



Review

Advances in Composite Materials and String Technologies for Optimised Tennis Equipment Performance

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Abstract

The evolution of tennis equipment is fundamentally linked to advances in materials science and engineering, which have enabled enhanced player performance through optimised racquet and string designs. This review comprehensively examines the critical role of modern composite materials, manufacturing methods, and string technologies in tennis equipment, focusing on how these elements influence mechanical performance and player experience. It first explores the contributions of matrix and reinforcing materials, particularly carbon fibre and aramid composites, to racquet stiffness, strength, and vibration damping. Next, it details advanced manufacturing techniques such as prepreg layup, autoclave curing, and hollow moulding, which enable precise control over mechanical properties and quality assurance. This paper further evaluates various string materials including natural gut, Kevlar, polyester, nylon, and emerging hybrid setups, analysing their mechanical characteristics, tension maintenance, and impact on ball response and player comfort. Special attention is given to the interaction between design choices and playing conditions, such as court surfaces and player sensitivity, underscoring the complex interplay between equipment mechanics and gameplay dynamics. Through an interdisciplinary lens, this paper synthesises current scientific knowledge and experimental findings, providing a critical foundation for optimising tennis equipment design. By integrating materials science with practical application, this paper provides a comprehensive understanding of tennis equipment design, identifying gaps in current research and offering insights to guide future innovation for manufacturers, coaches, and players.

Keywords: composite; polymer; fibre reinforced polymer composites; carbon fibre composites; epoxy matrix composites; polymer matrix composites; tennis racquet design; string materials



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1. Introduction

The development of modern sports is inextricably linked to advancements in materials technology. Tennis is a prime example. In both professional and recreational tennis, the performance of equipment, particularly the racquet and string, plays a crucial role in determining player outcomes. As sport evolves, so do the expectations for equipment that offers enhanced power, control, comfort, and durability. One of the most influential but often overlooked factors is string tension, which directly affects ball response, spin generation, and shock transmission [1]. Although a variety of string materials and configurations are available, the existing literature frequently falls short in addressing how changes in string tension and material composition translate to differences in player performance under

realistic playing conditions. This gap underscores the importance of a comprehensive review that links material properties with functional outcomes in gameplay.

This review extensively covers the key materials involved in modern tennis equipment, examining both the composite materials used in racquet construction and the diverse range of string types, including natural gut, Kevlar, polyester, and synthetic options. Advancements in matrix and reinforcement materials such as carbon fibre and aramid fibres have contributed to improved racquet stiffness, strength, and vibration damping, resulting in enhanced player comfort and performance [2–4]. Additionally, manufacturing processes including prepreg layup and autoclave curing enable precise control over mechanical properties, allowing equipment to be tailored to meet the specific demands of players [5]. By detailing the influence of material selection and fabrication techniques on performance and ergonomics, this paper provides a technical foundation necessary for understanding how equipment design can be optimised to meet the complex demands of the sport.

This paper aims to provide a critical overview of current knowledge related to the materials and mechanical behaviour of tennis strings and racquets. Particular emphasis is placed on hybrid string setups, which combine two distinct materials in the main and cross strings to optimise performance characteristics such as feel, power, and durability. Despite their growing popularity, these setups remain underexplored in the scientific literature. Studies indicate that hybrid configurations can improve tension maintenance and reduce injury risk while providing a balance of control and power [6].

By systematically reviewing published studies on tennis racquet and string materials, fundamental playing principles, and contemporary manufacturing methods, this paper aims to consolidate current knowledge and identify areas where further empirical investigation is warranted. The broader objective is to emphasise the central role of materials science in the design, performance, and customisation of tennis equipment. The review is structured to guide readers from foundational material concepts to sport-specific applications, offering insights relevant to researchers, manufacturers, coaches, and players.

2. Materials

2.1. Tennis Racquets

In the early days of tennis, wood was widely used for about a century. Early racquets were created from materials such as wood, steel, and aluminium. While these materials offer good stiffness, they have limitations in terms of weight, shock absorption, and durability. However, due to the fragility and structural instability of wooden products, wooden racquets gradually fell into disuse (Figure 1).

The transition from traditional materials to advanced composites marked a significant evolution in tennis racquet technology [8]. Modern racquets predominantly utilise fibre-reinforced polymer composites, combining a polymer matrix such as epoxy resin with high-performance reinforcing fibres including carbon fibre, aramid (Kevlar), and sometimes graphene oxide. These materials provide an excellent balance of low density, high stiffness, and superior strength, allowing for racquets that are lighter and more durable than their predecessors. Additionally, fibre composites exhibit enhanced vibration-damping properties [9], reducing the shock transmitted to the player's arm and thereby lowering the risk of injuries such as tennis elbow [10,11]. The orientation and layering of these fibres can be precisely controlled during manufacturing processes like prepreg layup and autoclave curing, enabling manufacturers to tailor racquet stiffness and flexibility to meet the specific needs of different playing styles [12]. This level of customisation has contributed significantly to performance optimisation, giving players improved power, control, and comfort on the court.

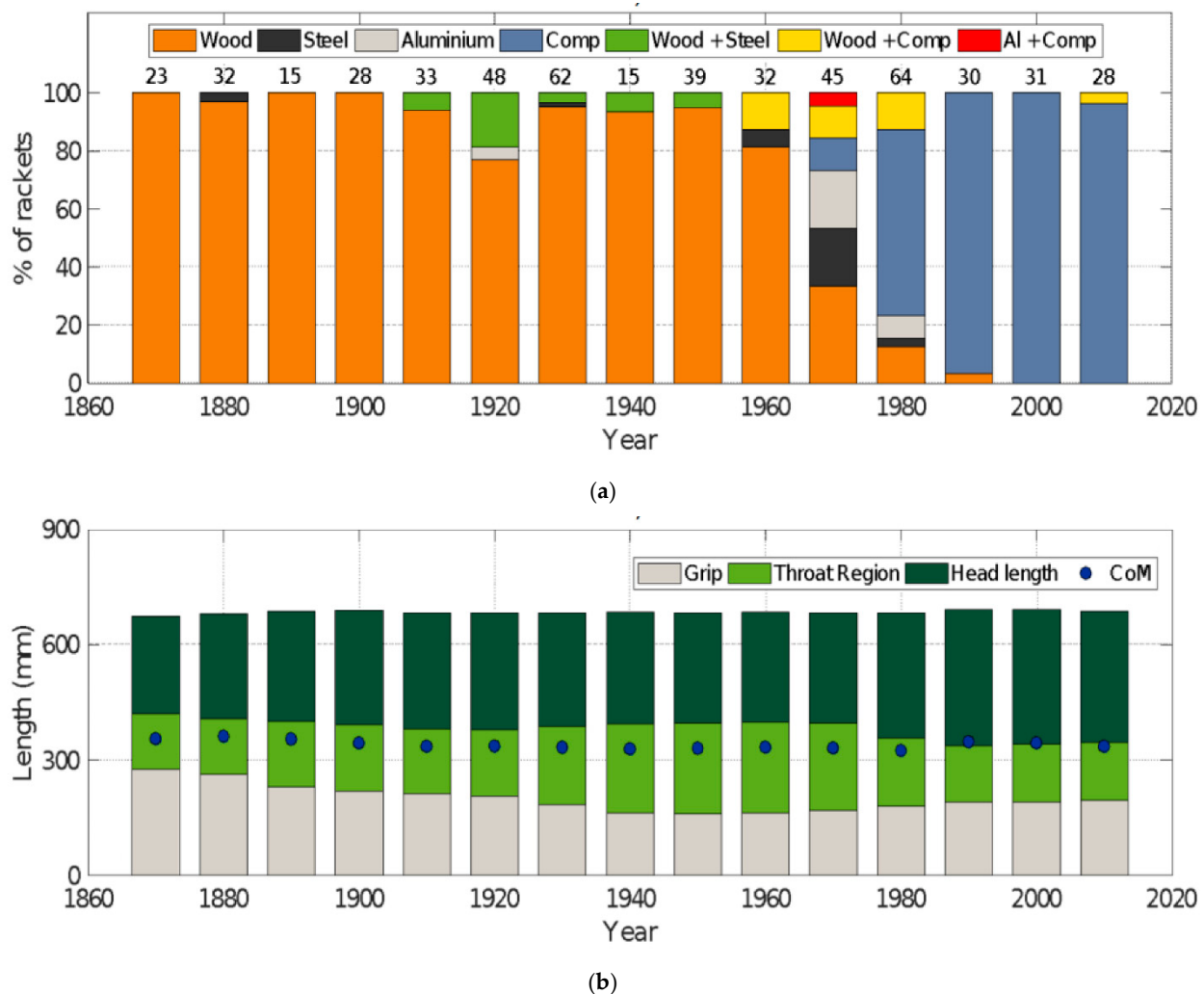


Figure 1. Bar charts showing: (a) the percentage of racquets of each material per decade (the values above the columns represent the number of racquets from each decade); and (b) the mean length of the grip, throat region and head (ext.), and centre of mass (CoM) location for the racquets per decade. Comp represents composites and Al means aluminium in the legend. Reproduced from [7], MDPI, 2019.

2.1.1. Matrix Materials

Composite racquets were initially manufactured by combining glass and carbon fibres with a polymer matrix [13]. The combination of a polymer matrix and functional reinforcements gives tennis racquets the advantages of wear resistance, low weight, and cost-effectiveness, which are critical for high-performance sports equipment [14]. Common thermoplastic and thermosetting polymer matrix materials are shown in Figure 2.

Thermoset and thermoplastic materials are used in different ways depending on their inherent properties. Thermosets are easier to combine with reinforcing fibres and shape into finished structures, and they are usually simpler to process than thermoplastics [15]. Thermoplastics, by contrast, are more flexible, less brittle, and can be reused or recycled more easily. They also provide stronger resistance to chemicals and impact damage. For the past three to four decades, thermoset composites have been widely used in the aerospace industry to create lightweight and high-performance structures due to their excellent thermal and mechanical stability [16].

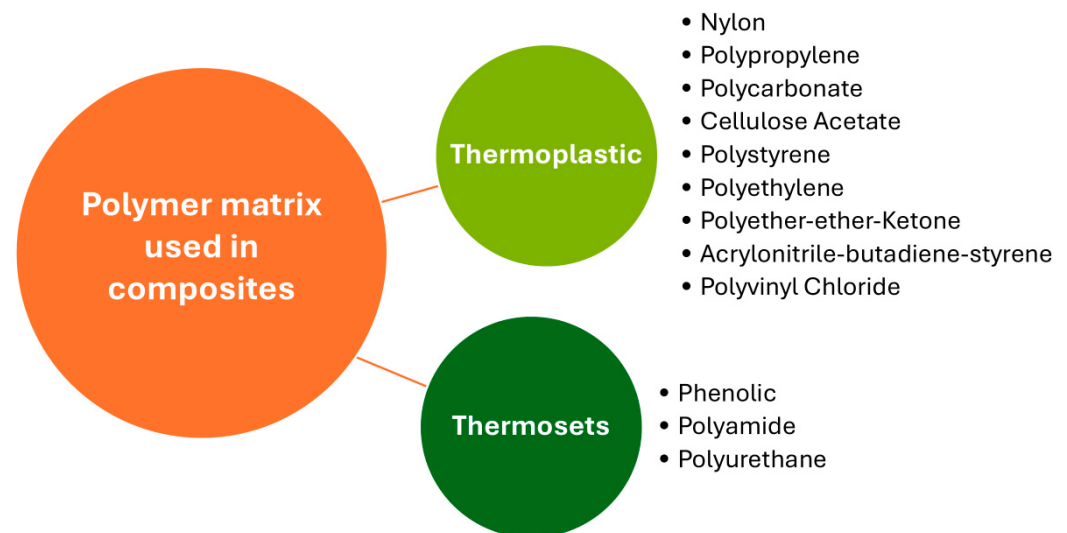


Figure 2. Polymers used in polymer matrix composites.

