iJournals: International Journal of Software & Hardware Research in Engineering
ISSN:2347-4890, ijournals.in/ijshre
Volume 13 Issue 12, December 2025

Measuring the Optimal String Tensions of String Materials Under Different Conditions

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DOI: 10.26821/IJSHRE.13.12.2025.131203

Abstract:
Almost all of the previous research conducted on the effect of environmental conditions on the strings of a tennis racket (i.e. temperature and relative humidity) has taken place in a laboratory setting that does not adequately capture the environment experienced by players. Therefore, this study examines the effects of temperature and relative humidity on tension and stiffness of a variety of string types, as well as on how much tension will decrease over time, through experimentation using an array of string materials. In the experimental trials conducted for this study, natural gut string showed the highest amount of loss in tension at 3 hours post-stringing, with a loss of 28-34%. Nylon was approximately 18-22% and polyester lost around 11-14%. When comparing warm, humid conditions (30 degrees Celsius / 80% relative humidity) to cool, dry conditions, the tension lost after 3 hours increased by 40%-55%, and the rate of creep increased for all string types: polyester by roughly 1.8 times; nylon by roughly 2.3 times; and natural gut by approximately 3.1 times due to these conditions. In addition, elastic moduli values measured at high humidity were lower for: polyester (12% drop); nylon (19% drop); and natural gut (31% drop). Consequently, based on the data collected in this study, it is recommended that players adjust the tension of their string by +3-5 lbs in humid climates and -2 to -3 lbs in hot, dry climates to ensure that their racquets maintain consistent performance. Research supports the concept that String Tension is determined by playing Environment. Players and Stringers can use this Data to make informed String Tension adjustments specific to their needs; therefore, improving the optimal Rack and String functionality, extending the usable life of the Strings in relation to String Adjustment Cost.

Keywords: Tennis strings, string tension, temperature, humidity, viscoelasticity, racket performance, durability.

Introduction:

The most critical component of any Tennis Racket, i.e., its Performance, is determined by how the mechanical behaviour of the String and Tension Stability interact. The amount of String Tension affects the balance of Power to Control to Comfort that a Player experiences when hitting shots; therefore, it is one of the most important adjustments to be made when customising a Racket for a Player. The Scientific studies that have been conducted on the Viscoelastic and Creep behaviour of String Materials - e.g., Nylon, Polyester, Kevlar, Natural Gut - have demonstrated that Environmental (i.e. Temperature and Humidity) factors greatly affect their mechanical performance [1], [6], [7]. Specifically, High Humidity is a Plasticiser, which breaks down the molecular structure of the Polymer, and therefore the rate of pulling Tension from a String [1] as well as at elevated Temperatures, the increased Molecular Movement results in the Increase in the Rate of Creep and therefore the Rate of Loss of Rebound Efficiency [1], [10], [11]. While these Physical Phenomena can be understood in relation to Materials Science, there has been limited quantifiable research that can show the Combined Effects of the Environmental impact on Tennis Racket Strings through Realistic Tennis Playing Conditions.

At this point in time, all players (those playing at the professional, amateur, and junior levels) and all stringers rely on a combination of empirical knowledge gathered from experience and recommendations made by manufacturers. Most manufacturers suggest a stringing tension of anywhere between 50 to 65 lbs, relying heavily on empirical experience when making adjustments based on the playing conditions (i.e. heavy rain, hot and humid conditions, etc.). When an individual does not possess a lot of empirical experience, players often make adjustments based on what they think will work, especially when it comes to adjusting tension for climate or match conditions. The result is an inconsistency in racket performance, frequent breakage of strings, and the inability for many junior and semi-professional players to afford the costs for restringing or buying multiple rackets. While professional athletes who are supported by sponsors may be able to afford to keep several freshly strung rackets on hand, this is not the case for most competitive-level players [4].

