

Optimization of Textile Material Properties for Sports Protection Needs and Analysis of Design Compatibility for Athletic Protective Gear

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ABSTRACT Addressing the issues of inadequate protective performance in sports protective gear textiles, poor alignment between material properties and athletic scenarios, and insufficient integration of comfort with protective functionality, this paper conducts research on optimizing textile material characteristics and adapting sports protective gear design based on core athletic protection requirements. First, integrating sports biomechanics theory, materials science principles, and ergonomic guidelines, we define core protective dimensions (impact absorption, freedom of movement, breathability/moisture wicking, fit/conformity) and key textile material performance metrics (mechanical properties, breathability, elastic recovery, abrasion resistance). Second, injury risk data and protective gear usage feedback from diverse sports (ball sports, contact sports, endurance sports) were collected to construct a multidimensional dataset (SPD-2024) encompassing 6 sports scenarios and 5 protection levels. Third, design a technical framework of “protection requirement decomposition - material property optimization - protective gear structural adaptation.” Enhance material protective performance through fiber modification, fabric structure design, and composite process optimization. Introduce a protection-adaptation collaborative evaluation model to strengthen the alignment between material properties and protective gear design.

INDEX TERMS sports protection requirements, textile material property optimization, athletic protective gear, design adaptability

I. INTRODUCTION

A. RESEARCH BACKGROUND

WITH the advancement of the national fitness strategy and the continuous improvement of competitive sports standards, the prevention and control of sports injury risks have become a core concern in the sports sector [1-2]. The 2024 China Sports Injury Survey Report released by the Chinese Society of Sports Science reveals that the annual incidence rate of sports injuries in China reaches 28.3%. Among these, joint sprains, soft tissue contusions, and impact injuries account for over 75% of cases. Furthermore, 62.1% of injuries are directly linked to inadequate or poorly fitted protective gear. As critical equipment for injury prevention, the protective efficacy and comfort of sports protective gear directly depend on the core properties of textile materials and the degree of design adaptability [3-4].

Therefore, based on core sports protection needs, conducting research on optimizing textile material properties and enhancing the design adaptability of sports protective gear is of great significance for improving protective effectiveness, ensuring athletic safety, and promoting high-

quality development in the sports industry [5-7].

B. CURRENT RESEARCH STATUS AT HOME AND ABROAD

1) Research Progress on Textile Materials for Sports Protective Gear

Optimizing textile material properties is a core approach to enhancing protective gear performance. A team from North Carolina State University [8] developed protective textiles using graphene-modified polyester fibers. By regulating fiber surface roughness and crystallinity, they increased impact absorption efficiency by 25.3%, though elastic recovery rate decreased to 78.6%. Domestically, Zhang et al. [9] from Donghua University designed a three-dimensional woven structure. By utilizing a gradient distribution of fabric porosity, they achieved layered absorption of impact energy. The material attained an air permeability of 156 L/(m²·s), but its abrasion resistance requires improvement (Martindale abrasion resistance was only 20,000 cycles) [10-11].

2) Current Research on Design Adaptability of Sports Protective Gear

Research on the design adaptability of sports protective gear primarily focuses on two dimensions: ergonomics and adaptation to sports scenarios. Bauer et al. [12] from the Technical University of Munich optimized protective gear patterns using motion capture technology, enhancing body-gear conformity and increasing movement freedom by 15.2%. Domestically, Wang et al. [13] from Beijing Sport University designed segmented protective structures by analyzing joint movement angles across sports, balancing protection and flexibility, though without establishing a synergistic adaptation system between material properties and gear structure.

Regarding protection level adaptation, the ISO 13287-2022 standard published by the International Organization for Standardization (ISO) specifies evaluation methods for sports protective gear protection levels but does not provide quantitative correlations between material properties and protection levels. The domestic GB/T 29510-2013 standard only stipulates safety performance requirements for protective gear, lacking differentiated adaptation specifications for various sports scenarios [14]. Existing design adaptation research predominantly relies on empirical approaches, lacking data-driven models for synergistic adaptation across materials, structures, and scenarios.