In the functional design of tennis racquets, polymer matrices such as polypropylene (PP) [4], epoxy resins [17], polyvinylidene fluoride (PVDF) [18], and polyamides (nylon) [19] are often used to increase strength and reduce weight, thereby improving performance and creating more durable and efficient equipment. Epoxy resins, in particular, are popular due to their excellent adhesion properties and resistance to environmental degradation, which extend the lifespan of the racquet under diverse playing conditions [20]. Polypropylene offers a good balance between toughness and processability, while PVDF provides excellent fatigue resistance and chemical stability.

Beyond sports, polymer matrix composites are widely used in the automotive, aerospace, marine, medical devices, roofing, furniture, and construction sectors, ranging from low-cost residential applications to high-end structural components [21]. Natural fibre-reinforced polymer composites further expand these application prospects by offering sustainable, lightweight, and cost-effective alternatives when the cost-benefit analysis is favourable, contributing to environmental goals without compromising performance [22].

2.1.2. Reinforcement Materials

The excellent performance of composite materials mainly comes from the contribution of reinforcement materials. Some nanoparticles or fibres are controlled to have functionalities such as strength-to-weight ratio, customised stiffness, fatigue resistance, and shock absorption and are increasingly used in sports and fitness equipment [23]. With a high tensile strength of 4.4 GPa, Young's modulus of 250 GPa, and density of 1800 kg/m³, carbon fibre is incredibly strong and durable yet lightweight [24]. This makes it the ideal material for equipment in most high-performance sports, ranging from golf to Formula (1) to tennis [25].

Over 90% of commercial carbon fibres produced in the world are created from polyacrylonitrile precursor fibres [24], popular due to their high strength yet low cost. After a wet spinning technique, pyrolysis takes place, in which the fibres experience a series of heat and stress treatments that determine their mechanical properties. This process results in variations of fibres like high strength, high modulus, and intermediate modulus fibres [9], which have the high tensile strength and tensile modulus that provide the overall strength necessary for a racquet frame [24]. Furthermore, the regularity of the carbon atom arrangement also affects the performance of the composite material. Irregularities in the arrangement, which can create micropores along the fibre axis, can become stress

concentration points and weak points. Therefore, current carbon fibre production processes focus on achieving a high degree of regularity in the carbon atom arrangement [26].

The high-strength carbon fibres have a sufficient high tensile strength and Young's modulus to withstand the repeated impacts that occur on the racquet frame. They are commonly integrated into the carbon fibre/epoxy composites that comprise most tennis racquet frames [9]. With continued advancements in material technology and processes, the implementation of carbon fibre has greatly improved the performance and safety of athletes.

As the first fibre to be used in a tennis racquet, the high resistance of glass fibre made it a suitable material for tennis racquet frames in the early 1970s [27]. However, its flexibility and weight halted the continued use of glass fibre as a standalone material for tennis racquets. As seen in the comparison of properties in Table 1, the E-glass category of glass fibre found in older racquets suffer from a lower stiffness and higher density than carbon fibre, making it less suitable for tennis racquet applications [24].

Table 1. Fibre properties.

Fibre	Density (kg/m ³)	Young's Modulus (GPa)	Tensile Strength (GPa)
Carbon Fibre	1800	250	4.4
Glass Fibre (E-glass)	2550	72	3.1–3.8
Aramid Fibres	1380–1440	60–150	1.5–2.5
Boron Fibres	2630	420	3.4

Aramid and boron fibres are very stiff but expensive, and so they are integrated sparingly as a reinforcement in tennis racquets into critical locations on a racquet composed of mainly carbon fibre to enhance impact resistance and vibration damping [27].

In addition to the high-strength carbon fibres that form the primary structure of the racquet frame, graphene-based nanoparticles were found to reinforce the resin-rich region of the handle, where the handle meets the head. The literature has omitted the fact that the addition of graphene nanoplatelets improves the mechanical properties of the resin-rich region [28]. The integration of high-strength carbon fibres forms the primary load-bearing structure of the racquet frame, while the incorporation of graphene-based nanoparticles is strategically applied to the resin-rich transition region where the handle meets the head. During manufacturing, this resin-dominated zone is more susceptible to stress concentrations and local deformation, and the addition of graphene nanoplatelets enhances the stiffness and strength of the cured matrix in this area. Thus, the choice of nanoparticle-reinforced resin is directly tied to manufacturing requirements, enabling improved consolidation and mechanical performance in regions that cannot be sufficiently strengthened through fibre layup alone.

2.2. Tennis String

Compared with the evolution of racquet frame materials, less advancements in strings come directly from the material and rather deeper understandings of the mechanics and the direct relationships between strings and desired outcomes of spin, power, and ball rebound speed have informed string choices.

Strings in tennis racquets are very efficient and need to be to ensure players are not having to put in excessive effort that could lead to injuries. These can be demonstrated through feats such as rebounding a pool ball to 95% of its dropped height [29], where even the height and speed of steel balls rebounding on stringbeds of tennis racquets is unaffected by string tension [30].

Depending on the type of string and player style, tennis strings fail under different methods. Most commonly, fatigue failure through repeated cyclic loading weakens the strings' strength to a point beyond plastic deformation [31]. Abrasion and notching, the constant rubbing of strings against each other, act as stress concentrators that can speed up the rate of string degradation and failure on top of adverse effects such as 40% and 70% lower spin rates for notched nylon and natural gut strings, respectively [32].

Tennis strings generally fall into four categories for both testing and retail purposes: natural gut, Kevlar, nylon (synthetic gut) and polyester/co-poly combinations [33]. Unlike racquet frame materials, there is no optimal material, so players need to make trade-offs between elastic return, durability, and other factors when deciding which string material to use, which then affects other choices such as string gauge and tension.

2.2.1. Natural Gut

Natural gut tennis strings are harvested from bovine intestines, which consist of highly oriented collagen fibres [34]. Unlike other string materials with a central core, collagen's chemical structure, displayed in Figure 3, is composed of three polypeptide chains wound together to form a triple helix with excellent properties [35].

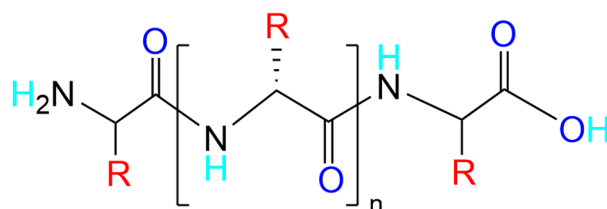


Figure 3. Chemical structure of collagen.

Natural gut continues to be used since its inception in 1876 because it is highly elastic and maintains tension better than other strings, providing both performance and durability benefits, with smaller dwell times (the time the ball is in contact with stringbed) and greater outbound velocities [36].

Because of this, natural gut has one of the lowest rates of tension loss and spring constants of 20 kN m⁻¹ for tennis strings, allowing for smaller forces, leading to prolonged use and tension maintenance [37]. When loaded in tension, infrared observations reveal that natural gut strings undergo reversible thermo-elasticity until enough tensile loading is applied to cause failure, at which point it undergoes irreversible plasticity [38], supporting the concept that if tension was applied at a different rate, a different Young's modulus would be obtained.

Environmental factors such as temperature and moisture are a major issue for natural materials such as natural guts. Unlike other tennis string materials, changing humidity levels directly impact the tension of the string over time, where Figure 4 shows the gut strings are unravelled. Additionally, fraying string decreases the tension such as the loss of nearly 7% of a string's tension over a period of 65 days solely due to humidity [39]. This creep effect was found to reduce exponentially over time. Thus, the performance of natural guts, more so than other string materials, is dependent on not only its properties but also the conditions it is subject to.



Figure 4. Section of gut string. The ‘twist angle’ is defined as the angular deviation of the twisted string from the untwisted case. Reproduced from [38], AIP, 2021.

2.2.2. Kevlar

Despite the mechanical benefits of natural gut, which made it a prominent choice for string material, its limited applications in just tennis and musical instruments combined with expensive costs and the shift to more sustainable synthetic materials in sport has reduced its popularity in favour of Kevlar, polyester, and nylon strings [40].

Kevlar is the strongest textile fibre available today, used in a variety of applications across fields such as cryogenics [41], vehicles [42], and protective armour [43]. In tennis, it is even incorporated into the racquet frame for its excellent strength and shock damping properties, with racquet frames composed of 80% graphite and 20% Kevlar [27]. Produced in a similar fashion to nylon strings through an extrusion process, Kevlar and nylon differ in the orientation of compounds which directly affect their properties. Unlike nylon which has a linear compound, Kevlar has a ring compound structure, giving it high thermal stability and strength with more density [44].

Due to this aromatic structure in Figure 5, Kevlar loses tension at a low rate, like that of natural gut. With a spring constant ranging from 90 to 140 kN/m [37], the peak forces on the Kevlar strings after impact is greatest, leading to the stringbed deforming the least with less energy loss but more energy transmitting through the body. Thus, Kevlar provides greater control and tension maintenance over time in exchange for less durability after repeated larger impacts.

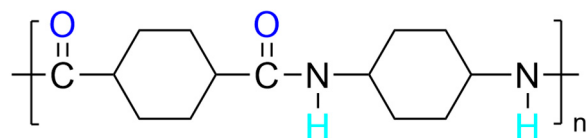


Figure 5. Chemical structure of Kevlar.

2.2.3. Polyester

Polyester strings are used both at the professional and amateur level, primarily produced from polyethylene terephthalate (PET) (Figure 6) or co-polyesters. PET is widely used due to its strength, durability, and versatility. When added to concrete, the addition of polyester fibres (and polypropylene) results in the flexural strength of concrete increasing by 37.06% [44]. With a high spring constant of 40–60 kNm^{−1}, this allows for greater control and spin capabilities but compromises on power by transmitting more of the energy through the player’s arm [37]. The coefficients of friction for polyester strings are considerably lower (0.11) than that of other materials, not requiring excessive coatings that detract from the desired properties of the strings.