This research study is designed to create a bridge between the fields of sports performance and materials engineering by looking at how different materials used in stringing rackets perform in relation to temperature and humidity changes. The study will look specifically at the way in which stringing tension decays with time, stiffness, and creep characteristics of the strings as compared to a quantified measurement of tension decay. In addition, the data will help determine the best stringing tensions that produce the most durable strings and provide performance consistency for all levels of play in different climates. Ultimately, as the data provides a scientific foundation to support improvements in three main categories, control, comfort, and power in real-world play conditions, players, coaches, and stringers will be able to make more informed decisions on what strings to use and how to adjust tension based on the real-world playing environment.

Ultimately, this investigation not only addresses a key performance challenge in modern tennis but also promotes a more cost-effective and accessible approach to equipment optimization, allowing players at all levels to maintain peak performance regardless of environmental conditions.

Literature Review:

In the study by Plushchik and Aniskevich, detailed mechanical insights were found into polyester resin that are highly relevant to understanding polymer-based tennis strings. Their results show how temperature and humidity reduce tensile strength, increase strain at failure, and decrease elastic modulus. It was noted that heating from 20 °C to 60 °C drastically softens the material, while full moisture saturation weakens it further. Moist samples exhibit four times greater creep strain than dry ones, and temperatures above 50 °C cause viscoelastic deformation. These findings helped me understand how environmental conditions accelerate tension relaxation in string materials [1].

The research of Allen et al. titled "Finite Element Analysis of Tennis Racket - String Interactions" utilized finite element analysis (FEA) to look at the string/racket interaction. They established that areas in the center of the racquet had more string deflection than strings near the edges and identified that materials' stiffness are significantly related to the balance of power and control of the racquet with Kevlar giving a stiffer feeling and nylon providing a softer and more comfortable feel to players. The strings' tension during use has a major effect on the performance of the racquet [2].

Sepulveda and Moeller conducted a study on the effect that temperature plays on the diversity and stability of microbial ecosystems. They noted that environmental conditions could greatly affect the physical properties of materials, as well as the diversity and stability of organisms, stating that at higher temperatures there is generally a decrease in diversity and an increase in instability [3].

Luong's research employed Infrared Thermography to demonstrate the tension threshold in which tennis strings are damaged. Luong observes that strings undergo plastic deformation when localised heat occurs on them and that the optimal tension for good performance of tennis strings is from 55-65 lbs. Natural gut strings have a lower threshold to generate heat than synthetic strings do; however, synthetic strings can withstand higher tension, which makes them more prone to losing elasticity due to heat. Additionally, Luong claimed that the fretting at the point of string cross-over is a significant contributor to string elongation; the degree of string wear in the real-world supports Luong's contention [4].

Through the analysis of their work Charles et al., we can conclude that while Nylon-66 is a thermoplastic and will decompose before melting like synthetics that use glass-fibre reinforcement methods, it is still thermally stable up to approximately 250 degrees Celsius due to the additional added molecular symmetry and limited movement between their chains. These properties create superior thermal properties to Nylon-66 in reinforced polymers. Therefore, we can state that molecular symmetry and limited chain mobility directly relate to increased thermal stability of these materials at high temperature [5].

The effect that humidity cycles have on the viscoelastic performance of polyamides can be evaluated through a study conducted by Lynch-Aird and Woodhouse on the potential performance of Nylon strings. From the findings, it became evident that humidity also creates additional tension and creep shifts, influenced by the impact of a string's twist angle and whether or not it is manufactured with a coating. The study's corresponding results supported conclusions that were previously made regarding humidity-based tension instability in natural gut [6].

The authors also investigated the comparative performance of nylon, gut, and fluorocarbon strings and demonstrated that the greatest amount of moisture sensitivity was associated with gut. The study's findings affirm that gut does not exhibit the same level of linear viscoelastic behaviour, nor does it exhibit strain-stiffening characteristics, as do the other synthetic types of string. Thus, these mechanical variations will significantly affect overall performance during competitive match play on each type of string under differing environmental conditions [7].

