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Molecular & Cellular Biomechanics 2024, 21(4), 906.
https://doi.org/10.62617/mcb906

Article

Biomechanics of conjugated materials in tennis racket swing action

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CITATION

Tian D. Biomechanics of conjugated materials in tennis racket swing action. Molecular & Cellular Biomechanics. 2024; 21(4): 906. https://doi.org/10.62617/mcb906

ARTICLE INFO

Received: 25 November 2024
Accepted: 10 December 2024
Available online: 19 December 2024

Abstract: In response to the problem of insufficient elasticity and high swing load in tennis rackets, this article adopted a new π conjugated material to optimize the tennis racket and conducted research on the biomechanical analysis of swing actions. Firstly, the Hummer method was used to oxidize and dry graphite to prepare graphene materials with low dispersion. Poly1, 5-diaminoanthraquinone (PDAA) nanocomposites were introduced, and they were fused with graphene materials through chemical oxidation polymerization to produce a new π conjugated material. Then, they were applied to the string surface and handshake improvement of tennis rackets through impregnation and vacuum drying methods, improving the elasticity of the strings while reducing the weight of the tennis racket. Finally, on-site material validation was conducted on the self built survey athlete dataset. The experimental results showed that the accuracy of the tennis racket made of the new π conjugated material reached 99.41%, which was 6.73% higher than that of carbon fiber material. The bending strength reached 97.53 MPa, and the weight of the racket was only 255 g. The application of conjugated materials has enhanced the elasticity of tennis rackets, reduced the weight of the racket, and promoted the fatigue resistance and accuracy of tennis players' swing actions.

Keywords: new π conjugated material; tennis racket; biomechanical analysis; tennis racket elasticity; fatigue resistance

1. Introduction

With the rapid development of social information technology and the urgent need to optimize sports actions, various types of sports action optimization have begun to emerge in public places, with the optimization of tennis swing actions being particularly prominent. At present, the elasticity of tennis rackets is insufficient, making it difficult for athletes to accurately control the swing speed and strength, resulting in poor accuracy of the swing and hitting the ball. Moreover, the racket burden is high, leading to increased fatigue and risk of injury during the game, which affects the performance of the tennis racket. The introduction of new π-conjugated materials provides an innovative way to optimize the performance of tennis rackets. π-conjugated materials have excellent mechanical properties, including high strength, high elastic modulus, light weight and good energy absorption characteristics, which promote the improvement of swing accuracy and the reduction of swing burden during competition.

In recent years, the country has attached greater importance to the optimization of sports actions and the in-depth development of the material industry. The optimization of tennis rackets has become a hot topic, and researchers have currently achieved a large number of research results in this field. Zhu and other scholars explored the application of π-conjugated materials in sports training to improve athletes' performance and contribute to the better development of sports [1]. Scholars such as Touzard analyzed the effect of scaled rackets on the biomechanics of the player's hitting arm when serving. The results showed that a scaled 23-inch racket can reduce the load on the shoulder and elbow [2]. In order to improve the performance of tennis rackets, Wang and other scholars used fiber nanocomposites to prepare tennis rackets. The physical resistance of the racket was increased by 42%; the chemical stability was improved by 30%; the weight was reduced by 25% [3]. Scholars including Yeh proposed a new type of vibration damping technology (VDT) for rackets, which improved frame stability, delayed muscle fatigue, and increased hit rate by 40% [4]. Deng and other scholars proposed an assembly mode of rubber-wood-bamboo laminated composite (RWBLC) for the modification of rackets, which improved their deformation resistance [5]. Scholars such as Park analyzed the impact of polymer composite materials on tennis rackets and explained that this material can make tennis rackets more lightweight and durable [6]. The above scholars have improved the pressure resistance and lightness of tennis rackets to a certain extent, but have not fully considered the elasticity of the racket, resulting in low accuracy of athletes' swing and hitting.

In order to improve the performance requirements of rackets and the necessity of introducing conjugated materials, many researchers have conducted research on conjugated materials. MacFarlane and other scholars elaborated on the methods and application fields for synthesizing π conjugated polymer nanoparticles in order to explore the application of new π conjugated materials [7–9]. Helten and other scholars synthesized a new material using π conjugated polymers and trivalent boron atoms to enhance the performance of amine sensors [10]. In order to solve the problems of small domain values and high defect density in material synthesis, scholars such as Galeotti proposed a preparation strategy for mesoscale ordered two-dimensional π conjugated polymers, which is conducive to molecular diffusion and eliminates voids in the network [11]. Miao and other scholars applied conjugated nanomaterials to the design of sports equipment such as tennis rackets, making them lighter and increasing the strength of the equipment [12]. Wu and other scholars found that the use of graphene materials to make sports equipment such as tennis rackets can make the sports equipment have high strength and light weight, reducing costs [13]. The above scholars have solved some density and stiffness issues in other fields, but other scholars have not been able to apply new π conjugated materials to the tennis field. Overall, it is feasible to adopt a new π conjugated material for improving tennis rackets. Therefore, based on the above literature, this article adopted a new π conjugated material to improve the tennis racket, which can improve the problem of insufficient elasticity in tennis swing actions, solve the problem of low swing accuracy, and to some extent reduce the fatigue of the swing.

In order to solve the problem of insufficient elasticity and high swing load of tennis rackets, this article adopted a new π conjugated material to improve the tennis racket. Firstly, graphite was oxidized and dried using the Hummer method to prepare graphene materials with low dispersion, and PDAA nanocomposites were introduced. A new π conjugated material was fused with graphene materials using chemical oxidation polymerization. Then, it was applied to the improvement of the string surface and handshake of tennis rackets through impregnation and vacuum drying methods. Finally, on-site material verification was conducted on a self built survey athlete dataset. The experimental results showed that the accuracy of tennis rackets made of the new π conjugated material reached 99.41%, which was 6.73% higher than that of carbon fiber materials; the bending strength reached 97.53 MPa, which was 24.89 MPa higher than that of wooden materials; the weight of the racket was only 255 g. Athletes had a satisfaction score of up to 34 points for rackets made of new π conjugated materials. The swinging speed of the hand joint reached 9.4 m/s, which was 2.1 m/s faster than that of the wrist joint; the impact strength under UV (ultraviolet) irradiation reached 5.24 kJ/mm^2. The use of conjugated materials has enhanced the fatigue resistance and precision of tennis players' swing actions, while also reducing the weight of the racket.