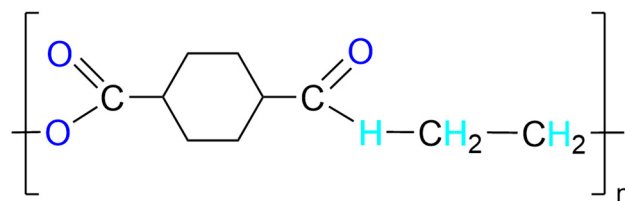


Figure 6. Chemical structure of PET.

Polyester strings are much stiffer than natural gut, leading to the same impact occurring in shorter durations, thereby losing tension at a faster rate, meaning that standalone polyester strings are inadequate for use [45]. Thus, polyester strings are either usually combined with a softer string or blend to form co-polyesters, which maintain tension better and are softer, bringing the properties of the string closer to that of natural gut [46].

2.2.4. Nylon/Synthetic Gut

Nylon strings are manufactured through a process of extrusion with nylon 6 or nylon 66 (Figure 7), in which multiple filaments are twisted together to replicate the properties of natural gut [47,48]. Nylon has become the most common type of tennis strings since it offers the best compromise of feel, control, price, and durability [37]. To produce a highly strong and elastic string, new methods such as infusing silica nanoparticles into nylon 6 have been tested. It enhanced the E-modulus by 15% and the stress at breaking to 352.43 MPa, 46.24% and 42.05% greater than that of standard nylon 6 and natural gut strings [47]. Unlike natural gut, nylon is unaffected by changes in humidity [49], making it more suitable for all playing conditions. From studying nylon strings which experience stress past their previous maximum after long periods of time (30–40 days), a gradual increase in polymer crystallinity was attributed to creep having a smaller effect, leading to prolonged string duration [50].

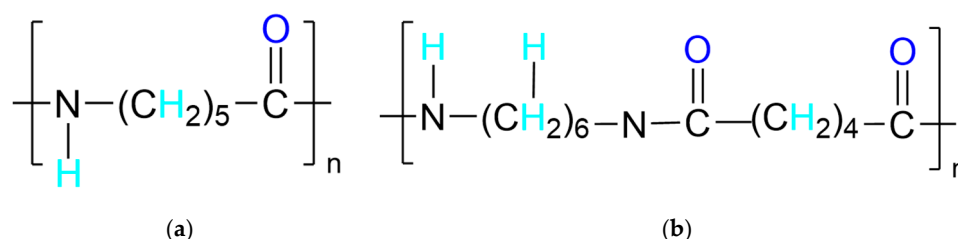


Figure 7. Chemical structure of (a) nylon 6 and (b) nylon 66.

2.2.5. Hybrid String Setups

It is not uncommon to combine a stiffer string with a softer string in a hybrid setup. By pairing two string types with different mechanical properties, much like that of fibre-reinforced composites, the concept is that these stiffer polyester strings provide the durability to the higher elasticity and thus energy return of more elastic strings like natural gut to balance aspects important to players such as durability, string longevity, and energy return. Professional players like Novak Djokovic and Roger Federer provide evidence that there are benefits to hybrid stringing, but little literature discusses this and even less analyse it, despite it being widely used by professionals.

3. Manufacturing Methods

Following advancements in material selection, new manufacturing processes were created to optimise the performance and production of primarily carbon fibre/epoxy composites, which currently offer the best mechanical properties in racquets for players.

For producing the main tool of the sport, the manufacturing procedures are summarised simply in Figure 8 [51].

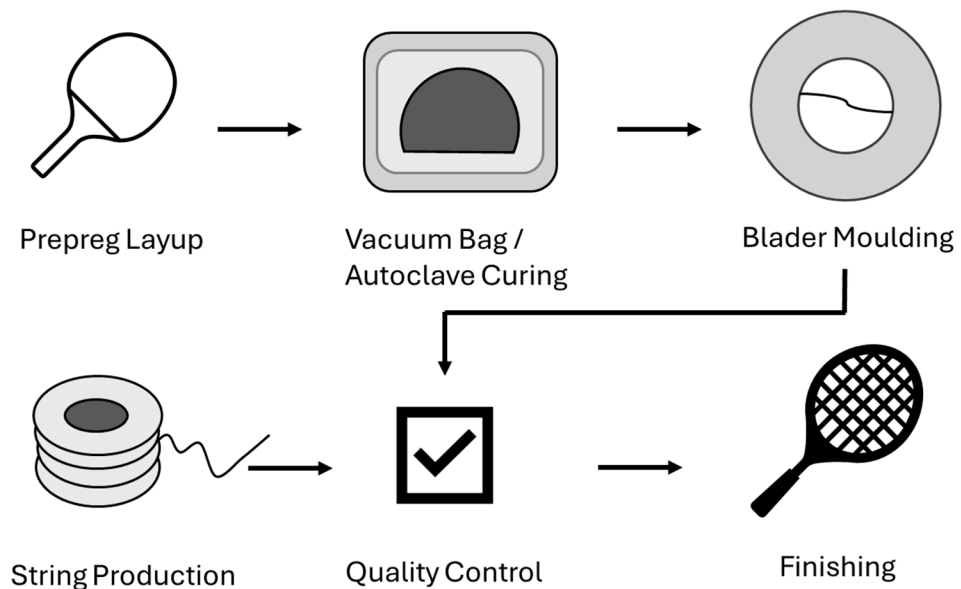


Figure 8. Manufacturing processes of a tennis racquet.

Figure 8 shows a simplified diagram of a typical manufacturing process for composite tennis racquets. Prepreg layup involves placing pre-impregnated epoxy resin-coated carbon fibre sheets into a mould or core, arranging the fibres in a specific orientation. The weave + unidirectional layers fibre arrangement is widely used in composite materials engineering. Its main function is to adjust the strength and stiffness of the material to withstand specific external loads. This customised process allows the material to have extremely high strength in the most needed direction to meet the requirements of different applications. Tennis equipment uses this technology to adjust the stiffness and strength of the head, throat, and handle. After layup, the racquets are cured and reinforced using a vacuum bag or autoclave process. A hollow-forming step produces lightweight tubular or hollow frames, typically using internal air bladders or core materials, maintaining pressure during composite curing to preserve the hollow cross-section. Once the frame is complete, the strings are manufactured separately and installed onto the frame during a finishing stage, which also includes trimming, drilling, painting, and grip assembly. Quality control is implemented throughout the process to ensure that the frame and string components meet quality standards.

Recent studies emphasise optimising autoclave curing because defects arising here strongly affect performance. For example, energy and thermodynamic analyses show that autoclave cure consumes substantial energy and that energy use is sensitive to mould design, tool thermal mass, heating rate, and pressurisation schedule [52]. Likewise, in material selection, recent work has compared carbon/epoxy systems (e.g., T300 carbon fibre with epoxy matrix) with more conventional fibre materials under static and dynamic stress analysis, demonstrating that the carbon/epoxy laminates achieve higher strength-to-weight and stiffness-to-weight ratios, but only when curing and consolidation are well controlled (i.e., minimum void content, good fibre waviness control) [53].

The hollow moulding method and the steps surrounding stringing and quality control are especially critical for the final racquet behaviour. According to the International Tennis Federation's manufacturing guidelines, during moulding, the mould is closed and heated (≈ 150 °C or more), and a plastic or inflatable tube (bladder) may be used internally to provide pressure from inside the hollow frame, ensuring uniform wall thickness and proper

contact between prepreg layers until the resin cures. After moulding, string holes are drilled and the frame is checked for excessive resin flash, sanded, and prepared for finishing [54]. Stringing adds further complexity: the tension in mains vs. crosses, precision of grommet placement, frame warpage under tension, and string thickness all affect vibration transmission and power/control characteristics [55]. Quality control after stringing often includes measuring string tension and assessing stringbed stiffness, as well as impact or drop tests on the head to simulate ball impacts, to verify mechanical performance [56].

Beyond the traditional autoclave-based method, alternative manufacturing processes such as out-of-autoclave (OOA) curing, compression moulding, and hybrid additive manufacturing have gained attention for producing composite racquets with reduced cost and energy consumption. OOA techniques, which rely on vacuum bagging and oven curing, avoid the need for high-pressure autoclave equipment and can still yield relatively high-quality laminates if the resin system is designed to allow air evacuation before gelation. However, OOA typically results in slightly higher void content and lower fibre volume fraction compared with autoclave-cured parts, which may compromise mechanical properties under dynamic loading conditions, as a key performance factor in tennis racquets [57]. Compression moulding, commonly used in mass production, involves placing sheet moulding compound or chopped prepreg into a heated mould and applying pressure to shape and cure the part rapidly. This method reduces cycle time significantly but offers less control over fibre orientation, making it less ideal for high-performance racquets where directional stiffness and vibration damping are critical. More recently, hybrid approaches have incorporated additive manufacturing (e.g., 3D-printed polymer or foam cores) combined with carbon fibre layup, enabling customisation of internal geometry for tuning weight distribution and vibration behaviour while maintaining surface integrity through traditional curing steps. While these approaches offer design freedom and potential cost savings, they currently lack the mechanical repeatability and certification maturity of autoclave processing for elite-level sports equipment [58].

3.1. Prepreg Layup and Autoclave Curing

Although prepreg fibres can be manufactured in countless ways, the carbon fibre content and resin content have been tested to find an optimal composition for modern racquets, composed of 80% graphite and 20% Kevlar [27].

During autoclave curing, the sheets are cut by hand or machine into different angles (0° , 30° , 45° , 60° , 90°) for different positioning according to application requirements. The choice of material system directly affects the racquet manufacturing process [9]. For carbon fibre-reinforced composites, design requirements determine the cutting and orientation of the prepreg before curing. Typical layup arrangements involve arranging fibres at 0° , 45° , and 90° angles to balance flexural and torsional stiffness, with additional layers added as needed to meet specific performance targets. These customised fibre orientations must be cured using processes such as air-bag moulding or autoclave curing, where heat and pressure ensure good resin flowability, tight fibre compaction, and final structural integrity. This interaction between material structure and processing technology forms the basis of the manufacturing method.

3.2. Hollow Moulding Process

Following the prepreg layup and autoclave curing process, hollow mouldings using very high injection speeds along with a temperature difference of about 130°C between melting points of plastic and metal had the benefits of improved mechanical properties at a similar weight while also eliminating the post-drilling process [51]. Thus, even though carbon fibre costs $30\times$ more than wood, the progression in manufacturing methods through

the injection moulding process presented a viable solution with improved accuracy and production efficiency.

Further progressions included a preliminary operation of using rigid polyurethane foam as an internal filling, which enhanced vibration properties and allowed for variations in grip sizes and racquet sizes that players could choose from. Melt-out moulding improved reliability and costs by preventing moulding distortion and resulted in less metal residue remaining in the mouldings as metal could be recycled [52].

3.3. Quality Control Procedures

Quality control points at various points in the development of a racquet and random testing from finished racquets ensure the reliability of high-quality racquets. Non-destructive and destructive testing are both utilised to primarily assess the stiffness and torsion properties of racquets. Non-destructive tests include bending, torsion, and tip deformation tests, which measure deformation to observe the structural integrity of a racquet. Destructive tests include a tip impact test, temperature resistance test, and side impact resistance test. These tests simulate the extremities of potential playing conditions a racquet could undergo.