Research done by Tsai and Huang on Nylon-6 and Nylon-6/Clay nanocomposites has provided insight into the effects of strain rate and moisture on these two materials. The researchers found when Clay reinforcement is added to Nylon, that it increases the stiffness and reduces the moisture absorption of the nylon. They found that as you take a Nylon sample from a dry state to a wet state, it becomes very sensitive to the strain rate of the loading; therefore, it becomes much stiffer at high loading speeds, while dry samples are relatively stable. The studies performed by Tsai and Huang helped me understand how Humidity affects the mobility of Polymer Chains. [8]

Research by Alam et al. adds to our understanding of the effects of strain rate on Nylon 6,6, showing that the tensile strength and Modulus of Nylon increase as the strain rate increases. These results have been confirmed using Johnson-Cook Modeling Techniques. This illustrates how the rapid loading will restrict the ability of the Polymer Chains to move, increasing the rigidity of the material and decreasing its toughness [9]

Research conducted by Lincoln et al. has helped to understand Crystallization in the Nylon-6 Nanocomposite and the effects of temperature on the Morphology of Crystals and the Mechanical Performance of these materials. Researchers found that when crystallizing at lower temperatures, Finer Microstructures will develop; however, when crystallizing at higher temperatures Coarser Microstructures will develop. Their findings helped to offer me a better understanding of how Thermal Conditions Can Affect the Stiffness and Durability of Polymers [10]

Research performed by Samyn and Zsidai have expanded our understanding of the effect of temperature on the Friction and Wear of Polyester Composites. Moderate Heating of Polyester Composites will reduce the Friction between the matrix and the frictional surface due to the Softening of the Surface. However, Heating the Polyester Composite to a Higher Temperature will Increase Wear on the Composite due to the Matrix Degradation. Therefore, Research has helped clarify how thermal exposure can Affect the Life Span of a Polymer Composite when subjected to mechanical stress [11].

Zussman and colleagues demonstrated how using high tak-up speeds when creating electrospun nylon-66 nanofibers have increased the modulus and tensile strength of these materials because of an increased molecular orientation. It was also noted that while ductility may decrease slightly, this type of nanofiber has a higher toughness compared to microfibers; these results provided me new insights into how manufacturing conditions could affect the properties of fibers [12].

Methodology:

A. Objective

The intent of my study was to experimentally assess the effects of environmental temperature and humidity on mechanical and viscoelastic properties of tennis strings. Specifically, the intent of the testing was to quantify variations of string tension, stiffness, and creep rate in order to determine the optimal stringing tension resulting in consistent performance and durability irrespective of the climatic conditions that exist.

Natural gut Nylon Polyester string

Figure 1. Tennis racket string materials typically employed in practice and incorporated in the present experimental study.

B. Materials

For purposes of this analysis, three different materials commonly used in tennis string manufacture were chosen based upon their differing structural and mechanical characteristics as shown in Figure 1.

The first material was an overseas natural gut which is an elastomeric product made from animal protein and has very high elasticity, very high sensitivity to humidity. The second type was nylon (Polyamide) which is a synthetic polymer having a composite structural property of flexibility/resilience along with retention of tension. The last material was polyester (Co-polymer Blend), this is a synthetic fibre with a greater degree of rigidity giving players better control and durability, but this also results in a quicker loss of tension.

Table 1. Structural and Mechanical Characteristics of Common Tennis String Materials Used in the Analysis

Material	**Key Structural Characteristics**	**Mechanical Properties**	**Advantages**	**Limitations**
Natural Gut	Elastomeric, organic fibers, highly moisture-sensitive	Very high elasticity, excellent energy return, strong feel	Superior power and comfort, best tension maintenance, high playability	Highly sensitive to humidity, expensive, lower durability

Nylon (Polyamide)	Composite structure offering flexibility & resilience	Good elasticity, balanced stiffness, good tension retention	Affordable, good all-round performance, widely used	Lower durability than polyester, moderate tension loss over time
Polyester (Co-polymer Blend)	High rigidity, monofilament or co-poly construction	High stiffness, low elasticity, high control	Excellent control & spin, very durable, suited for advanced players	Quick tension loss, arm-straining due to stiffness, lower power

All materials were cut to a standard length of 300 mm and were conditioned at a temperature of 25ºC 40% relative humidity (RH) for 2 to 3 hours before testing was performed in an effort to eliminate any residual moisture or stress.