2. Conjugate material selection

Graphene Nanosheets (GNS), as two-dimensional structured nano carbon materials [14–16], are a two-dimensional lattice composed of single-layer carbon atoms, which have outstanding conductivity and thermal conductivity, as well as extremely high mechanical strength. The arrangement of carbon atoms forms a hexagonal lattice structure, with each carbon atom forming a conjugated double bond system, generating a large area of π electron clouds, which endows graphene with excellent electron conductivity and optical transparency. Graphene is introduced into conjugated polymers and, and through π-π interactions, the conjugated polymers are deposited on the surface of graphene at a nanoscale, improving the utilization efficiency, cyclic stability, and charge transfer performance of the conjugated polymers. The crystal structure diagram of graphene is shown in **Figure 1**.

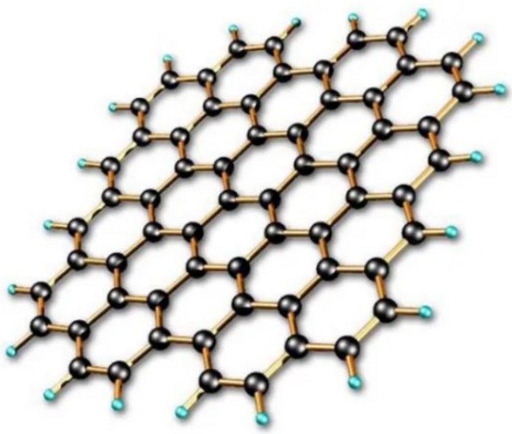

Figure 1. Graphene crystal structure diagram.

PDAA is a polymer compound that possesses a polyaniline conductive skeleton and 1,4-benzoquinone groups, exhibiting excellent electrochemical activity. Meanwhile, strong π-π electron stacking and hydrogen bonding interactions between molecules are beneficial for improving cyclic stability. In addition, PDAA's *p*-type and *n*-type fusion ability gives it a very wide point window.

Carbon fiber composite materials are prepared from organic fibers, which are combined with matrices such as resin and metal to achieve high strength. In order to study the performance of carbon fiber composite materials under high temperature conditions of water absorption machines [17], scholars such as Yu Long used vacuum assisted molding to prepare carbon fiber composite laminates due to the advantages of good corrosion resistance. Firstly, he made carbon fibers into 450 mm × 450 mm carbon fiber cloth, spread it flat on the peeled panel washed with acetone, and applied it evenly with a release agent. Finally, he fully soaked the carbon fiber with resin connected at both ends of the tee, and then obtained the carbon fiber material through curing, cooling, and other treatments. Experiments have shown that carbon fiber can better control the changes in humidity and heat under suitable conditions, demonstrating its excellent performance in sports training equipment. However, the tensile strength of carbon fiber materials is often reduced due to the interaction between thermal stress and internal stress, resulting in cracks and damage to the interface between carbon fiber and resin matrix [18,19].

In this article, based on GNS, a new π conjugated composite material is synthesized through chemical oxidation polymerization. Firstly, graphene is gently reduced by radiation to suppress irreversible aggregation of graphene during the reduction process, and then a thin layer of graphite is output. In addition, camphor sulfonic acid is selected as a soft template and dopant, giving the composite a uniform nanopore structure.

3. Preparation and design of conjugated materials

3.1. Preparation of conjugated materials

(1) Preparation of graphene

This article refers to the preparation of graphite oxide using the Hummer method [20–22], where graphite micropowder is used as the raw material. Firstly, graphene micropowder is acidified with 0.9 $mol \cdot L^{-1}$ hydrochloric acid and treated at 1200 ℃ temperature to obtain expanded graphite. Then, 135 ml of 98% sulfuric acid is gradually added to 4 g of expanded graphite and stirred evenly. When the temperature is lowered to 5 ℃, 15 g of potassium permanganate is added then, and the temperature is maintained at 0–5 ℃. After adding water, the temperature is raised to 36 ℃ and maintained for half an hour. 220 ml of deionized water is added, and the temperature is controlled below 10 ℃. The reaction took place at 95 °C for 15–20 min. Finally, the mixture is added to 600 ml, stirred evenly in 4% hydrogen peroxide water for about 1 hour, filtered, and washed to obtain neutral graphene oxide (GO) raw material [23,24]. The structure of oxidized graphene is shown in **Figure 2**.

On the basis of the above oxidized graphene, graphene is reduced [25–27]. The specific process is as follows: first, GO is dispersed in deionized water; the concentration is adjusted to 2 $mg \cdot mL^{-1}$, and aqueous ammonia is dropped to adjust the PH of the solution to 10. At room temperature, magnetic force is used to stir for 3 days to completely peel off and obtain a colloidal solution of graphene oxide. Then, the same volume of propan-2-ol is added to form a solution of 1 $mg \cdot mL^{-1}$. Argon gas is introduced to remove oxygen from the solution and sealed in a stainless steel tube. At the same time, CO is added for reduction at a dose of approximately 100 kGy. Finally, the reaction solution is freeze-dried to obtain dispersed graphene.

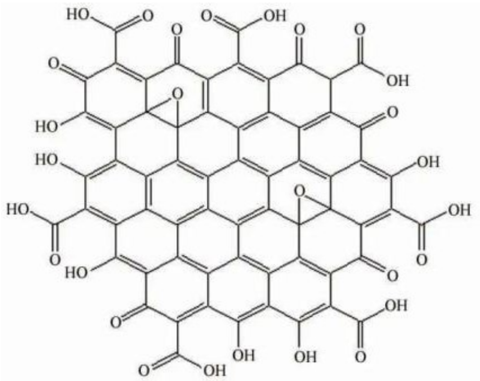

Figure 2. Structure of oxidized graphene.