3.4. Finishing Process

Even though the basic racquet shape has been created through the prepreg layup and moulding process, the finishing portion of the manufacturing process is critical for ensuring the racquet performs and looks as designed. Thus, the following finishing process takes place:

- Removing excess resin from the moulding process;
- Any surface inconsistencies are filled with body putty and sanded;
- Frames are painted;
- Final heating;
- Detailed aesthetics added.

4. Performance Properties and Ergonomics

4.1. Mechanical Properties

Over time, advancements in materials and manufacturing methods have drastically changed the landscape of tennis racquet performance, directly improving the stiffness, strength, and vibration-damping properties of modern racquets, which the player experiences in the form of a racquet's power, control, and vibration. Polymer binder systems apply their advantages in sports [3], as shown in Figure 9. Different sports equipment has varying requirements for the mechanical properties of materials during use. However, the application of diverse composite materials has promoted the development of modern sports equipment, profoundly impacting athletes' experience and performance improvement.

4.1.1. Stiffness and Strength

Stiffness refers to a racquet's resistance to bending and torsion. Stiffer racquets tend to cause faster rebounds with more energy transfer capabilities [59]. Strings return up to about 90% of the deformed energy on impact, meaning that 10% of that impact remains with the racquet frame repeatedly [31]. This signifies the importance of integrating a strong and durable yet light racquet frame.

Polyester Epoxy
• Low shrinkage • Corrosion and temperature resistance • Superior mechanical, electrical properties • Excellent substrate adhesion
Vinyl
• Mechanical strength, corrosion resistance • Better handling/faster cure • Easier processing/handling/fabrication than epoxy
Phenolic
• Creep resistance • Thermal insulation • Corrosion resistance • Sound dampening • Excellent fire/smoke resistance
Polyurethane
• Abrasion resistance • Impact resistance • Chemical resistant • Good substrate adhesion and rapid curing

Figure 9. Polymer resin advantages used for sports goods.

From the observation of the bending stiffness of 525 diverse tennis racquets [31], several observations were made:

- There was no clear relationship between stiffness and frame width;
- Composite racquets with narrow frames tend to have higher stiffness than wooden racquets with wide frames (due to composites' inherent higher Young's modulus);
- Frame depth is more important than frame width for stiffer racquets.

Increasing beam width and throat geometry also increase bending stiffness and thereby shot power in exchange for control and feel [31]. With a head size increase to 32 inches, which was not possible with wood or aluminium, racquets with composite frames were able to provide more power while weighing less. This was due to carbon fibre frames outperforming aluminium frames by 39% in the strength-to-weight ratio with 8% less deformation [59].

Additives are also a relatively new form of racquet technology that aims to further improve the performance or durability of carbon fibre. In a study conducted by HEAD, their 'graphene-enhanced' racquets were found to have a significant increase in strength while being much lighter [60].

4.1.2. Vibration Damping

Excessive vibrations during a tennis swing can have an impact on not just performance but also injury risk. Thus, the increased stiffness of modern racquets, if combined with insufficient vibration damping, harms shot control and is theorised to be a major cause of tennis elbow [61].

The natural frequency of wooden racquets ranges from 80 to 120 Hz while modern composite racquets can vibrate up to 200 Hz. Despite this, wooden racquets have double the damping capabilities of composite racquets, meaning that they only vibrate for half a second after contact while composite racquets vibrate for about a second [61]. Therefore, even though composite racquets offer more power, they also result in less control. Because of carbon fibre's inadequate damping properties, Kevlar or aramid fibre reinforcements are integrated in critical locations of the racquet to reduce the shock transmission that is harmful to players [27].

4.1.3. Uniform Properties for Tennis Strings

Few studies have focused on the durability of tennis strings under load conditions similar to those of a match. In a match, the contact time between the ball and the string is only about 5 milliseconds. The stress–strain curves shown in Figure 10a describe the quasi-static behaviour of the string material with an associated tensile rate of up to 40,000 mm/min, which is unreasonable [37]. Therefore, it is difficult to conduct impact testing in a laboratory setting for this amount of time as even hammers take up to 30 ms for a replicated ball–string impact. Thus, dynamic stiffness, elastic energy return, and tension maintenance are more commonly measured through the hysteresis curve in Figure 10b to compare string types and materials in experiments, where insights about the effects of the chosen materials and string types can be analysed as opposed to the properties of the material itself as it has less relevance in the context of a dynamic environment such as tennis.

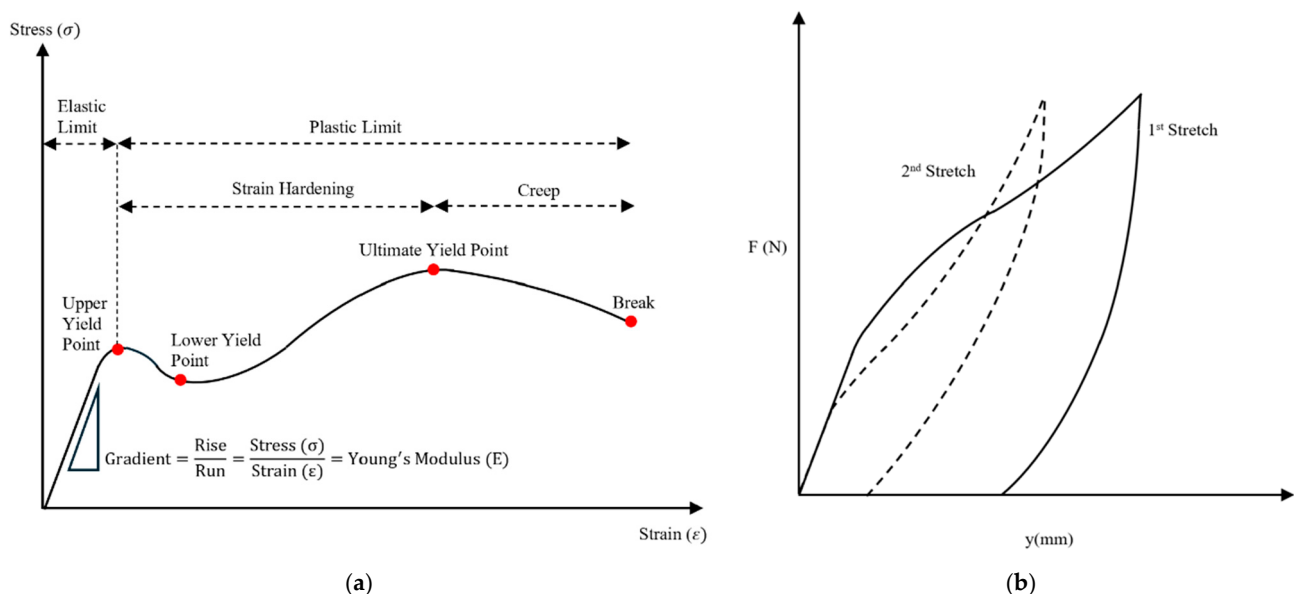


Figure 10. (a) Stress–strain curve and (b) hysteresis curve for tennis strings behaviours.

The tensile Young's modulus for viscoelastic materials such as tennis strings vary with frequency and the duration of stress/deformation upon applying loads, for which any obtained Young's modulus values would differ if neglecting these critical factors [62]. The mechanical and thermal properties of each tennis string material are summarised in Table 2 below [36,46].

Table 2. Properties of tennis string materials.

Strings Material	Diameter (mm)	Diameter at 25 kg Force (%)	Spring Constant k (kN m^{-1})	Elongation When Tensioned to 28 kg of Force (%)	Dynamic Stiffness (kN m^{-1})	Melting Temperature ($^{\circ}\text{C}$)
Natural Gut	1.255	96.41	20	7–15%	17.5–21.9	152
Nylon (Synthetic)	1.25–1.35	97.60	30–40	7–15%	26.2–45.5	187–210
Polyester	1.1–1.32	97.98	40–60	4%	66.4	182–235
Kevlar	1.25–1.40	-	90–140	1–2%	90–140	370

The performance of tennis racquet strings is determined by their strength, impact resistance, abrasion resistance, shock absorption, and control. Achieving a balance across these properties is a significant challenge in materials science. Generally, durable strings sacrifice impact resistance, while abrasion-resistant strings compromise on shock absorption.

Furthermore, lighter strings offer more power, while heavier strings provide better control. Balancing these properties to meet the needs of different players is crucial for producing high-quality tennis racquet strings. Kevlar and Vectran fibres share many similarities, including excellent thermal stability, water resistance, chemical resistance, insulation, and physical properties.

Kevlar has become a popular choice for tennis racquet strings in recent years. While Kevlar is durable, its lack of elasticity results in a stiff feel, making it unsuitable for professional players who prioritise responsiveness. Kevlar is often blended with more elastic materials, such as using Kevlar longitudinally and nylon transversely. Structurally, nylon 66 is 12% stiffer than nylon 6, but this also means it is more brittle and prone to breakage. In the mid-to-high-end badminton racquet strings market, nylon 6 refers to high-strength nylon, often blended with similar materials like nylon 66 and Vectran. Examples of badminton racquet strings using these materials include Yonex BG70, Yonex BG80, and Yonex BG85 [63].

4.2. Stringbed

Several factors affect the principles explored above, specifically on the stiffness of stringbeds. The transverse stiffness of the stringbed is proportional to the string tension in the stringbed, where smaller strings spacing and head sizes leads to larger transverse stiffness of the stringbed [64].

Stringbed patterns were found to not affect ball speed, but instead a negative correlation on spin was found [65]. With fewer less cross strings, larger main string deflections caused greater rebound spin. Studies quantify this effect through comparing an insufficient number (12–13) of cross strings to a stringbed with 19 cross strings. However, given that only 16 and 18 cross strings are typically used in modern day racquets with string patterns of (a) 16×19 and (b) 18×20 in Figure 11, the results are invalid for real-world conditions.

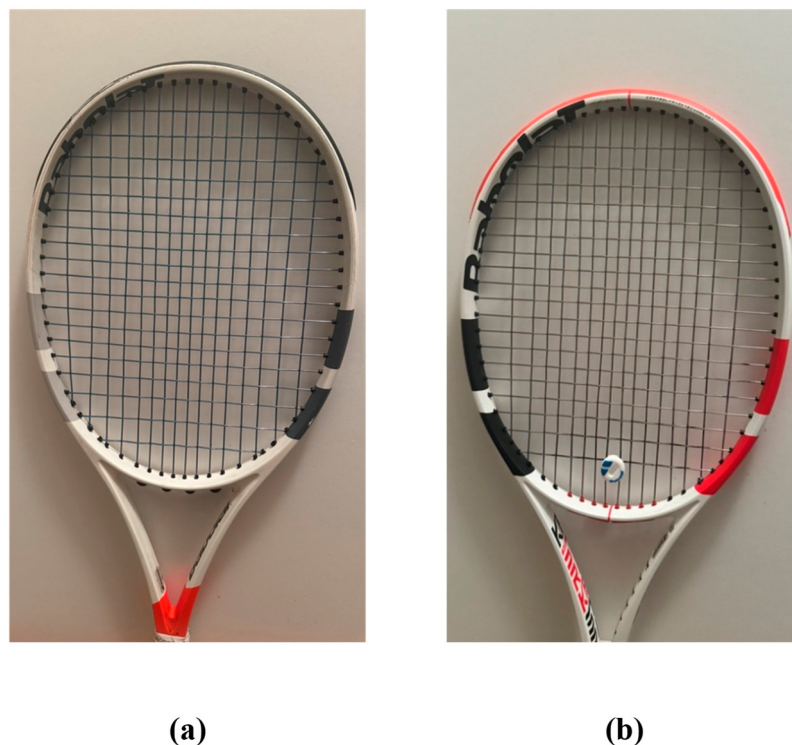


Figure 11. Racquet with (a) 16×19 pattern and (b) 18×20 pattern.