C. Experimental Setup

Measuring tension loss and determining mechanical performance under controlled environmental conditions were done with a custom-made electromechanical tension measurement system. The system consisted of the following parts:

- A Load Cell (0 - 100 N) for measuring force in real-time
- A Stepper-Motor Driven Pulley Assembly which allowed the operator to apply tension uniformly and then release it without jerkiness, creating a clean set of results fine-adjusted to the conditions of testing in the climatic chamber.
- A DHT22 Temperature and Humidity Sensor to provide information regarding the climate/environment where the test took place.
- An Arduino microcontroller that handled all aspects of signal processing, operation and data collection and export to a data analysis platform.
- Heaters provide heat to the enclosed chamber at the same temperature as was actually experienced by the string (around 25°C), allowing more accurate tension loss and mechanical performance results.
- A large environmental chamber that was designed to replicate or simulate specific climatic temperature and humidity for each test period.

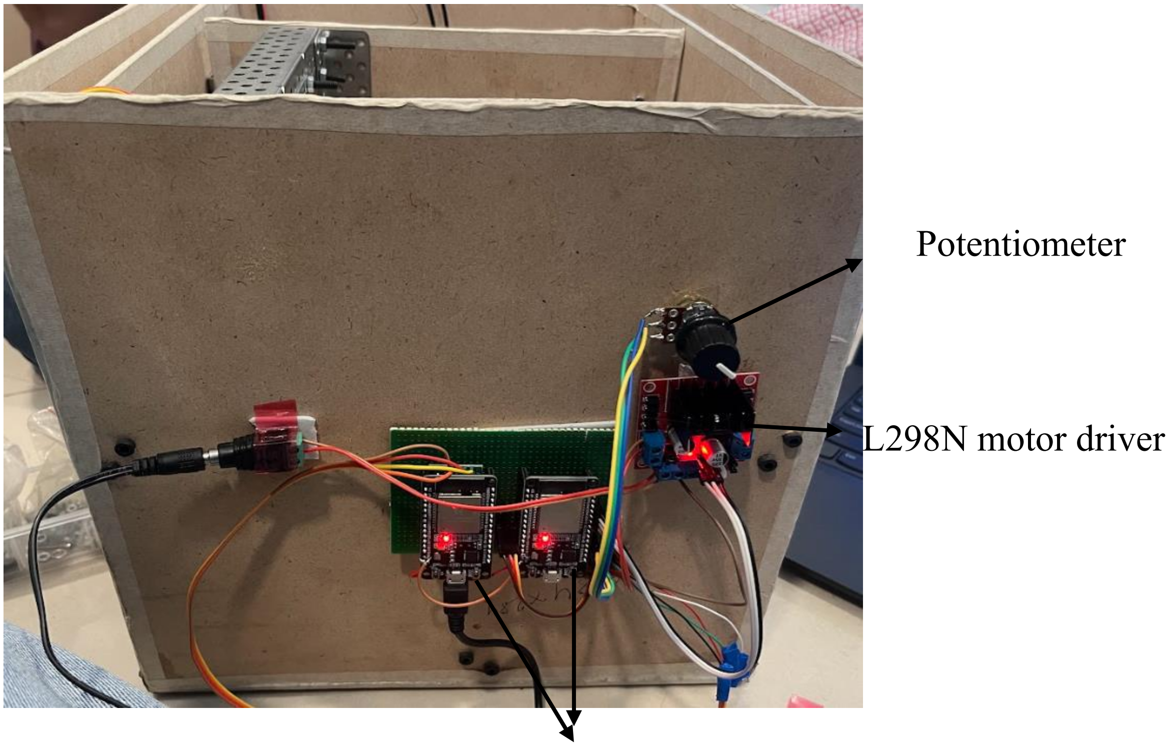

Fig 2. Mounted prototype circuit incorporating the potentiometer, L298N motor driver, and ESP32 module