(2) Preparation of GNS and PDAA nanocomposites

GNS and PDAA nanocomposites are synthesized using GNS as the carrier using chemical oxidation polymerization [28–30] to synthesize new π conjugated composite materials. The specific process is as follows: firstly, 160 mg, 55 mg, 27 mg, and 13.7 mg of GNS are added to 30 ml of sulfuric acid at a concentration of 1 $mg \cdot mL^{-1}$. Among them, in the N-dimethylacetamide solution, the solution is uniformly dispersed using ultrasonic dispersion, and 1.25 mmol of camphor sulfuric acid is added. Then, 1.25 mmol of N, N-dimethylacetamide solution of 1,5-diaminoanthraquinone is added to the mixed solution and stirred for 5 h. 2.50 mmol of ceric sulfate $Ce(SO_4)_2$ is added and stirred uniformly at 20 ℃ for 2 days. Finally, dimethylacetamide (DMAC), ethyl alcohol, and deionized water are washed and purified, followed by freeze-drying treatment to obtain the composite material.

The discussion results of the influence of different preparation conditions on material properties are shown in the table.

Table 1. Material properties under different preparation conditions.

Preparation conditions	**Conductivity (S/cm)**	**Mechanical strength (GPa)**	**Thermal stability (℃)**
Oxidant concentration (graphite: potassium permanganate)			
1:25	100	2	280
1:3.75	150	2.5	300
1:5	50	1.8	250
pH reduction			
9	120	2.4	310
10	150	2.5	300
12	80	2.1	280
Reduction reaction time (h)			
24	100	2.3	290
48	150	2.5	300
72	120	2.2	280

In **Table 1**, it can be seen that when the oxidant concentration is 1:3.75, it can better ensure the oxidation degree of graphite and achieve ideal electrical conductivity, mechanical strength and thermal stability. Regarding the reduction pH value, when the pH value is 10, the peeling effect of graphene is the most significant and the performance is superior. However, damage to the structure of an excessively alkaline environment must be avoided. In terms of reaction time, it is 48 hours, the reduction effect is the most complete, the performance of graphene is stable, and the conductivity and strength are the best.

3.2. Conjugate material design

Through the preparation of the aforementioned material, it is integrated into the tennis racket. Firstly, the coating or embedding position is determined on the racket frame, and the impregnation method [31] is adopted to evenly coat the new π conjugated composite material on the string surface and handle of the frame, which can reduce the impact during swing and improve comfort and racket elasticity. Then, the material is solidified onto the tennis racket frame by being subjected to solution drying and material drying treatment in a vacuum drying environment, and then used by heating to ensure firm adhesion.

4. Performance verification experiment of new π conjugated composite materials on tennis rackets

4.1. Experimental subjects

This experiment collected the swing actions of 100 tennis players in the field. The swing states were all right handed, and the hitting methods were divided into five types: high, middle, low swing, forehand swing, and backhand swing. The selection criteria for the experimental subjects are as follows:

(1) 100 tennis players, including 50 males and 50 females, ranging in age from 18 to 40 years old, with an average age of 26 years old.

(2) All experimenters have amateur and intermediate technical levels, have at least 3 years of tennis training experience, and can complete basic swing movements.

(3) The athletes are in good physical condition and have no history of major sports injuries that affect the swing movement, ensuring the accuracy and representativeness of the experimental results.

The experimental data of tennis players includes changes in shoulder and hip torsion angle with instrument speed, relevance (R), probability of hitting the ball (P), and other data. In the experiment, this paper compared the new π-conjugated material with other materials, including wood materials, graphene materials, and carbon fiber materials. **Figure 3** shows the satisfaction scores of wooden materials, graphene materials, carbon fiber materials, and new π conjugated materials.

Evaluation index	Wooden material				Graphene material				Carbon fiber material				New π-conjugated materials			
	Exterior (10 points)	Comfort (10 points)	Fatigue level (10 points)	Swing skills (10 points)	Exterior (10 points)	Comfort (10 points)	Fatigue level (10 points)	Swing skills (10 points)	Exterior (10 points)	Comfort (10 points)	Fatigue level (10 points)	Swing skills (10 points)	Exterior (10 points)	Comfort (10 points)	Fatigue level (10 points)	Swing skills (10 points)
Li*	1	2	1	1	3	6	6	5	4	8	5	8	8	9	6	8
Wang*	2	5	2	2	4	4	6	5	9	8	5	3	8	8	8	8
Liu*	1	4	1	1	4	4	4	3	7	6	6	5	7	8	8	9
Sun*	4	4	1	1	4	3	4	4	8	5	3	8	5	6	9	9
Gong*	1	2	3	3	5	5	3	2	6	6	4	9	6	6	9	9
Zhang*	2	3	2	2	5	5	5	6	5	4	8	4	9	6	8	6
Wan*	0	6	1	2	5	5	5	6	5	7	9	8	9	5	8	6
Shi*	1	4	2	4	6	3	8	5	8	9	2	9	9	8	9	7
Chen*	2	1	3	2	7	1	2	4	8	8	5	5	8	9	7	8

Figure 3. Raw data of partial experimental satisfaction of tennis players.

Note: In **Figure 3**, in order to protect user privacy and avoid infringement issues, only the surname is shown, and * is used to represent the name.