C. RESEARCH QUESTIONS

1. How can a quantitative evaluation system for sports protection needs be established to define key material performance indicators and optimization targets across diverse athletic scenarios?
2. How can synergistic enhancements in multiple textile material properties—such as impact absorption, breathability, moisture wicking, and elastic recovery—be achieved through fiber modification, fabric structure design, and composite process optimization?
3. How can an adaptability evaluation model linking “material properties-protective gear structure-sports scenario” be established to guide precise sports protective gear design?

D. RESEARCH SIGNIFICANCE

1) Theoretical Significance

1. Enrich interdisciplinary research between sports biomechanics and materials science, revealing intrinsic mechanisms linking athletic protection requirements with textile material properties to provide theoretical foundations for precision optimization of sports protective materials;
2. Establish an evaluation system for sports protective gear design compatibility, filling existing theoretical gaps in material-structure-scenario synergistic adaptation and offering new perspectives for scientific and standardized gear design.

2) Practical Significance

1. Provide textile enterprises with optimization solutions for sports protective materials, enhancing the core competitiveness of material products and driving the textile industry's transition toward high-performance and functional materials;
2. Offer design adaptability guidance to protective gear manufacturers, shortening product development cycles, reducing R&D costs, and improving the protective efficacy and market acceptance of protective gear products;
3. Offers athletes and fitness enthusiasts safer, more comfortable, and better-fitting sports protective gear, reducing the risk of sports injuries while enhancing athletic experience and performance;
4. Provides data support for establishing standards related to sports protective equipment, driving the standardized and regulated development of the sports protection industry.

II. THEORETICAL AND TECHNOLOGICAL FOUNDATIONS

A. CORE REQUIREMENTS THEORY FOR SPORTS PROTECTION

1) Classification of Protection Requirements

Based on sports biomechanical analysis and injury type research, sports protection requirements can be categorized into three core dimensions [15-16]:

1. Impact Protection Requirements: Addressing collision, fall, and other impact loads during sports, protective gear must possess high-efficiency shock absorption capabilities to reduce tissue damage caused by impact acceleration;
2. Movement Adaptability Requirements: Protective gear must align with human range of motion and biomechanical characteristics, avoiding restrictions on joint movement, muscle contraction, and other athletic behaviors to ensure freedom of movement;
3. Comfort Experience Requirements: Including breathability, moisture-wicking, lightweight design, and snug yet non-restrictive fit to minimize discomfort during prolonged wear and enhance user retention.

2) Quantitative Evaluation of Protection Requirements

The Analytic Hierarchy Process (AHP) was employed to determine the weighting of each requirement dimension. Combined with the Fuzzy Comprehensive Evaluation Method, this established a quantitative evaluation model for protection requirements [17].

Protection requirements vary significantly across different sports scenarios: Impact protection carries a weight of 0.55 for contact sports (basketball, soccer, boxing); comfort experience increases to 0.30 for endurance sports (running, cycling); and movement adaptability reaches 0.40 for flexibility-based sports (yoga, gymnastics) [18-19]. To clarify the calculation logic of weights, the AHP pairwise comparison matrices, eigenvalues, and consistency ratio (CR) for each sports scenario are presented as follows:

TABLE 1. Contact sports (impact protection as core demand)

Demand Dimension	Impact Protection	Movement Adaptability	Comfort Experience
Impact Protection	1	3	5
Movement Adaptability	1/3	1	3
Comfort Experience	1/5	1/3	1

Eigenvalue $\lambda_{\max} = 3.038$, CR = 0.037 < 0.1 (meets consistency requirement).

B. CORE PROPERTIES AND EVALUATION METRICS OF TEXTILE MATERIALS

1) Mechanical Protective Properties

1. Impact Absorption Performance: Measured via drop hammer impact testing, with the evaluation metric being impact absorption efficiency (%).
2. Elastic Recovery Performance: Measured via constant elongation elastic recovery testing, with the evaluation metric being elastic recovery rate (%). A minimum of $\geq 85\%$ is required to ensure protective efficacy after repeated use of the protective gear.
3. Abrasion Resistance: Measured via Martindale abrasion test, with the evaluation metric being abrasion cycles (cycles). Different sports scenarios require $\geq 15,000$ – $30,000$ cycles [20];
4. Tear Strength: Measured via single-seam tear test, with the evaluation metric being tear strength (N). A minimum of ≥ 15 N is required to prevent protective gear damage during sports activities.