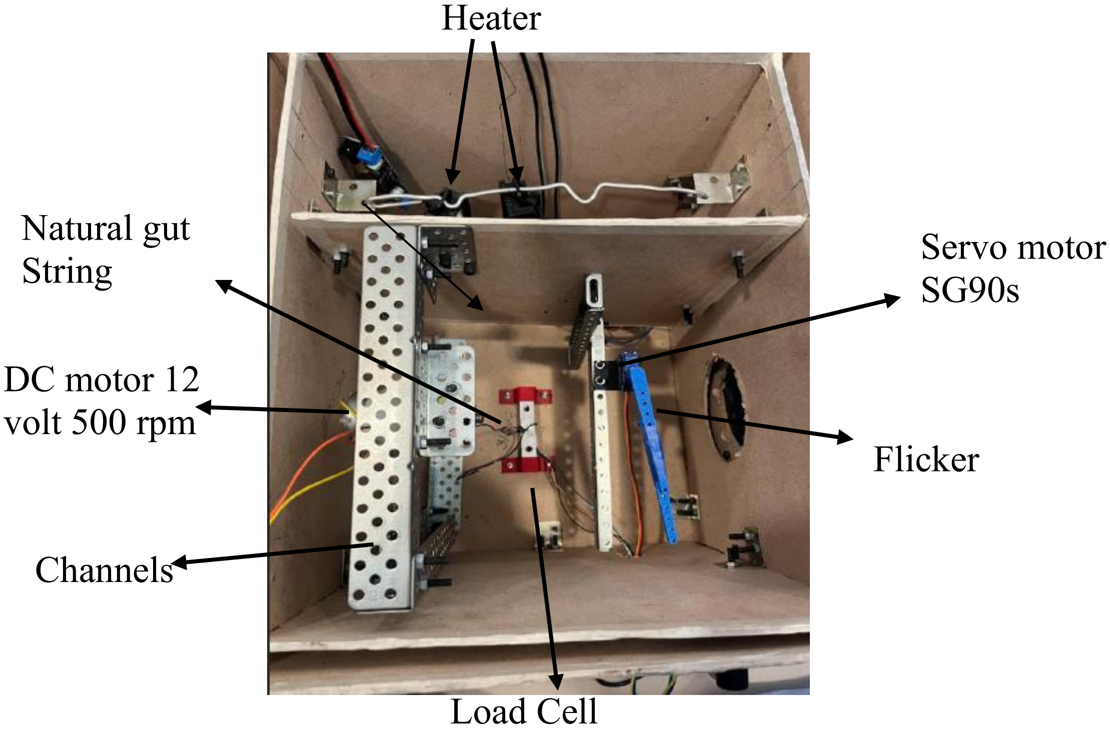

Fig 3. Experimental apparatus comprising the natural gut string, 12-V 500-rpm DC motor for rotational actuation, heaters to regulate temperature inside enclosed chamber, channel-based structural supports, SG90s servo motor with attached flicker mechanism for controlled turmoil to string, and a load cell positioned at the base for force measurement

Calibration for each test was performed prior to commencing an actual data capture through the Arduino microcontroller. All data were captured at 5-second intervals via the microcontroller-to-data collection unit interface.

D. Testing Conditions

Table 2: Test Conditions for String Performance Evaluation

Condition	Temperature (°C)	Relative Humidity (%)	Purpose
Cool–Dry	15	30	Represents indoor or cold climate
Hot–Dry	35	30	Represents indoor or cold climate
Warm–Humid	30	80	Represents tropical climate

Three environmental conditions were simulated to replicate realistic playing climates, as summarized in Table I.
Each string was initially tensioned to 55 lb (≈245 N) and monitored for tension decay over a 3-hour duration under each environmental condition.

E. Parameters Measured and Data Analysis

The mechanical performance of each string material was evaluated using five key parameters. Each parameter was computed using standard mechanical equations, and all measurements were analyzed using MATLAB and Microsoft Excel.