4.2. Experimental process

The research process of this experiment was divided into three parts: the selection of raw materials for new π conjugated materials, the preparation of new π conjugated materials, and the application of new π conjugated materials. The first step is to prepare graphene materials by oxidizing and drying the graphite. The second step is to fuse the prepared graphene material with PDAA nanocomposites, and adjust the mass ratio of m(DAA)/m(GNS) and chemical concentration composition to ensure that the experimental material achieves the best effect. The third step is to apply the prepared composite material to the tennis racket, using impregnation and vacuum drying methods to improve the string surface and handshake of the tennis racket, thereby improving the elasticity of the strings. Finally, through the analysis of the refined composition of tennis rackets, the maximum changes in swing speed and angle of each joint during the swing and hitting stage, the relevance analysis between the changes in shoulder and hip torsion angle and instrument speed, the bending strength and accuracy of rackets made of different materials, the comparative analysis of swing speed and weight of different materials, and the durability analysis of material rackets in different situations, the research was conducted to verify the performance of the new π material on tennis rackets.

5. Experimental results of new π conjugated composite materials on tennis rackets

5.1. Experimental results

After the above experiment, in order to better analyze the material properties of tennis rackets, repeated experiments were conducted based on the relevant results of scholars such as Zhou [27]. The refined photos of the tennis racket after introducing new π conjugated materials are shown in **Figure 4**. From left to right, the mass ratio of DAA/GNS is 6/1,12/1,18/1. The specific chemical composition is shown in **Table 2**.

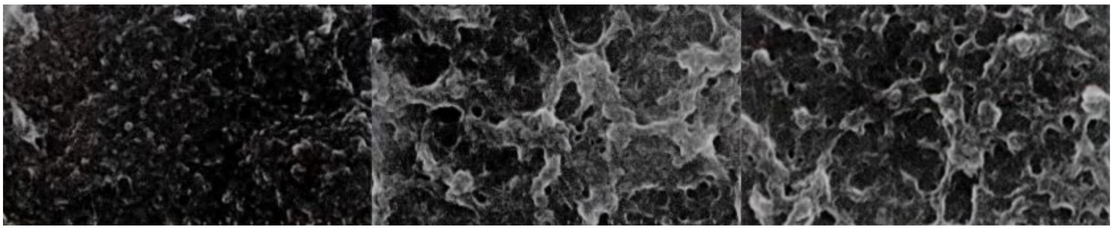

Figure 4. Detailed photos of tennis racket composition at different proportions.

Table 2. Chemical composition of composite materials under different DAA/GNS mass ratios.

	m(DAA)/m(GNS)	C(DAA)/(mol · L^{-1})	R_{mol}	w(PDAA)%
GNS@PDAA-1	6/1	0.016	0.5	60.0
GNS@PDAA-2	12/1	0.016	0.5	72.1
GNS@PDAA-3	18/1	0.016	0.5	83.8

5.2. Experimental discussion

(1) Refined composition of tennis rackets

Figure 4 shows detailed photos of tennis rackets at different scales. When the mass ratio of DAA to GNS was 6/1, which was the first image in **Figure 4**, it can be seen that a large number of PDAA nanomaterials were uniformly deposited on the surface of GNS, and there were many small pores. When the mass ratio of DAA to GNS was 12/1, the content of 1,5-diaminoanthraquinone (DAA) was increased, and the PDAA nanoparticles in the composite material appeared in clusters, as shown in the second figure in **Figure 4**. With the continuous increase of DAA, when the mass ratio was 18/1, as shown in the third figure in **Figure 4**, the cluster appeared as a relatively regular polymer, and the pores gradually increased. Therefore, it can be seen that when the mass ratio of DAA to GNS was 6/1, the morphology was obvious; the particles were clear; the effect was the best.

When further analyzing the experimental results, it can be seen that the mass ratio of DAA to GNS has a significant impact on the performance of composite materials. As the proportion of DAA increases, the structure of the composite material gradually exhibits a more regular polymer cluster distribution, which is related to the enhanced interaction of DAA molecules on the GNS surface. The benzene ring and amino group in the DAA molecule can combine with the GNS surface through π-π interactions, which enhances the stability and mechanical properties of the composite material at a certain proportion. Moreover, the increase of DAA will promote the aggregation of PDAA chains and change the pore structure of the composite material.

The chemical composition of the composite material under different mass ratios of DAA and GNS is shown in **Table 2**. To reasonably control the composition of the content, the concentration of DAA was fixed at 0.016 mol · L^{-1}, and R_{mol} was 0.5. When the mass ratio of DAA to GNS was 6/1, the weight percentage of PDAA reached 60.0%, which was 12.1% less than when the mass ratio of DAA to GNS was 12/1. The highest weight percentage of PDAA reached 83.8% when it was 18/1. In summary, a mass ratio of 6/1 between DAA and GNS meets good experimental requirements.

Further analysis of the chemical composition shows that when the mass ratio of DAA to GNS is 6/1, the mass percentage of PDAA is 60.0%, the PDAA distribution in the composite material is relatively uniform, and the performance of the material is relatively excellent. As the proportion of DAA increases, the mass percentage of PDAA gradually increases, resulting in further improvement in the mechanical properties of the composite material, but the plasticity of the material decreases due to the increase in the degree of PDAA aggregation.

(2) Maximum variation in swing speed and angle of each joint during the swing hitting stage

In order to analyze the role of new π conjugated materials in tennis swing actions, reference was made to Wei Wenjing's biomechanical analysis of tennis hitting [32]. The comparison of the maximum changes in swing speed and angle of each joint during the swing hitting stage is shown in **Figure 5**. The joints are sequentially ankle, knee, hip, shoulder, elbow, wrist, hand, as well as center of head, shoulder, and hip. Overall, the speed of the shoulder, elbow, wrist, and hand joints was higher, with the lowest being the center of head. Specifically, in terms of speed, the ankle joint reached 1m/s; the knee joint reached 1.2 m/s, which was 0.2 m/s faster than the ankle joint; the shoulder joint reached 2.2 m/s, which was 0.8 m/s higher than the hip joint. The elbow joint and wrist joint also reached 4.9 m/s and 7.3 m/s respectively, with relatively large amplitude. However, the maximum amplitude was in the hand joint, reaching 9.4 m/s, which was 2.1 m/s faster than the wrist joint. The lowest was in the center of head, which was only 0.8 m/s.