2) Comfort Functional Properties

1. Breathability: Measured using a breathability tester, with breathability ($L/(m^2 \cdot s)$) as the evaluation metric. Requirement: $\geq 120 L/(m^2 \cdot s)$ to meet sweat-wicking demands during prolonged physical activity;
2. Moisture Absorption and Wicking Performance: Measured using capillary action and evaporation rate tests. Evaluation metrics include capillary rise height (cm/30 min) and evaporation rate (g/h). Capillary rise height must be ≥ 8 cm/30 min, and evaporation rate must be ≥ 0.8 g/h [21].
3. Lightweight Performance: Evaluated by mass per unit area (g/m^2), with a requirement of $\leq 350 g/m^2$ to minimize the burden of protective gear on athletic performance;
4. Skin Affinity: Assessed through skin irritation testing and contact comfort evaluation, requiring no skin irritation and contact pressure ≤ 2 kPa [22].

C. THEORETICAL FRAMEWORK FOR SPORTS PROTECTIVE GEAR DESIGN ADAPTABILITY

1) Ergonomic Adaptation Principles

Ergonomic adaptation of sports protective gear manifests in two primary aspects [23–24]:

1. Static Adaptation: Gear dimensions and shape align with human anatomical structures, conforming to body contours to prevent localized compression;
2. Dynamic Fit: Protective gear properties like elasticity and hardness align with human biomechanical characteristics

during movement, allowing synchronous deformation with joint motion and muscle contraction without restricting range of motion.

Motion capture technology collects data on joint angles and muscle strain during various sports scenarios, establishing digital human movement models to inform protective gear structural design [25].

2) Scenario Adaptability Evaluation

The scenario adaptability of sports protective gear requires synergistic matching among “protection level-activity intensity-environmental conditions” [26]:

1. Protection level matched to injury risk: High-risk sports (e.g., boxing, rugby) require high-protection gear (impact absorption efficiency $\geq 70\%$);
2. Material properties matched to activity intensity: High-intensity activities demand materials with superior abrasion resistance and elastic recovery;
3. Protective gear structure matching environmental conditions: Gear for high-temperature environments requires enhanced breathability and sweat-wicking design, while gear for low-temperature environments must incorporate thermal insulation properties [27].

III. RESEARCH METHODS AND TECHNICAL FRAMEWORK

A. OVERALL TECHNICAL FRAMEWORK

This paper proposes a four-phase technical framework: “Protection Requirement Analysis - Material Property Optimization - Protective Gear Design Adaptation - Experimental Validation and Evaluation,” detailed as follows:

1. Protection Requirement Analysis Phase: Through biomechanical testing and user surveys, identify protection needs across different sports scenarios and establish a quantitative evaluation system for protection requirements;
2. Material Property Optimization Phase: Based on protection requirements, enhance the mechanical protective performance and comfort characteristics of textile materials through fiber modification, fabric structure design, and composite process optimization;
3. Protective Gear Design Adaptation Phase: Design structural parameters for protective gear by integrating ergonomic principles and scenario-specific adaptability requirements, establishing the relationship between material properties and gear design;
4. Experimental Validation and Evaluation Phase: Validate research outcomes through laboratory testing and field trials, assessing protective performance, athletic adaptability, and comfort experience across three dimensions.

B. PROTECTIVE REQUIREMENT ANALYSIS METHODS

1) Sports Injury Risk Assessment

Six representative sports (basketball, soccer, boxing, running, cycling, yoga) were selected. Thirty participants per

sport (10 professional athletes and 20 recreational enthusiasts) underwent motion capture testing (This study was approved by the Ethics Committee of SHANDONG HUAYU UNIVERSITY OF TECHNOLOGY, and was performed in accordance with the principles of the Declaration of Helsinki. All eligible participants signed an informed consent form.):

1. Vicon motion capture system (12 cameras, 100 Hz sampling rate) recorded joint angles and movement velocities during activity;
2. Kistler 3D force sensors measured impact load magnitude and duration during movements;
3. Combined with athlete injury history surveys, high-risk body regions and injury types across sports were analyzed to determine protective level requirements for each discipline [28].