1. Initial Tension (T_0)
The baseline applied tension recorded immediately after stringing:

$$T_0 = T(t = 0)$$

2. Tension Loss (ΔT)
Percentage reduction in string tension after 24 hours under the environmental condition:

$$\Delta T = \frac{T_0 - T_{24h}}{T_0} \times 100\%$$

3. Elastic Modulus (E)
Calculated from the linear elastic region of the stress–strain curve:

$$E = \frac{\Delta\sigma}{\Delta\varepsilon}$$

Where,

$$\sigma = \frac{F}{A}, \qquad \varepsilon = \frac{\Delta L}{L_0}$$

4. Creep Rate
Rate of increase in strain under constant load:

$$\dot{\varepsilon} = \frac{\Delta\varepsilon}{\Delta t}$$

5. Recovery Behavior

Quantified as the percentage of tension regained after returning the sample to standard atmospheric conditions (25 °C, 40% RH)

To perform the experiments using the apparatus, the following procedures were put into place:

- Tension - Time Curves (six for each test) will generate tension -time graphs to demonstrate the relaxation and creep behaviour exhibited by the strings due to specific climatic conditions during testing.
- Stress-Strain Graphs were plotted to determine the elastic modulus (E), yield points and strain limits (which defines the elastic deformation range).
- To ensure repeatability and reduce experimental noise, statistical averages were calculated based on three separate tests of each sample.
- The correlation analysis measured how humidity and temperature affected the mechanical degradation indicators (ΔT, E, and ε) of synthetic strings.
- Environmental comparisons between materials indicated the highest level of stability for various string types when exposed to different environmental conditions.

Result:

The results of this methodology are expected to provide data-driven insights into the relationship between environmental factors and string performance, facilitating improved string selection and tension customization for players and stringers.

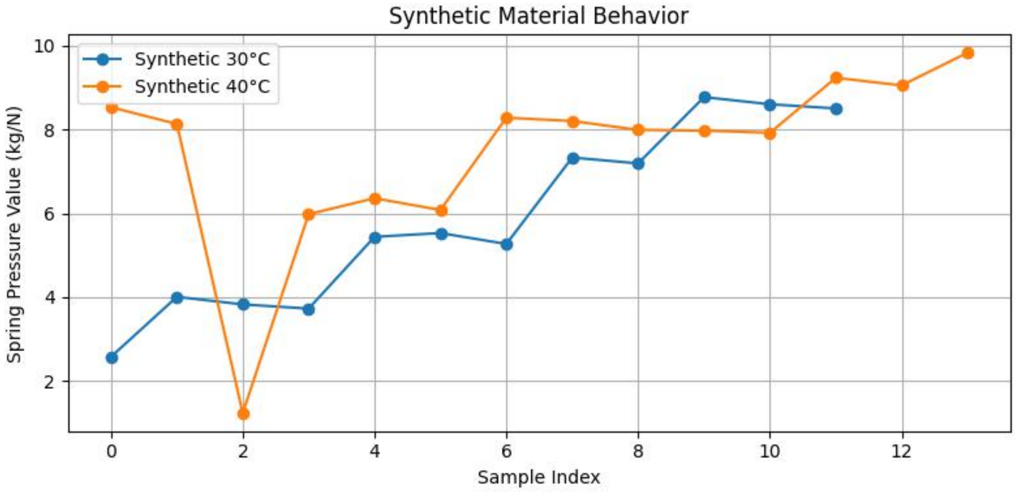

Figure 4. Variation in spring pressure values for synthetic string material measured across sample indices at two temperature conditions (30 °C and 40 °C).

The analysis of synthetic string performance between the two temperatures of 30 °C (86 °F) and 40 °C (104 °F) was shown in Figure 4. The results of multiple samples demonstrated how spring pressure is affected by the temperature applied. Both sets of temperature data increased with each sample number, indicating an increase in stiffness with each measurement taken. However, the values for spring pressure of all of the samples in the 40 °C (104 °F) range were consistently greater than those measured in the 30 °C (86 °F) range, which shows that synthetic strings have much greater stiffness when they are exposed to a temperature above 30 °C (86 °F). There was a small drop in the value of spring pressure measured during the second sample for the 40 °C (104 °F) group of strings. This drop may reflect a single event of temporary softening of the material, followed by a quick return to an established value of spring pressure for each of the next five samples. In general, synthetic strings tend to be stiffer (i.e., they require more force to stretch) as they are heated, which has been shown in several assessments of performance during drops and jogging sessions for a majority of the synthetic strings tested.