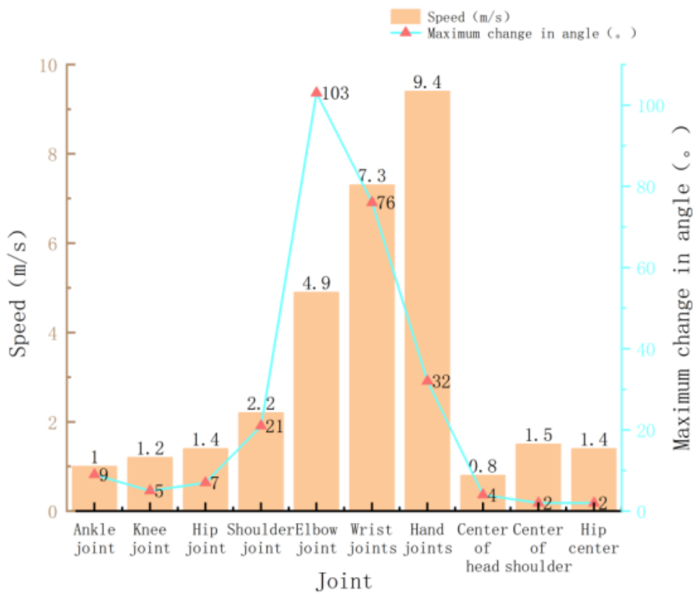

Figure 5. Maximum variation in swing speed and angle of each joint during the swing hitting stage.

For the maximum change in angle, the maximum change in angle reached 103 degrees, with the lowest being only 2 degrees. The maximum angle of change in the ankle joint reached 9 degrees, which increased the amplitude of change by 4 degrees compared to the knee joint; the maximum change angle of the shoulder joint reached 21 degrees, which was 14 degrees higher than the hip joint angle; the maximum amplitude of change was at the elbow joint, reaching 103 degrees, which was the highest point on the line graph, with an additional 27 degrees of rotation compared to the wrist joint. In addition, the hand joint also reached 32 degrees, with the lowest being the maximum change angle of 2 degrees for both the center of shoulder and hip. Overall, it can be seen that tennis rackets made of new π conjugated materials can optimize swing actions to a certain extent.

(3) Relevance between changes in shoulder and hip torsion angle and instrument speed.

Table 3. Relevance analysis between changes in shoulder and hip torsion angle and instrument speed.

Name	Change in shoulder and hip torsion angle	Instrument speed (m/s)	*R*	*P*
Li*	0.84	9.72	0.710	0.016
Wang*	0.72	9.15	0.821	0.009
Liu*	0.61	7.93	0.783	0.031
Sun*	0.89	8.85	0.879	0.017
Gong*	0.78	9.34	0.775	0.004
Zhang*	0.60	7.96	0.893	0.025
Wan*	0.51	8.09	0.813	0.012
Shi*	0.96	9.70	0.927	0.024
Chen*	0.81	8.87	0.768	0.034

Note: In **Table 3**, in order to protect user privacy and avoid infringement issues, only the surname is shown, and * is used to represent the name.

In order to explore the relationship between the variation of shoulder and hip torsion angle and instrument speed, the relevance was analyzed as shown in **Table 3**. Overall, there was a high relevance between the variation of shoulder and hip torsion angle and instrument speed. Li's shoulder and hip torsion angle variation was 0.84; the instrument speed was 9.72 m/s; the relevance coefficient reached 0.710; the probability of hitting the ball reached 0.016. The highest relevance was 0.927; the corresponding change in shoulder and hip torsion angle was 0.96; the instrument speed was 9.70 m/s; the highest probability of hitting the ball was 0.034; the corresponding change in shoulder and hip torsion angle reached 0.81; the device speed reached 8.87 m/s; the relevance coefficient was 0.768. In summary, it can be seen that the change in shoulder and hip torsion angle is the main reason for affecting the release speed of the instrument. In the hitting stage, the relative movement of the upper and lower limbs can form a good effect. By increasing the speed of the lower limbs and slowing down the speed of the upper limbs, a good surpassing mechanism can be formed, which reserves strength for hitting and improves the hit rate. For different swing actions, especially high swing, middle swing, and low swing, the middle swing is the best to form relative movements of the upper and lower limbs; the high swing is difficult to accelerate the speed of the lower limbs; the low swing is difficult to reduce the speed of the upper limbs.

(4) Bending strength of rackets made of different materials and the accuracy of swinging and hitting the ball

In order to verify the elasticity of the new π conjugated material and the accuracy of swing hitting, a comparative analysis was conducted as shown in **Figure 6**. Among them, materials were divided into wooden materials, graphene materials, carbon fiber materials, and new π conjugated materials. From the perspective of bending strength, the bending strength of tennis rackets made of wooden materials reached 72.64 MPa, while the bending strength of tennis rackets made of carbon fiber materials reached 87.96 MPa, an increase of 15.32 MPa compared to wooden materials. In addition, the bending strength of tennis rackets made of graphene material reached 90.38 MPa, and the new π conjugated material had the best bending strength effect, reaching 97.53 MPa, which was 24.89 MPa higher than that of wooden materials, indicating a significant improvement effect.