Thus, both studies present insights into how different stringbed patterns impact spin generation but are not representative of real-world conditions to confirm the notion that more open patterns (16 cross strings) allow for easier spin and higher shot trajectories compared with denser patterns (18 cross strings).

Using parameters representative of playing conditions, different impact locations had significant effects on the performance of the stringbed [66]. The sweet spot is a commonly used term by tennis players for the optimal spot to hit on a racquet's stringbed, which can be explained through mechanical behaviour. The sweet spot was originally thought to just be the centre of percussion (COP), where no reactive shock occurs [67]. The sweet spot formula relates the moment of inertia (I), the distance from the centre of mass to the gripped location (a), and the mass of the racquet (M) in Equation (1).

$$b = \frac{I}{aM} \quad (1)$$

Upon further analysis, it was determined that impacts on node points, including the first mode of vibration, would lead to the player to not experiencing any vibration or impact on their hand [68]. A total of 80% of all recorded impacts were located at these node points [69], later confirmed by the node point acting as a sweet spot through measuring vibrations using a piezoelectric transducer on the racquet handle [70]. COR reaches up to 0.90 for sweet spot impacts [71].

String tension was found to influence rebound velocity and rebound angle but not rebound spin [72]. However, balls consistently had more spin than would be generated by just rolling, with the lateral motion of the stringbed believed to cause this extra spin. No further quantitative analysis was performed, where a detailed model of the shape of the ball during impact was suggested, allowing the location of the reaction force and ball centre-of-mass to be defined.

What is not explored in the literature are the exploration of key factors that affect the mechanics of stringbeds. Equipment factors such as type of strings, string gauge, and relevant strings patterns need to be examined in connection with tennis conditions such as the spin and speed of incoming ball and the type of shot to draw meaningful conclusions.

4.3. Player Considerations

4.3.1. Equipment Perception and Performance Feedback

Given recreational players cannot identify differences in a swing weight difference of 25% but good tennis players can distinguish differences that exceed 2.5% [73], these factors have the potential to impact not just a player's performance but also their feel of the racquet. It was found that only 28% of players could detect a 50 N difference, only 44% could detect a 69 N difference or less, and 37% could not identify a 98 N difference [74]. Despite the limited dataset of 17 participants, this suggests even elite players cannot identify strings' tensions. However, methods which accurately reflect real playing conditions need to be developed since there is potential for studies that aim to extract insights from real-time hitting to be flawed and contradict previous mechanical testing results.

The trend that lower string tensions produce higher ball speeds is well understood in the literature and the broader tennis world; however, some literature directly contradicts this well-known concept. When racquets were strung at 210 N (the lowest tension in an experiment), they produced the lowest ball speeds [74]. This was explained by observation of the participants lowering their swing speed to accommodate for this excessively low tension, which could be seen in another similar setup where higher stroke speeds and ball speeds with lower deformations upon ball impact were obtained at the middle tension of 240 N (from 213.5, 240.1, 266.9 N) [75].

From these tests, conclusions, such as racquet vibration frequencies being unaffected by tension and that racquets strung at this ‘medium tension’ absorb the impact load best, both reducing the risk of arm injuries and providing more control for players, were made. However, these are very limited datasets where the analysed tensions outside the typical range of 220–240 N and thus the ball speed output may not be dependent on the effects of different tension but rather due to an experimental error. Thus, further literature should implement better testing methods to both encompass the typical tension values and replicate playing conditions as best as possible.

4.3.2. Stroke Technique and Equipment Interaction

Technique is critical for not just player performance but also injury prevention, especially in the player’s grip and swing of the racquet. Many of the body’s functions are shared between serves and topspin forehands; however, ulnar hand flexions are required for serves while radial flexion is critical to topspin forehands [76]. This emphasises the importance of relating biomechanics to future studies since outcomes like the amount of topspin a player can generate is determined by the combination of their equipment, characteristics, and ability. Topspin has been shown to be highly correlated with the head impact angle and racquet head vertical velocity, with tilts of 5–20° producing the highest spin of up to 500 rad/s or 4750 rpm [1].

Players like Nadal and Ruud are famous for their heavy spin shots, which are accentuated by their semi-Western or Western grips in Figure 12a. In contrast, players like De Minaur and Medvedev share an Eastern grip on their racquet as shown in Figure 12b, leading to less promotion on their forehand, and this grip is a major reason why they generate the least spin on tour. Thus, the constant fine-tuning of racquet frame, technique, string type, and tension need to account for the needs of the players. Whether it is intentional or not, differences in the techniques of players have effects on the outcomes of shots and thus their player performance, which are often neglected in the literature.

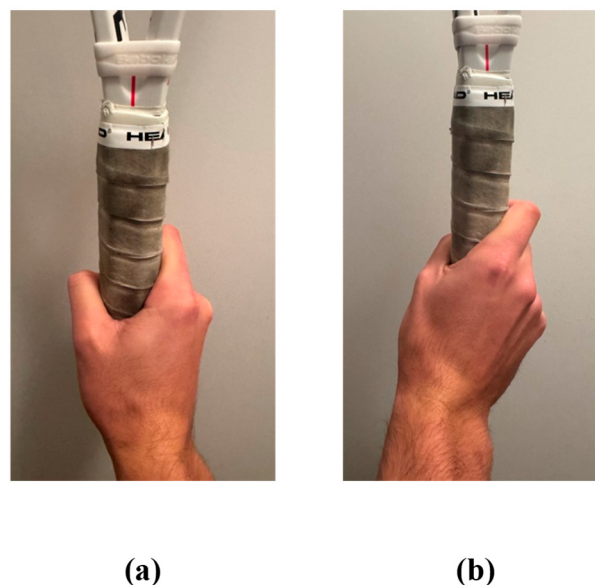


Figure 12. Forehand grip for (a) Western and (b) Eastern.

Accompanying trends in sports engineering, tennis players often customise their equipment in attempts to enhance performance. Professional tennis players add lead weights on the outside of the racquet frame to increase the racquet’s inertia and therefore the swing weight of the racquet, which has since become a common consideration for advanced players. Swing speed decreases when swing weight increases but not when

swing mass increases (considering swing weight is fixed) [77]. By increasing racquet swing weight with lead weights, the biomechanical strain decreases as the impact location shifts away from the player's grip to the tip of the racquet while still producing the same ball speed [78]. This needs to be examined further as racquets with lower swing weights have also been shown to produce higher ball speeds and be more accurate [79].

Any increase in weight and its placement will have an impact on the stiffness of the frame and the mechanical properties of the stringbed, such as sweet and dead spot locations, centre of percussion (COP), and coefficient of restitution (COR). Even though any weights added to specific points such as sweet spots, dead spots, or the COP do not change their location, given that these critical points directly affect ball velocity and spin, which can be detected by elite players, the relationship between racquet swing weight, swing speed, and the resultant outcomes which directly affect player performance need to be studied through a quantitative method.

The variety of racquets, strings, and tensions used in tennis today reflects the advancements made to give players greater customisability and performance. According to Mouratoglou Academy, a prominent tennis academy [80], the choices of the top professional players to achieve their desired outcomes are shown in Table 3.

Table 3. Professional player strings setups.

Player	Strings	Tension (kg Force)	Style of Play
Carlos Alcaraz	Babolat RPM Blast (monofilament)	24–25	Strings allow for heavy topspin, moderate tension for balance of control and power
Jannik Sinner	Head Hawk Touch	28	Dominant baseline style with powerful groundshots
Rafael Nadal	Babolat RPM Blast (monofilament)	25	Strings allow for heavy topspin, moderate tension for balance of control and power
Novak Djokovic	Babolat VS Team Natural Gut Hybrid/Luxilon Big Banger Alu Power	26 (main) 28 (cross)	Hybrid setup with high tension in main strings and lower tension in cross strings for higher control
Roger Federer	Wilson Natural Gut/Luxilon Big Alu Power Rough (hybrid)	26.5 (main) 25 (cross)	Natural gut gives power, Luxilon Alu Power Rough improves control

5. Principles for Tennis

5.1. Tennis Ball and Racquet Constraints

When analysing the key variables pertaining to tennis strings and by extension the effect of varying tension on mechanical behaviour, balls and racquets must be controlled variables. The wear of tennis balls after repeated impacts with a stringbed has a significant effect on its mechanics and aerodynamics, which need to be accounted for in the methodology of any mechanical testing with tennis balls. There is a significant difference in COR between 50 and 100 impacts [81], so to ensure consistency where wearing is important, 50 impacts should be the upper bound for any experiments.

The racquet frame is an integral component of the racquet with properties that directly affect the characteristics of the racquet. In 1979, the International Tennis Federation (ITF) introduced regulations on the dimensions for all racquets, which limited experimentation with different shapes and sizes to maintain a consistent, fair level across players that stands to this day [82]. The benefits of the material evolution of racquet frames are reflected in player performance with current carbon fibre racquets improving serve speeds by 4.5% (9 km/h) and by over 17.5% (35 km/h) compared with metal racquets and wooden racquets,

respectively [31]. By observing the bending stiffness of 525 diverse tennis racquets [6], there was no clear relationship between stiffness and frame width; instead, increasing beam width and throat geometry increases bending stiffness and thereby shot power in exchange for control and feel. Thus, the variables of tennis balls and racquet frames need to be controlled when conducting tests or running simulations so that these results can be compared with previous methodology and experiments in a valid fashion.

5.2. Mechanics of Individual Strings

To understand the complex dynamics of ball impacts on stringbeds, an understanding of the properties and outcomes of tests on individual string movements is necessary. Prior to and during ball impact in Figure 13 (a) and (b), respectively, a string can be modelled through a prestressed beam model. T denotes the applied tensile force, and T_0 is the initial pre-tension. F represents the normal force generated during impact. L and L_0 denote the current and initial string lengths, respectively. θ is the deformation angle of the strings under compression, and y is the maximum displacement in the deformation direction. The prestressing of string-like elements to contribute to a beam model has been supported by its use in applications such as construction projects, where tensile forces are required to keep roofs functional [83].

