settling times (0.18–0.67s), these may not correspond to realistic inter-shot intervals determined by shuttle flight, player positioning, and tactical decisions (36). Natural frequency of the racket-string system was not measured, precluding assessment of whether shot timing synchronization with vibration cycles confers mechanical advantage.

4.5.6 *Correlation of gauge with elasticity*

Although it would seem that gauge and elasticity are correlated, consideration must be given to the type of polymer(s), its crystallinity, molecular weight, composition, sheath and

coating. Changing these factors can offset the effect of gauge on elasticity. Consequently, the correlation observed in this study must be considered coincidental and not causative.

Finally, due to ethical and safety considerations, live player testing was not performed. As a result, the study's controlled impacts describe mechanical responses of strings rather than full biomechanical performance during gameplay.

While these limitations constrain generalization to live competitive conditions, they establish a controlled foundation for future investigations integrating higher-impact energies, player biomechanics, and expanded material comparisons to translate mechanical findings into practical performance and safety insights.

4.6 Perspectives

Building on the controlled methodology established here, future studies should expand the sample to include all strings in the Yonex BG series and other manufacturers, incorporating fatigue analysis to track how elastic and viscoelastic properties shift as polymers degrade with repeated impacts.

Additionally, extending the time-domain analysis would enable full constitutive material modeling with longer time windows and varied sampling rates, moving beyond qualitative envelope shape descriptions to quantitative viscoelastic parameters. This would require controlled tensile testing of isolated string samples under various strain rates to separate material properties from racket system

dynamics. Modal analysis of the complete string-racket system could reveal whether vibration cycles align with shot timing, though practical application remains constrained by player movement and reaction time.

Validation through trained attacking players in a controlled experimental design would determine whether the settling time differences measured here translate to observable performance differences in actual play. Such studies would require careful methodology to minimize injury risk while capturing kinematic and outcome data during rapid shot sequences over sufficient trials.

The envelope analysis methodology developed here could be applied to other racket sports, particularly tennis and squash (24), where string vibration and player injury risk are also concerns. The approach offers a cost-effective way to characterize string behavior without requiring complex finite element modeling.

This data-driven approach can encourage manufacturers to develop targeted innovations such as vibration-reducing technology for high-repulsion strings or customized string recommendations based on playing style and possible injury prevention needs. The findings also suggest a need for industry standards regarding acceptable vibration exposure in competitive play.

By addressing a gap in badminton string research, this study offers preliminary data that may inform attacking players, coaches, manufacturers, and sports medicine specialists

with evidence-based insights for optimizing performance and safety. It establishes methodology for future equipment design research and the development of safety standards that support both peak performance and long-term athlete well being.

5. Conclusion

This study quantified vibration response differences among three Yonex BG string types under controlled impact conditions. BG66-Ultimax and BG80 produced significantly higher peak accelerations than BG65 ($p < 0.001$), supporting predictions based on polymer microstructure. The stretched, high molecular weight, low gauge, crystalline structure of BG66 Ultimax and the nylon/Vectran[®] combination construction of BG80 exhibited elastic-dominant behavior with rapid energy transfer, while the unstretched, low molecular weight, lower crystalline structure of the nylon fibers making up BG65 showed viscoelastic damping. Settling times (0.18–

0.67s) varied by distance and string type but did not reach statistical significance ($p = 0.298$). However, descriptive trends aligned with polymer theory, with BG66-Ultimax exhibiting the shortest mean settling time.

This research provides quantitative data linking string properties to vibration characteristics, offering objective performance metrics for equipment selection. The findings suggest that high intensity nylon (BG66 Ultimax) and the combination of nylon/Vectran[®] strings (BG80) may suit players prioritizing power transfer, such as offensive playstyle, while the less crystalline, low molecular weight, unstretched nylon fiber construction (BG65) provides damping characteristics potentially favorable for control-oriented play, such as for varied playstyle. Future research should validate these mechanical findings under game-speed with player-driven conditions to determine how these differences manifest in actual performance.

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Appendix 1. Characteristics of the various strings compared in this study

Attribute / Feature	BG65	BG66 Ultimax	BG80
Gauge (diameter)	0.70 mm Yonex+1	0.65 mm Yonex+1	0.68 mm Sam's Strings+1
Core / Construction	High-polymer nylon multifilament, braided nylon outer Yonex+1	High-intensity nylon multifilament, braided nylon outer Yonex+1	Multifilament with additional high-modulus fibre (Vectran [®]) + braided nylon outer (in many BG80 variants) BadmintonBites+1
Repulsion / Power	Medium / Moderate Racket Source+1	High (fast shuttle repulsion, very “lively” feel) Sam's Strings+1	High, especially good for hard smashes / power shots BadmintonBites+1
Control & Feel (touch, net play, precision)	Soft/medium feel — forgiving for off-centre hits or less-consistent technique Racket Source+1	Crisp, sharp feel — good for precise net play, quick reflex shots, fast rallies shuttlesmash.com+1	Firm, stable feel — offers solid feedback, good control especially for strong hitters BadmintonBites+1
Durability / String Life	High — among the most durable strings around Racket Source+1	Low to Medium — thin gauge leads to faster wear / breakage, especially under high tension / mis-hits shuttlesmash.com+1	Medium — better durability than thinner strings, but less than BG65 BadmintonBites+1
Suitability / Ideal Player Type	Beginners → intermediate, players who want reliability and fewer restringings, recreational / casual play Racket Source+1	Intermediate → advanced players focusing on speed, repulsion, aggressive play, quick attack & net play Sam's Strings+1	Intermediate → advanced players — especially those who favor powerful smashes, strong clears, hard hitting and stability under power BadmintonBites+1
Trade-offs / Cons	Less power / repulsion; feels less “lively” and can feel “soft” for aggressive attacking play Sam's Strings+1	Significantly reduced durability; frequent restringing if used heavily; prone to early wear or breakage under mis-hits or high tension shuttlesmash.com+1	Slightly thicker / heavier feel; less “snap-back” repulsion compared to BG66; may feel less forgiving than BG65 for off-center hits BadmintonBites+1

Appendix 2. Polymer structure comparison between BG65 and BG66 Ultimax

Feature	Standard Nylon 66 in BG 65	High-tenacity / High-intensity PA66 in BG66 Ultimax
Molecular weight	Lower	Higher
Draw/orientation	Low	High (fibers stretched to align chains)
Crystallinity	Moderate	High → more elastic + stronger
Fiber strength	Medium	Very high → better tension retention
Repulsion / “ping”	Softer feel	Crisper, more lively
Durability	OK	Medium (depends on gauge)
Typical use	Budget strings	BG66 Ultimax, high-performance strings