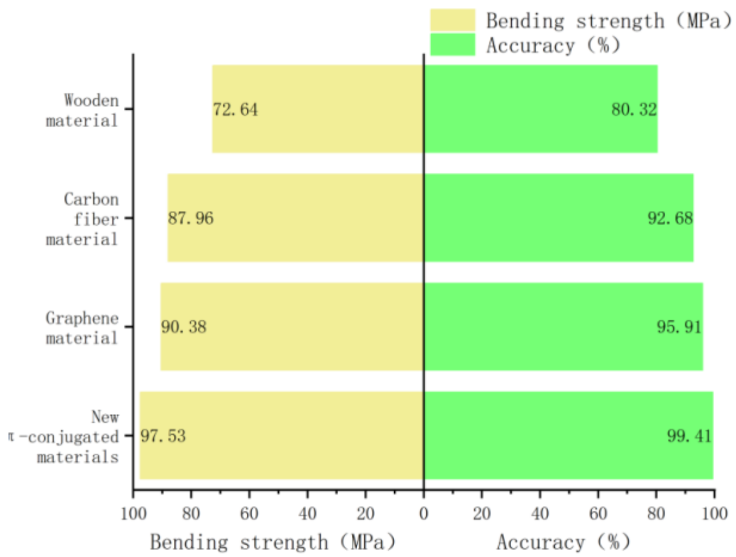

Figure 6. The elasticity of rackets made of different materials and the accuracy of swinging and hitting the ball.

For the accuracy of swinging and hitting the ball, the tennis racket made of the new π conjugated material had the highest accuracy of swinging and hitting the ball, reaching 99.41%, which was 19.09% higher in accuracy compared to wooden materials. In addition, the tennis racket made of graphene material had a hitting accuracy of 95.91%, which was better than that of carbon fiber material, with an improvement of 3.23% in accuracy. In summary, the new π conjugated materials and graphene materials have shown good performance in racket elasticity and hitting accuracy.

(5) Comparative of swing speed and weight of different materials

Figure 7 shows the comparative analysis of swing speed and weight of different materials. From the perspective of swing speed, tennis rackets made of wooden materials had a swing speed of 10.8 m/s; the tennis rackets made of carbon fiber materials were faster, with a swing speed of 15.9 m/s, which was 5.1 m/s higher than those made of wooden materials; the tennis racket made of graphene material achieved a swing speed of 16.4 m/s, a decrease of 4.8 m/s compared to the new π conjugated material. From the perspective of racket weight, the heaviest tennis racket was made of wooden material, with a weight of 341 g; the tennis racket made of graphene material was reduced, reaching 299 g, which was 42 g less than that of wooden material; the tennis racket made of carbon fiber reached 273 g, which was 68 g lighter compared to wooden materials; the lightest was the new π conjugated material, with a racket weight of only 255 g, which was reduced by 86 g compared to wooden materials. This has significantly reduced the visible weight and reduced the burden on tennis players, reducing the fatigue of the swing.

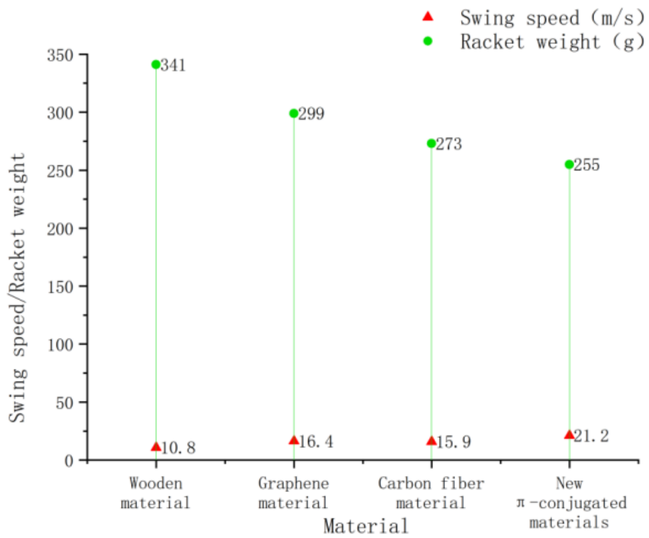

Figure 7. Comparative analysis of swing speed and weight of different materials.

(6) Durability of rackets under different conditions and materials.

Table 4. Durability analysis of new π conjugated materials.

Different situations	**Impact strength (kJ/mm^2)**	**Service life (years)**	**Surface wear degree (%)**
Temperature of 40 degrees	3.39	0.8	76.82
90% humidity	7.21	0.5	83.21
Ultraviolet irradiation	5.24	1.3	65.93
long-term exposure to dust	2.36	2	40.67

In order to explore the durability of the new π conjugated material, it was exposed to different environmental conditions, including 40 °C high temperature, 90% humidity, ultraviolet (UV) radiation, and long-term exposure to dust. Analysis was conducted from three aspects: impact strength, service life, and surface wear degree, as shown in **Table 4**. For impact strength, at a high temperature of 40 degrees Celsius, the material's impact strength reached 3.39 kJ/mm^2, while at a humidity of 90%, the impact strength reaches 7.21 kJ/mm^2, reaching the highest level. It can be seen that high humidity conditions had the greatest damage to the racket. In addition, the impact strength under UV irradiation reached 5.24 kJ/mm^2, a decrease of 1.97 kJ/mm^2 compared to 90% humidity. In a better situation, long-term exposure to dust had the lowest degree of damage to tennis rackets, with an impact strength of only 2.36 kJ/mm^2. Compared to 90% humidity, the impact strength decreased by 4.85 kJ/mm^2.

The service life of tennis rackets was investigated under different conditions through testing, as shown in **Table 4**. The shortest service life was only half a year at 90% humidity, and the experimental life reached 0.8 years at a high temperature of 40 degrees Celsius. Compared to the experimental life at 90% humidity, the experimental life was longer, indicating a lower degree of damage to the tennis racket. In addition, the service life under ultraviolet radiation was 1.3 years, an increase of half a year compared to 40 ℃ high temperature. For long-term exposure to dust, the service life of the new π conjugated material reached 2 years, equivalent to 4 times that under 90% humidity.

For the degree of surface wear, the new π material had the lowest wear level under long-term exposure to dust, only 40.67%, and the highest wear level was 83.21% under 90% humidity, with a span amplitude of 42.54%. In addition, under ultraviolet radiation, the wear degree of tennis rackets reached 65.93%, which decreased by 10.89% compared to 40 ℃ high temperature. Overall, the new π conjugated material has good durability and can exhibit good performance in different situations.

The durability analysis results of different materials are shown in **Table 5**.