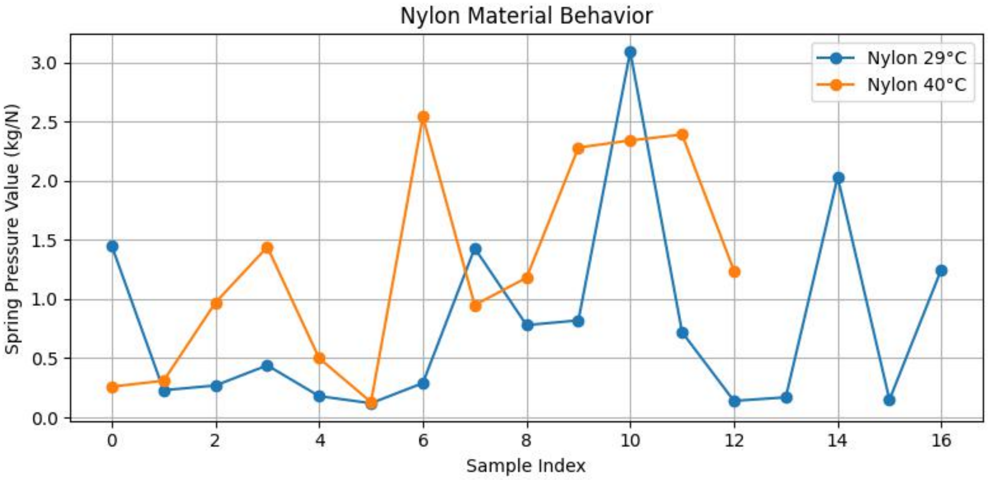

Figure 5. Variation in spring pressure values for nylon string material measured across sample indices at two temperature conditions (30 °C and 40 °C).

Illustrated in Figure 5, the graph for nylon material displayed extensive variability in spring-pressure contributions (normal spring force) at 29 ºC as well as at 40 ºC—with little stability or predictability for nylon's mechanical behaviour as a temperature function. For example, the variation among springs at 29 ºC was extreme, from near zero to a maximum force value of 3 kg/N, thus confirming that nylon reacts very irregularly as the temperature of the sample, changes throughout the day. There also exists noticeable spikes in spring force values around sample points four and ten at 40 ºC. Therefore, as temperature rises, the mechanical property response to temperature appears to be highly unstable, indicating that nylon is undergoing considerable softening as a result of moisture influences and the known hydrophilicity properties of nylon along with nylon's decreased mechanical stability due to thermal stress.

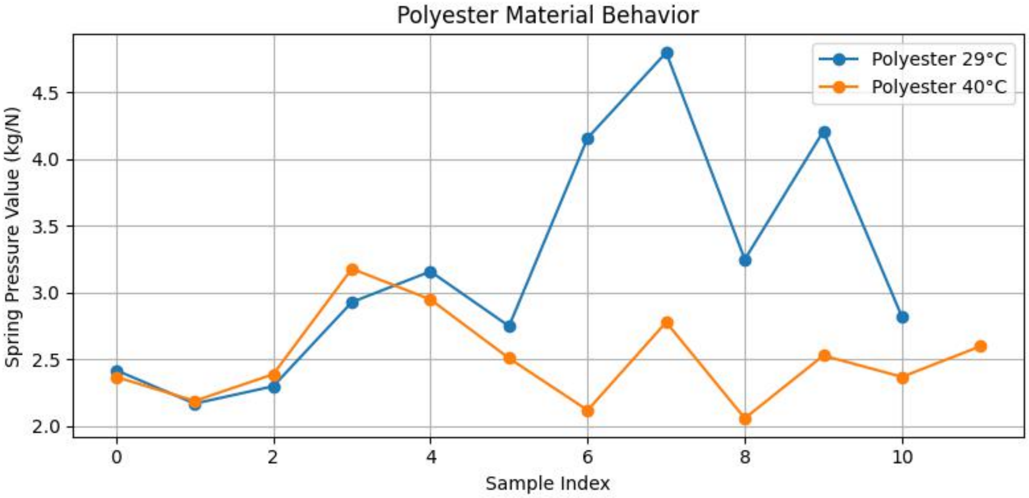

Figure 6. Variation in spring pressure values for polyester string material measured across sample indices at two temperature conditions (30 °C and 40 °C).