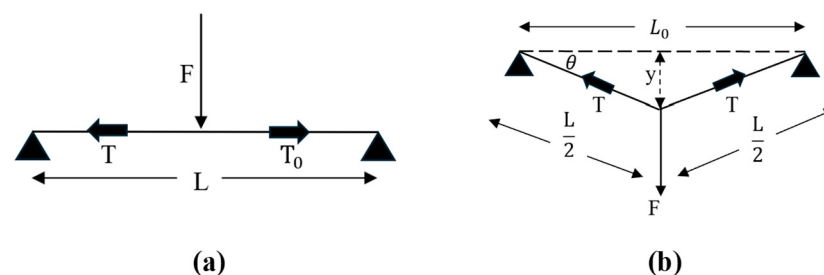


Figure 13. Mechanics of a string (a) before impact and (b) during impact, the triangular symbols represent fixed supports at both ends. Arrows labeled T indicate the tensile force acting along the cable segments.

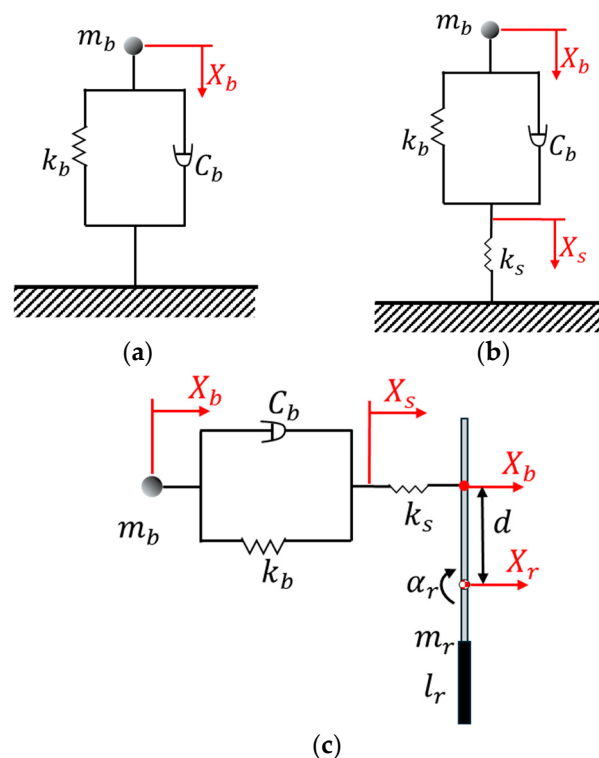
Assuming the ball impacts the middle of the string, the deflection of an individual tennis string can produce insights about the strings using equations from Table 4.

5.3. Mechanics of Stringbed

Perpendicular impact experiments can be represented through evolved models shown in Figure 14a,b. For a ball impacting a freely suspended racquet, the representation in Figure 14c is most valid with a spring and a damper in parallel (ball), another spring in series (stringbed), and the racquet's mechanics [84,85]. In the motion of a tennis ball hitting the racquet stringbed, m_b is the effective mass of the ball; k_b and C_b represent the stiffness and damping of the ball, respectively; k_s is the support stiffness of the racquet; X_b and X_s represent the displacement of the ball and racquet stringbed; m_r and l_r are the mass of the racquet and the length of the handle, respectively; α_r is the rotation angle of the racquet segment; d is the offset distance from the point of impact to the centre of mass of the racquet; and X_r is the corresponding racquet displacement. However, these models do not replicate the angled racquet orientations seen in real-world conditions.

Table 4. Equations pertaining to the mechanics of strings.

Parameters	Equation	Relevance
Length (m)	$L = \sqrt{L_0^2 + 4y^2}$	Provides deformed length of strings after impact.
Tension (N)	$T = T_0 + k(L - L_0)$	Tension after deformation.
Force (F)	$F = 2T\sin(\theta) = 4Ty/L$	Force of impact.
Perpendicular Stiffness (N/m)	$k_{perp} = \frac{F}{y} = \frac{4T}{L}$ $k_{perp} = \frac{4T}{L} \sim 4 \frac{T_0 + \frac{2ky^2}{L_0}}{L_0 + 2y^2/L_0} = 4 \frac{T_0 L_0 + 2ky^2}{(L_0)^2 + 2y^2}$	Perpendicular stiffness of strings based on impact results.
Length and Tension Approximations	$L \sim L_0 + 2y^2/L_0$ $T \sim T_0 + 2ky^2/L_0$	Since y is much smaller than L_0 for a string, the contribution by y to L and T can be approximated.
Dynamic Stiffness (N/m)	$\lim_{y \rightarrow 0} k_{perp} = 4 \frac{T_0 L_0 + 2k(0)^2}{(L_0)^2 + 2(0)^2} = \frac{4T_0}{L_0} = k$	Thus, for very small values of y , these extra components become negligible such that the dynamic stiffness of the strings is independent of the perpendicular stiffness.
Frequency	$f = \frac{1}{2L} \sqrt{\frac{T}{\mu}} = \sqrt{\frac{T}{2A\mu}}$	Relates the vibration frequency of a single string of length L with average string tension T to the frequency of the whole stringbed, with just a correction of 15.7% despite noisy data [54].
Logarithmic Decrement and Damping Ratio	$\delta = \frac{1}{n} \ln \left(\frac{y(t)}{y(t+nT)} \right)$ $\zeta = \frac{\delta}{\sqrt{4\pi^2 + \delta^2}}$	Given the logarithmic decrement (δ) is dependent on the damping response of the system and the residual vibrations of stringbeds indicate an underdamped system, the following equations can be used to determine the damping response (ζ) for a string, which can then be applied to the stringbed.

**Figure 14.** Mechanics diagram of (a) stringbed and racquet as rigid bodies; (b) racquet as a rigid body; and (c) model without rigid bodies.

5.4. Testing Methods

5.4.1. Mechanical Testing

For string-like materials, ASTM D2256 [85,86] is used to obtain the fundamental properties of a material that defines its characteristics such as the Young's modulus, tensile strength, elongation at break and stress–strain curve in the setup [87]. These properties are directly relevant to tennis equipment, as they influence string performance under dynamic loads during play, including tension maintenance, energy transfer, and durability. The extension rates of the instrument are automatically adjusted to ensure an individual fibre breaks in 20 ± 3 s as per the ASTM standard to output reliable results [88].

Typically, compression tests like ASTM D695 [88,89] operate by placing a specimen in a secured support jig subject to increase compressing loads to measure compressive strain, modulus, and strength values [90]. However, the measured stiffness of a deformed stringbed is affected by the rate of loading. Thus, a similar setup is used; however, a distributed load with a shape resembling that of a tennis ball is applied at increasing magnitudes and held for periods of time to obtain reliable results for stringbed stiffness and load–displacement responses [91,92]. One such setup is shown in Figure 15, where there is a displacement sensor placed at the top of the racquet frame and force is applied to the central (elliptical) disc **B** through a connecting rod **C** attached to a controllable actuator.

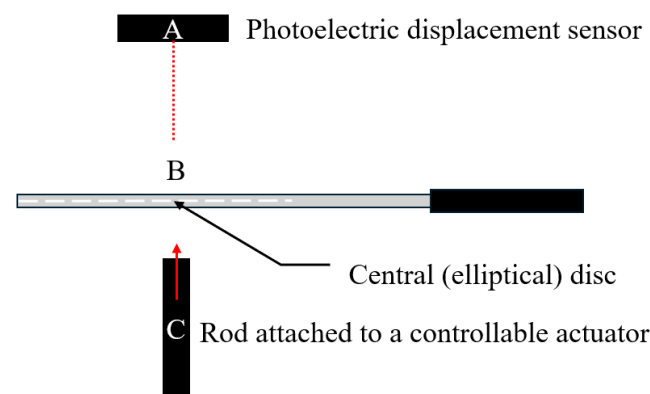


Figure 15. Scheme diagram of the experimental setup while the racquet frame is rigidly clamped about its perimeter. The red dashed line represents the optical axis of the displacement sensor. Red arrows indicate the direction of controlled actuator motion.

Very similar experimental setups are used to assess the peak forces and deformation from impact testing alongside the natural frequency and damping ratio results from vibration testing. Most setups consist of a custom rig with a racquet securely clamped to ensure no deformation of the racquet frame upon impacts from a hammer hit [37] or ball launcher [85,93]. Setups with rollers to provide vertical support underneath a racquet frame rather than clamps can also be used to assess vibration [71].

5.4.2. Numerical Analysis

The design and optimisation of modern tennis racquets increasingly rely on numerical methods, particularly finite element analysis (FEA), in combination with experimental validation. This hybrid methodology has become a standard practice in sports engineering due to its ability to predict structural performance, reduce prototyping costs, and accelerate design iteration. As illustrated in Figure 16, the process begins with defining user requirements and design constraints, followed by the selection of appropriate materials based on mechanical properties such as stiffness, strength, and damping characteristics. Subsequently, detailed structural models of racquet frames are developed using parametric computer-aided design tools and analysed through FEA to evaluate static and dynamic

behaviours. Static analyses focus on stress and deformation under loads like swing forces and string tension, while dynamic simulations, including modal and explicit dynamic analyses, assess vibrational modes and impact responses during ball contact [94]. This comprehensive approach ensures the rational design of racquets that meet performance, durability, and player comfort criteria.

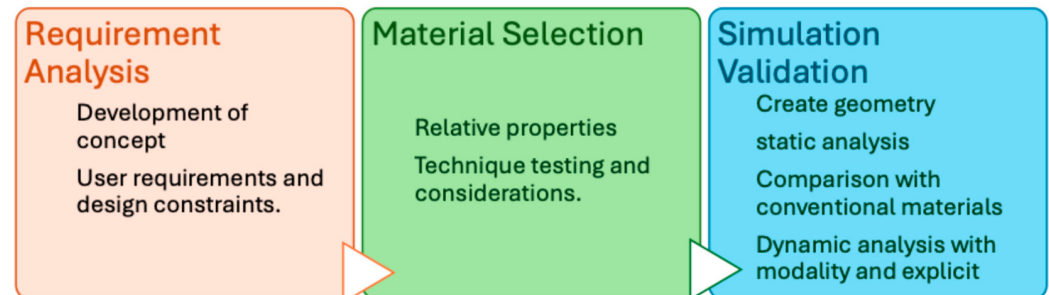


Figure 16. Design and composite material selection methodology.

The methodology commonly adopted in recent research combines FEA with experimental validation to improve model reliability and ensure practical relevance to in-play conditions. Numerous studies have demonstrated the value of this hybrid approach in sports equipment design, particularly for tennis racquets, where dynamic loading, vibration control, and impact response are critical to performance. FEA is typically employed to simulate the structural response of racquet frames under various static and dynamic conditions, including ball impact, player swing forces, and string tension effects. Material behaviour, especially for carbon fibre composite layups, is incorporated using orthotropic properties derived from experimental testing. Modal analyses are conducted to determine natural frequencies and corresponding mode shapes, while explicit dynamic simulations model high-speed interactions between the racquet and the ball. These simulations are frequently validated against experimental data obtained through vibration testing (e.g., accelerometers, laser Doppler vibrometer), drop weight impact tests, or high-speed video capture of ball–racquet interaction [94,95].