Table 5. Durability analysis of different materials.

Different materials	Impact strength (kJ/mm^2)	Service life (years)	Wear degree after one year of use (%)
Wood materials	4.56	0.6	88.32
Carbon fiber material	3.12	1.2	75.48
Graphene material	2.58	1.8	56.23
New π-conjugated materials	2.22	2.5	32.14

In **Table 5**, the new π-conjugated materials show better performance than other materials in various indicators. In terms of impact strength, the new π-conjugated material is only 2.22 kJ/, which is significantly lower than the 4.56 kJ/ of wood materials and 3.12 kJ/ of carbon fiber materials, indicating that the new π-conjugated materials can absorb and disperse external impact forces more effectively, reducing damage. The new π-conjugated material has a unique π-conjugated structure that gives the material good flexibility and ductility, allowing it to disperse energy and avoid rapid rupture when subjected to external forces. Wooden materials and carbon fiber materials are prone to greater damage under impact due to their fragile structures or strong rigidity.

In terms of service life, the new π-conjugated material has the longest service life, reaching 2.5 years, while the service life of wood materials is only 0.6 years, carbon fiber materials are 1.2 years, and graphene materials are 1.8 years. It shows that the new π-conjugated material can maintain good performance during long-term use, and its long service life is closely related to the corrosion resistance and weather resistance of the material. New π-conjugated materials have better resistance to ultraviolet, moisture and high temperature, and can maintain a long service life under various environmental conditions. However, other materials, especially wooden materials, are easily affected by environmental factors, resulting in material Performance degradation. In terms of wear degree, the new π-conjugated material shows the smallest wear, only 32.14%. Because of its uniform and dense surface structure, it can effectively reduce wear and extend the service life of the material in long-term use.

The new π-conjugated material shows significant advantages over wood, graphene and carbon fiber materials in the racket's bending strength, swing speed and weight, and durability. In terms of bending strength, the high elasticity of the new π-conjugated material enables it to better disperse energy when subjected to external forces, reducing the risk of damage to the material and improving its durability. The unique molecular structure of the new π-conjugated material makes the material more flexible and ductile, providing higher bending strength for tennis rackets. In terms of swing speed and weight, the lightweight characteristics of the new π-conjugated material reduce the overall weight of the racket, reduce the burden on players during the swing process, increase swing speed, and improve hitting accuracy. The lightweight properties of the new π-conjugated material can improve athletes' performance, especially in fast-moving tennis matches. From a durability perspective, the new π-conjugated material shows a longer service life and lower surface wear. Because of its corrosion resistance, weather resistance and strong UV resistance, the racket can be used in a variety of environmental conditions. Stable performance can be maintained under all conditions. The new π-conjugated material combines multiple advantages such as high elasticity, light weight, and excellent durability, making it an ideal material for making high-performance tennis rackets, and its potential application prospects are very broad.

(7) Athletes' satisfaction with different rackets

In order to test the satisfaction of athletes with different tennis rackets in practice, satisfaction scores were given in terms of appearance, comfort, reducing fatigue, and improving swing skills, as shown in **Figure 8**. From the perspective of appearance, the lowest scoring was for wooden materials, only 2 points, while the highest scoring was for new π conjugated materials and carbon fibers, both reaching 8 points. In terms of comfort, the lowest score was for wooden materials, which reached 4 points; the graphene reached 5 points; the carbon fiber was the better, which reached 8 points; the new π conjugated material was the best, which reached 9 points in comfort. From the perspective of reducing fatigue, wooden materials were the lowest and the heaviest. Athletes gave an average satisfaction score of 1 point, while graphene and carbon fiber materials were relatively good, both reaching 6 points. The best was the new π conjugated material, which had the lightest weight and could greatly reduce joint fatigue, with a score of 9 points. From the perspective of improving swing skills, the worst score was only 2 points for wooden materials, while the best score was 8 points for new π conjugated materials and carbon fibers. Overall, the total score of the new π-conjugated material reached 34 points, accounting for 85% of the total score, reaching the highest score. The worst was the wooden material, which only scored 9 points, accounting for 22.5% of the total score. Overall, the new π conjugated material has the highest satisfaction score among athletes, making it a more preferred material for athletes and resulting in better tennis racket performance.

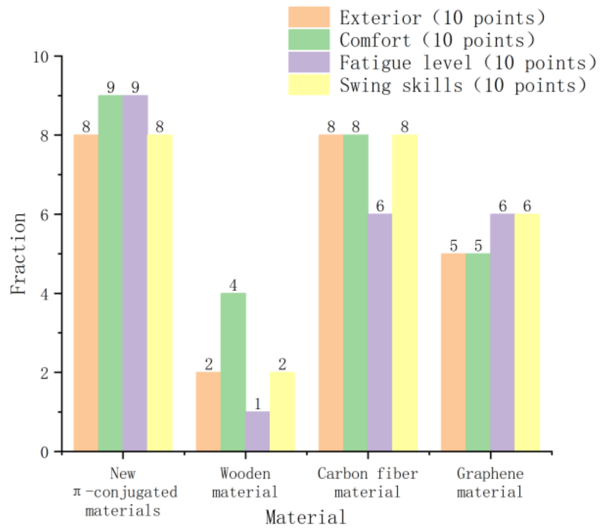

Figure 8. Athletes' satisfaction with different rackets.

(8) Contribution of different muscle groups during swing

Figure 9 shows the contribution of different muscle groups during swing, including upper limb muscles, core and waist muscles, lower limb muscles, abdominal muscles, back muscles, and others. From the pie chart in **Figure 9**, it can be clearly seen that the gray sector accounted for the largest proportion, namely the upper limb muscles, with a contribution of 41.2%, followed by the lower limb muscles, with a contribution of 20.7%. Correspondingly, the blue sector in the pie chart reduced the contribution of the upper limb muscles by 20.5%. In addition, the contribution of core and waist muscles reached 20.4%, which was equivalent to that of lower limb muscles, corresponding to the red sector in the pie chart. The lower contribution level was in the abdominal and back muscles, with the abdominal muscle group having the lowest contribution during swing, only 5.1%, and the back muscles reaching 6.6%. In summary, the muscle group has achieved good performance in tennis swing through coordination and cooperation.