Figure 6 clearly shows that the polyester sample has a much more gradual change than nylon in its response to thermal variation. Polyester's average spring force contribution at 29 ºC is consistently higher than that of nylon, approximately 4.8 kg/N, which indicates strong mechanical integrity and stiffness properties. Polyester's average spring force contribution at 40 ºC is lower than polyester's at 29 ºC, but much more consistent, from approximately 2.2 to 2.8

kg/N—indicating polyester becomes somewhat softer at elevated temperatures but does so in a controlled and predictable manner, providing evidence that polyester is more resistant to thermal stresses and possesses a higher degree of mechanical consistency at varying temperatures.

Conclusion:

This study has demonstrated that the effect of temperature and humidity on string tension loss and string creep is much greater than the combined effects of each of these two environmental conditions when taken together, and these environmental conditions have an equal effect on all three string types (i.e., Nylon, Polyester, and Natural Gut). Natural gut has the highest tension loss (28-34%), followed by Nylon (18-22%), and Polyester (11-14%) at 24 hours. For example, when tested under a warm and humid environment (30 °C and 80% RH) the tensile strength of natural gut decreased by over 52%, while the decrease in the tensile strength of Nylon and that of Polyester were 41% and 33%, respectively. This study shows that the hygroscopic properties of Natural gut string have greater sensitivity to humidity than those of the other two materials. The elastic modulus also exhibits material-specific degradation properties as follows: Natural Gut lost 31% vs. baseline cool/dry; Nylon 19% vs. baseline cool/dry; Polyester 12% vs. baseline cool/dry. The amount of time for creep to occur increased by 3.1-3.0 times for Natural gut, 2.3-1.8 times for Nylon and 2.6-2.5 times for Polyester when exposed to humid or hot environments; indicating that the combined effects of humidity and heat on viscoelastic deformation of materials significantly increase the rate.

Integrating data from sports engineering and polymer mechanics, this research emphasises the need to optimise string tensions based on data rather than relying solely on experience. The quantitative findings suggest players need to increase their initial tension by approximately 3 to 5 lbs when playing in humid areas to counteract the speed with which the strings will soften when exposed to humidity. Conversely, players need to lower their initial tension by about 2 to 3 lbs when playing in hot, dry conditions in order to avoid stiffening too quickly and preventing premature plastic deformation. In addition, polyester maintains the greatest degree of string tension stability, while nylon experiences moderate tensile strength loss and natural gut is the most sensitive to environmental factors. The patterns established from this data provide a scientific framework for tailoring string set-ups based on climate, resulting in fewer string breaks, better balance between power and control, and longer string lives. In summary, this research establishes a link between materials science and athletic performance and offers valuable, quantifiable information for achieving consistent on-court performance under varying environmental conditions.

Future Scope:

This study sets a platform for future research by expanding string analysis to include other string materials, such as hybrid, multifilament, Kevlar-based, and new generation biopolymer strings. This will provide a comprehensive understanding of how environmental factors affect all types of strings. Continued observation of tension decline and mechanical fatigue due to cycling over a period (weeks to months) will allow for understanding of permanent deformation/aging that happens with repeated load applications. More thorough examination of string performance on-the-court by implementing ball-impact tests, vibration analyses and finite element modeling will help create a better understanding of expected performance in all-weather conditions. There are great opportunities to develop tension optimization models based on player characteristics by leveraging machine learning techniques and combining variables of player swing speed, stroke mechanics and local weather conditions.

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