In the current literature, this integrated methodology has emerged as a standard in high-fidelity sports engineering studies. For example, validated dynamic analyses of racquet–ball impacts using explicit FEA have been shown to accurately predict rebound velocities and stress distributions when compared with ITF-standard mechanical testing rigs [96]. Other studies have investigated vibrational behaviour by correlating simulated modal frequencies with those measured experimentally on suspended racquets [97,98], while others explore how various damping systems influence impact absorption and structural response [59,99]. More recent research incorporates advanced modelling techniques such as coupled stringbed dynamics or hybrid mesh modelling to increase simulation accuracy during oblique ball strikes [59]. This iterative cycle of simulation, testing, and refinement supports optimisation in both material selection and racquet geometry and remains a cornerstone of current tennis racquet research methodology.

After importing the relevant geometry from a design software such as SolidWorks 2026, the choice of analysis based on desired outcomes is outlined in the next section. To ensure results are valid, all the steps prior to solving need to be performed accurately. The choice of element to represent a design/object is a critical step in FEA [100] since it not only affects computational cost but also the accuracy of results.

Beam element models are the most simplified elements to use, needing less computational power to produce good representations of bending behaviour through Timoshenko's beam theory, making it suitable for applications of slender bodies like tennis strings. Shell

elements represent a geometry in 2D, utilising shell theory formulation for thin-walled structures to provide more realistic results than the beam element model, but they require more computational cost. Results for stress and deformation for simulations using beam and shell elements are typically less than that of solid elements and real life since stress concentrations occurring at non-uniform areas, especially welded joints, simply cannot be represented in these simplified 2D models [101].

Using 3D strain–stress formulation, solid elements capture a high level of accuracy and detail through the analysis of a 3D structure. Despite its drawbacks of the highest computational cost and no rotational degrees of freedom for a solid element model, they are the only element type that can offer multiple scales of analysis, providing accurate results for small sections like the welded joint of a racquet frame [102].

Applying material properties, boundary conditions, and loads to be representative of what the FEA analysis attempts to simulate is critical to obtaining relevant results [94,103]. These results become more detailed with finer meshes, which require greater computational costs. Therefore, after solving, it is best practice to perform a supplementary analysis on areas of interest by refining meshes and element choices for these areas while keeping irrelevant sections unrefined to save computational cost. This further validates any results to be compared with other studies or experimental data [104].

Static structural analysis allows for a greater understanding of the stress, strain, and deformation characteristics of an object under a static load. Thus, this module is typically used in industries like construction and civil engineering to assess the deformation and stress–strain relationships of safety-critical components [105,106]. The benefit to this approach is that analysis is very simple and thus computationally inexpensive to establish the basic stiffness and deformation characteristics of a given object. However, this type of analysis cannot replicate any dynamic conditions where different loads (in magnitude and duration) occur, limiting it to purely static scenarios or reducing these dynamic conditions to be represented by static scenarios that may not fully resemble them.

Modal analysis provides the mode shapes of an object to reveal quantitative information about the vibration characteristics of a racquet. It outputs mode shapes in a computationally efficient way where the natural frequencies and vibrational behaviour of the racquet can be determined [106]. The location and magnitude of results can inform how designs could be iterated to reduce vibrations. However, it has the same disadvantage as the static structural analysis, being unable to replicate dynamic conditions. It also does not account for nonlinear material behaviour where large deformations occur (requiring the use of a nonlinear analysis module).

Explicit analysis (dynamic) employs explicit solvers that can compute loads which are time-dependent. Unlike a static structural analysis, this type of analysis can simulate dynamic responses such as impacts and vibrations, especially useful for replacing destructive tests such as car crashes [105,106]. However, this requires greater computational costs and accurate representations of contact and damping characteristics to be fully accurate, which is more difficult to achieve.

This paper numerically verifies the feasibility of obtaining significant damping using interparticle friction and impact mechanisms by combining the finite element model, discrete element model, and single-degree-of-freedom model. It is assumed that a spherical envelope transmits the impact force inside the racquet. As shown Figure 17, the finite element analysis results facilitate comparison of modes under different boundary conditions, including bending, in-plane bending, torsion, and chord bed [97].

Combining the analyses above provides a deep understanding of how an object performs when subjected to a static load and changing loads over time. However, without validating each analysis through other means, simulation results have no basis for real-

world applications. Typically, FEA results are compared against previous experimental studies to show that the setup and outputs can transfer over. Similarly, comparing with other similar FEA setups should yield similar results, and thus, any discrepancies with the current model or in literature can be explained. Hand calculations usually require simplifying a model down but enable calculations to be applied to provide rough results that should be close to any simulation results.

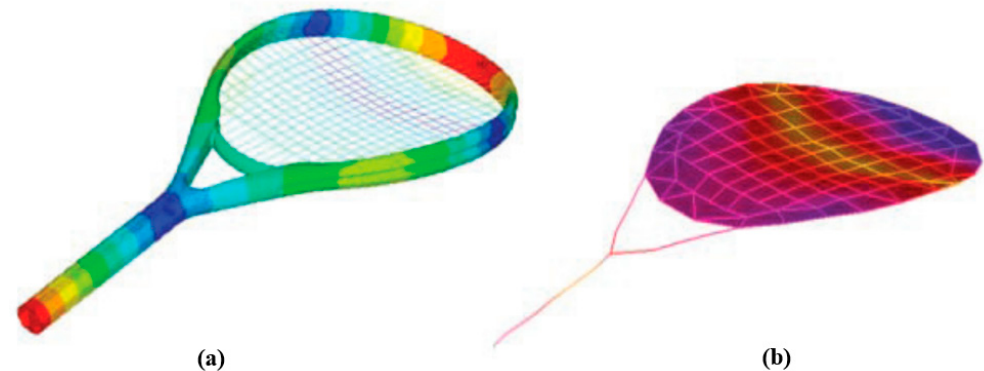


Figure 17. Mode shape of (a) FEA model, the color contours represent the normalized modal displacement amplitude (blue: minimum; red: maximum). And the experimental modal analysis in (b), the color distribution indicates the measured relative vibration amplitude reconstructed from experimental modal analysis, with warmer colors corresponding to higher response levels. Reproduced from [97], ScienceDirect, 2012.

6. Application

6.1. Global Market for Composites

In functional composite materials, the matrix material acts as a binder, firmly holding the fibres together in fibre-reinforced, layered, or particulate-reinforced composites. The properties of fibre-reinforced composites depend on fibre length: shorter fibres form discontinuous or short-fibre composites. While fibres have high tensile strength, their small diameter makes them prone to buckling under axial compression. Metal fibres, despite their higher density, are widely used in metal matrix composites due to their lower cost; good fibre matrix compatibility is one of their main advantages. Functional composites also have high melting points and can reversibly soften at high temperatures, restoring their properties upon cooling, making them suitable for processes like injection moulding. Thermoplastic matrix composites are a rapidly developing class of materials, with research focusing on improving resin performance, optimising material properties, and exploring alternative moulding methods for difficult-to-machine metals. Reinforcing materials significantly influence the properties of crystalline thermoplastic resins by promoting crystallisation. Reinforcements can enhance creep resistance and load-bearing capacity. Market growth is primarily driven by increased use of thermoset resins. Despite significant fluctuations in raw material prices, Asia is currently the world's largest and fastest-growing market due to the rapid development of emerging economies in the late 1990s. North American demand is driven by government policies aimed at improving fuel efficiency through vehicle weight reduction [26]. Globally, polyester and polyurethane are the two most widely used thermoset resins, primarily used in industrial applications. Composite materials offer significant advantages over metals and wood, including their light weight, high stiffness, and strength. They have found widespread applications in transportation, sports equipment, energy, fashion, and biomedicine, revolutionising these industries (Figure 18).

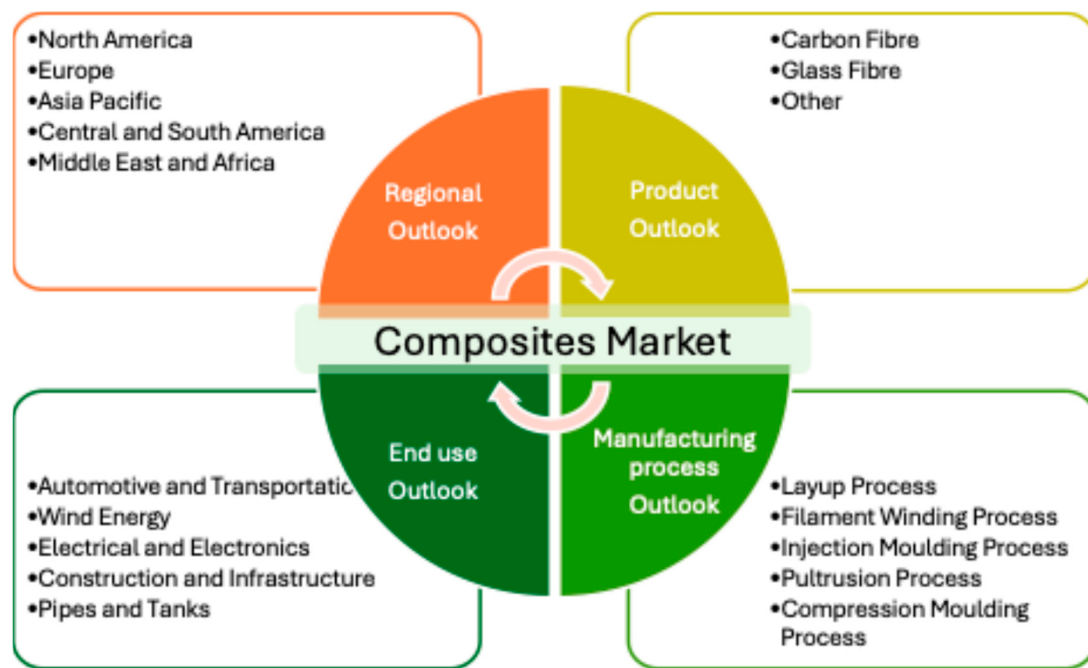


Figure 18. Sector-wise composite materials.

Lightweight composites improve fuel efficiency in vehicles, enhance the performance of sports equipment like tennis racquets and golf clubs, and reduce the weight of wind turbine blades, thus increasing wind power generation efficiency. In everyday applications, rubber has replaced wood for producing wheels, while nylon and polyester have replaced cotton for clothing. Although the initial cost of composites is often higher, their durability, corrosion resistance, and long lifespan make them more cost-effective in the long run. They protect metal components from harsh environments, reduce resource consumption, and lower transportation costs by improving fuel efficiency. The flexibility of composites allows for innovative designs without compromising strength or performance. Advanced surface treatment technologies also simplify the manufacturing process. Fibre-reinforced composites are particularly suitable for electronics due to their flame resistance and heat resistance, while aluminium-based composites provide lightweight, economical solutions for the automotive industry. In the biomedical field, composite materials play a crucial role in wound healing, tissue engineering, and the development of biomaterials for organ and tissue repair or replacement. Their versatility, corrosion resistance, high strength-to-weight ratio, and compatibility with various processing methods continue to drive innovation across various industries [107].