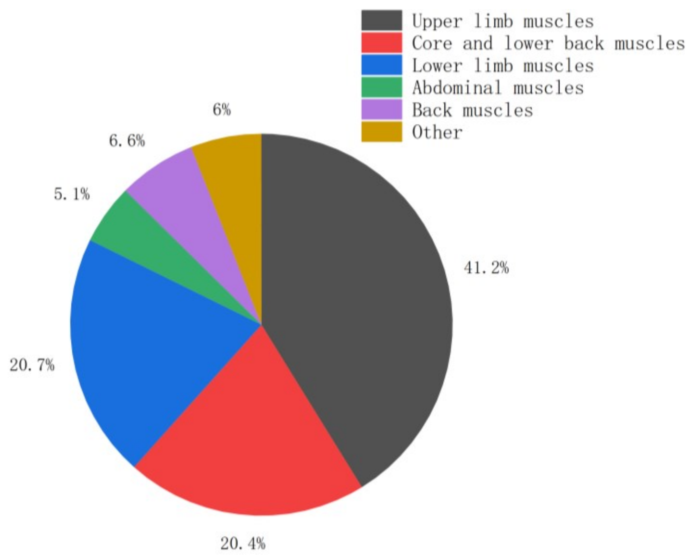

Figure 9. Contribution of different muscle groups during swing.

(9) Comparison of swing accuracy and vibration frequency under different swing actions

Figure 10 shows the comparison of swing accuracy and vibration frequency under different swing actions. The swing actions are divided into high swing, middle swing, low swing, forehand swing, and backhand swing. From the perspective of accuracy, the accuracy of high swing hitting reached 94.81%, which was 3.55% lower than the middle swing. It can be seen that the accuracy of high swing was worse than that of middle swing. The accuracy of low position swing was only 92.57%; the forehand swing had the highest hitting accuracy, reaching 99.16%; the backhand swing was only 82.64%. Among them, the accuracy of the forehand swing increased by 16.52% compared to the backhand swing. From the perspective of vibration frequency, the high swing and forehand swing had higher vibration frequencies, reaching 73.8 HZ and 78.9 HZ respectively, while the low swing had the lowest vibration frequency, only 62.6 HZ. Overall, the middle swing and forehand swing show good performance in swing actions.

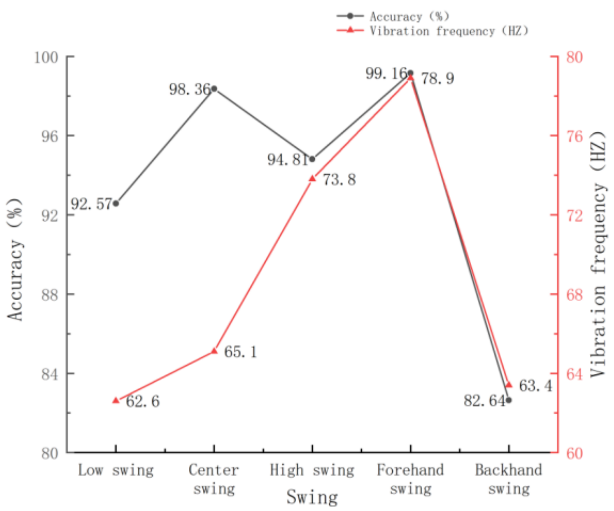

Figure 10. Comparative analysis of swing accuracy and vibration frequency under different swing actions.

This study has reached a series of conclusions after analyzing the above results. In terms of the broad impact and long-term impact of the experimental results, the new π-conjugated materials demonstrated in this study are of significant significance for improving the performance of tennis rackets. From a broad impact perspective, the tennis racket made of the new π-conjugated material used in the study is superior to traditional materials in terms of structural stability and mechanical properties. It can also improve the player's hitting efficiency and accuracy by optimizing the swing action. sex. The good mechanical properties of the new π-conjugated material, especially its advantages in swing speed and accuracy, can effectively reduce athletes' fatigue and burden during games and improve sports performance. The lightweight design of the racket also has a positive effect on the comfort of long-term training, especially suitable for high-intensity and long-term competitive environments.

From the perspective of long-term impact, the durability of the new π-conjugated material is excellent, and its stability under extreme environmental conditions gives tennis rackets a long service life, which is particularly important for professional athletes who train and compete frequently. The new π-conjugated material has low wear under different conditions, which shows that it can maintain excellent performance during long-term use, reduce the need for frequent replacement of equipment, have sustainable economic benefits, and help improve the market of tennis rackets. Competitiveness will also promote the development of the tennis equipment industry in the direction of higher performance and long-life materials.

6. Conclusions

This article studies the use of new π-conjugated materials to optimize tennis rackets, successfully prepares low-dispersion graphene materials, and fuses them with graphene materials through chemical oxidation polymerization to produce new π-conjugated materials with excellent properties. Experimental results show that the application of new π-conjugated materials to tennis rackets significantly improves the elasticity and swing accuracy of the tennis racket, reduces the weight of the racket, and effectively reduces the fatigue of tennis players' swing movements, making it a great sports equipment Lightweighting and performance optimization provide new ideas and material foundations. This study has made some achievements, but there are some shortcomings. Due to insufficient experimental data, the specific performance of the material under different application conditions cannot be fully revealed, and this article is limited to tennis rackets. Future research will further expand the scale of experimental samples, increase testing of different racket types, explore the performance stability of test materials under complex conditions such as long-term use and extreme environments, and explore the potential applications of new π-conjugated materials in other sports equipment fields, verify its wide applicability and further optimize material performance.

Ethical approval: Not applicable.

Conflict of interest: The author declares no conflict of interest.

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