6.2. Materials in Sports

6.2.1. Equipment

Polymer and fibre composite materials have wide applications in sports equipment manufacturing, particularly with graphene's role in enhancing material properties. Graphene-reinforced rubber composites, such as those using graphene oxide (GO) as a reinforcing agent, have demonstrated improved interfacial adhesion, higher dielectric properties, and superior tribological performance. Experimental studies show that GO-reinforced materials reduce wear and friction by forming a protective film under dry conditions and enhancing the lubricating film under wet conditions [63]. These improvements directly contribute to enhanced durability and performance in dynamic applications.

Fibre-reinforced composites also play a crucial role in sports equipment due to their light weight, high strength, corrosion resistance, design flexibility, and ease of

processing [108]. Glass fibre, high-strength polyethylene, and aramid fibres are widely used in golf clubs, tennis racquets, bicycles, and skis. These composites not only increase load-bearing capacity but also enhance athlete performance by reducing equipment weight while maintaining mechanical reliability.

Currently, the development of modified fibre composites further expands the possibilities in this field. Graphene–carbon fibre composites can improve the strength and durability of golf clubs and enhance the damping performance of tennis racquets, thus improving gameplay, as shown in Table 5. Compared with conventional carbon fibres, graphene-reinforced systems dispersed in epoxy resin exhibit higher modulus and toughness, extending the service life while maintaining a lightweight design [108].

Table 5. Expected improvement of graphene fibre composite sports equipment.

Expected Improvement	Golf Clubs	Tennis Racquets
Tensile Strength	3.9%	5.4%
Fracture Strength	3.9%	5.2%
Compressive Strength	1.7%	2.3%
Compressive Modulus	2.3%	3.2%

Advancements in fibre composites demonstrate tremendous potential to transform the sports equipment manufacturing industry. These innovations not only enhance mechanical and functional performance but also highlight the role of materials science in advancing sports technology and supporting athlete performance.

6.2.2. Comfort of Sports and Fitness Facilities

In the manufacturing of sports facilities and equipment, rubber-based composite materials are one of the most commonly used polymer materials. Their excellent elasticity enhances safety and comfort during sports activities. These materials are widely used in products such as volleyballs, basketballs, soccer balls, dumbbells, badminton racquets, and racquet grips (Table 6). For example, polyvinyl chloride effectively absorbs impact forces, significantly improving comfort and reducing the risk of injury [109].

Table 6. Performance of polymer materials commonly used in sports.

Category	Example	Main Materials	Key Properties
Sports Equipment	Sports bike	Polyetheretherketone, polycarbonate	Strong, heat- and impact-resistant
	Rubber track	Polyurethane rubber	Friction, solvent, oil, and aging resistance; high strength
	Basketball	Polyvinyl chloride	Anti-aging and corrosion resistance
Recreational Gear	Table tennis	Polyester	High toughness and friction resistance
Footwear and Protection	Racing	Natural rubber, polyisoprene	High elasticity for racing tires
	Sports shoes	styrene-butadiene rubber, polystyrene-butadiene	Anti-wet, low rolling resistance
	Protective equipment	Nitrile rubber, acrylonitrile-butadiene copolymer	Oil, aging, and friction resistance

Fibre-reinforced polymer composites also play a crucial role in sports equipment design. In material selection, health and comfort are primary considerations. For example, composite fabrics used in water sports are often treated with a primer and topcoat to enhance their flexibility and breathability, thus improving the athlete’s freedom of movement.

Beyond personal equipment, synthetic materials are widely used in sports venues and facilities. Track surfaces have transitioned from traditional concrete to synthetic composites, and synthetic materials are also used for flooring in stadiums and gyms to enhance performance and safety. These surfaces offer elasticity, sound absorption, shock absorption, wear resistance, and slip resistance, effectively reducing stress on the legs during long training sessions or competitions, thus lowering the risk of injury. Synthetic tracks use a multi-layered structure, with a stable base layer and a top layer composed of materials such as polyacrylate, ensuring elasticity, comfort, and breathability [110].

In water sports, composite materials must withstand the weight of the athlete and the dynamic pressure of the water, requiring high strength and rigidity. Thermoplastic and thermoset composites are widely used due to their light weight, durable nature, and ease of controlling speed and direction. Polyurethane foam composites are often used for the outer layer of surfboards and water skis, and their good thermal insulation properties can effectively reduce energy loss in cold water environments [111]. Other functional composite materials are used for components such as speedboat seats, further enhancing comfort and performance in extreme conditions.

In nanocomposite reinforcement, carbon nanotubes weigh only one-sixth as much as steel, yet their strength is 100 times greater. They are used in professional tennis racquets, golf clubs, and bicycle frames to achieve superior stiffness and impact resistance. Other common nanomaterials, such as graphene, nanoclay, silica nanoparticles, and carbon nanofibres, are also used in equipment like fishing rods, baseball bats, bows, skis, and hockey sticks [111]. These technological advancements deliver higher power, more precise control, and superior performance that traditional materials cannot achieve.

Nanotechnology also plays a crucial role in sports medicine and protective equipment (Table 7). Its applications include tissue regeneration, targeted drug delivery, implants, diagnostic imaging, and wound dressings and immobilisation devices. Nanotechnology is also highly customisable, allowing for the design of equipment tailored to each athlete's individual needs, rather than relying on standardised, mass-produced products.

Table 7. Properties of sportswear and equipment incorporated with nanotechnology.

Function	Nanotechnology Feature	Sporting Examples
Performance and Recovery	Enhanced blood circulation, electronic textiles	Therapeutic gear, sensor-embedded clothing
Protection and Durability	Water-proof, Self-cleaning, UV protection	Outdoor and water sports gear, tents, cycling wear
Comfort and Hygiene	Comfort, antibacterial	Everyday sportswear and shoes
Thermal Regulation	Protection from cold and heat	Skiing, diving, mountaineering clothes

In the textile industry, the combination of nanotechnology and composite materials has enabled the development of waterproof, quick-drying, and breathable sportswear. Furthermore, adding nanoparticles to fabrics improves comfort while maintaining environmental friendliness [111]. For example, silver nanoparticles are widely used in sports socks to inhibit bacterial growth and reduce odour. Similarly, graphene and other nanomaterials are used to create lightweight, thermally conductive fabrics, improving breathability and comfort (Table 8).

Table 8. Fabrication methods and advantages for composites in sport equipment.

Category	Example Applications	Nanotech Used	Performance Benefits
Precision and Control	Golf clubs, golf balls	Nanoparticles, CNT coatings	Improved control, uniformity, and directional accuracy
Durability and Strength	Hockey gear, ski/snowboard equipment	CNTs, nanomaterial coatings	Enhanced stiffness, strength, and fatigue tolerance
Speed and Efficiency	Swimwear, sport cars	Nanotech coatings, CNT structures	Reduced drag, lighter materials, better aerodynamics
Protection and Safety	Helmets, smart sensors	Nanocomposites, smart foams	Impact resistance, real-time monitoring
Comfort and Hygiene	Footwear, sports balls	Nanocoatings, AgNP, nanoclay	Waterproofing, odour resistance, stable pressure

7. Conclusions and Outlook

7.1. Summary

The integration of advanced composite materials has fundamentally transformed tennis equipment, setting new standards across the sports industry. Innovations in carbon fibre, Kevlar, and polymer composites have significantly enhanced the strength-to-weight ratio, shock absorption, and durability of tennis racquets. Coupled with sophisticated manufacturing techniques such as prepreg lamination, hollow moulding, and surface functionalisation, these advances enable precise tuning of mechanical properties to meet diverse player needs. Modern racquets are not only lighter and more robust but also highly customisable, catering to a wide range of skill levels and playing styles. Similarly, tennis strings have evolved from predominantly natural gut to engineered high-performance fibres and composite structures, striking a nuanced balance between durability, elasticity, and control. Together, these developments have elevated equipment performance, contributing directly to improved player experience and competitive outcomes. These advancements represent a successful convergence of materials science, engineering, and design, demonstrating how targeted innovation can address the complex demands of sports equipment. The ability to optimise stiffness, strength, vibration damping, and tension retention has transformed tennis racquets and strings from simple tools into sophisticated performance enhancers. Furthermore, quality control and manufacturing precision have ensured consistency and reliability in equipment, reinforcing player confidence and safety. This holistic improvement underscores the importance of interdisciplinary research and development in pushing the boundaries of athletic performance.

7.2. Future Work

Looking ahead, material technology trends will move toward customisation and functionalisation. Emerging nanomaterials and smart composites hold the promise of integrating sensing, energy absorption, and adaptive stiffness directly into sports equipment. Simultaneously, advances in computational modelling and simulation will play a key role in accelerating innovation in tennis equipment design. FEA multiscale modelling and machine learning algorithms are increasingly being used to predict and optimise material behaviour, structural properties, and player–equipment interactions under real-world match conditions. These tools enable researchers to simulate the complex dynamics of racquet–string impact, vibration damping, and stress distribution without the cost and time constraints of extensive physical testing. Future work may focus on combining these simulation methods with experimental data to develop predictive models that can tailor racquet and string properties to individual players’ biomechanics and playing styles. The synergy between scientific discovery and computational simulation will deepen our un-

derstanding of the relationship between materials and performance, enabling the design of next-generation tennis equipment that offers unprecedented precision, comfort, and injury prevention. In summary, the application of modern materials in tennis equipment represents a delicate balance between science, engineering, and industry.

The future development of tennis equipment is expected to focus on improving performance while addressing emerging technological and social challenges. Smart materials and sensing technologies can be integrated into sports equipment. For example, embedding strain-sensitive fibres, piezoelectric elements, or graphene-based sensors can enable real-time monitoring of string tension, impact force, player technique, and equipment wear, thus opening new avenues for data-driven performance optimisation. Another area requiring further research is the development of digital platforms for personalised equipment design. Advances in simulation, digital twins, and player-specific biomechanical modelling technologies promise to allow for more precise customisation of racquet layering, handle geometry, and stringing patterns to individual playing styles than currently possible.

Simultaneously, future research should focus on the increasingly important environmental sustainability issues in material selection and manufacturing processes. Research on recyclable composite matrices, bio-based fibres, solvent-free processing, and low-energy curing methods is crucial for reducing the environmental burden of composite sports equipment. A deeper understanding of material performance under actual competition conditions, particularly by combining laboratory testing with usage monitoring, will help identify failure mechanisms and provide a basis for improving design strategies. In conclusion, these directions highlight the need for continued interdisciplinary collaboration in fields such as materials science, sports engineering, data analytics, and sustainability to support the development of next-generation sports equipment.

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Abbreviations

The following abbreviations are used in this manuscript:

CNTs	Carbon nanotubes
CoM	Centre of mass
COP	Centre of percussion
COR	Coefficient of restitution
FEA	Finite element analysis
GO	Graphene oxide
ITF	International Tennis Federation
OOA	Out-of-autoclave
PET	Polyethylene terephthalate
PP	Polypropylene

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