2) User Needs Research

User requirements were gathered through a combination of online questionnaires and offline interviews:

1. Online Questionnaire: Distributed via sports platforms, yielding 1,200 valid responses to assess user evaluations and demands regarding protective gear efficacy, comfort, and sport adaptability;
2. In-Person Interviews: Conducted focus group discussions with 50 users of varying athletic levels to uncover latent needs and usage pain points;
3. Data Processing: Factor analysis was employed to extract core demand factors, constructing a quantitative mapping matrix between protective requirements and material properties [29].

C. TEXTILE MATERIAL PROPERTY OPTIMIZATION SCHEME

1) Fiber Modification Technology

A modification scheme combining nanoparticle doping with plasma treatment was adopted to optimize fiber mechanical properties and surface characteristics:

1. Select polycaprolactone (PCL) and polyurethane (PU) blended fibers as the base material, add 5%-10% nano-silica (SiO_2) particles, and prepare modified fibers via melt spinning; nano- SiO_2 particles enhance fiber strength and hardness, improving impact absorption capacity [30];

The 5%-10% concentration range of nano- SiO_2 is determined based on impact mechanics principles and multiple control experiments. We tested modified fiber properties at concentrations ranging from 2% to 15% (Table A), and the results show:

When concentration < 5%: The improvement in fiber strength and impact absorption efficiency is insufficient (only 8%-12% higher than unmodified fibers), failing to meet high-risk sports protection requirements;

When concentration = 5%-10%: Performance reaches the optimal state (impact absorption efficiency increases by more than 30%, elastic recovery rate remains above 90%), and particle dispersion is uniform without agglomeration;

When concentration > 11%: Particles tend to agglomerate, leading to increased fiber brittleness (elongation at break decreases to below 250%) and significantly higher processing difficulty.

TABLE 2. Core performance of modified fibers at different nano- SiO_2 concentrations

Nano- SiO_2 Concentration	Impact Absorption Efficiency Improvement	Elastic Recovery Rate (%)	Elongation at Break (%)	Particle Dispersion State
2%	+8.2%	88.5	320	Uniform
4%	+11.7%	89.3	310	Uniform
5%	+30.5%	91.2	305	Uniform
8%	+34.8%	92.1	298	Uniform
10%	+32.3%	90.7	290	Slight agglomeration
11%	+28.6%	87.4	245	Obvious agglomeration
15%	+22.1%	83.6	210	Severe agglomeration

2. Surface modification of the modified fibers was achieved via argon plasma treatment at 300 W for 3–5 min, improving surface hydrophilicity and enhancing moisture absorption and wicking performance.

Performance optimization targets for modified fibers: Tensile strength ≥ 5.5 cN/dtex, elongation at break $\geq 300\%$, moisture absorption rate $\geq 8\%$.

2) Fabric Structure Design

Differentiated fabric structures are designed based on protective requirements for various sports scenarios:

1. Impact Protection Structure: Utilizes a three-dimensional knitted structure with a fabric thickness of 3–5 mm and a gradient porosity distribution (surface layer: 15–

20%, middle layer: 40–50%, inner layer: 25–30%). This multi-layer structure enables synergistic deformation for layered absorption of impact energy.

2. Comfortable Breathable Structure: Utilizes a warp-knitted Jacquard jacquard structure with specially designed irregular cross-section fiber arrangements to enhance fabric breathability and moisture-wicking performance. Fabric thickness: 1–2 mm; porosity $\geq 50\%$.
3. Sports-Adaptive Structure: Combines double-rib weave with spandex-core yarn, achieving $\geq 90\%$ elastic recovery rate and $\geq 80\%$ transverse elongation to accommodate extensive joint movement.

3) Composite Process Optimization

A three-layer composite process ("Functional Layer + Cushioning Layer + Comfort Layer") achieves synergistic multi-performance:

1. Functional Layer: High-abrasion-resistant fabric woven from modified fibers, thickness 0.5-1 mm, providing impact protection and abrasion resistance;
2. Cushioning Layer: Needle-punched nonwoven composite with elastic foam material, thickness 2-4 mm, impact absorption efficiency $\geq 70\%$;
3. Comfort Layer: Utilizes a cotton-Modal blend fabric, 0.3-0.5 mm thick, for moisture wicking and skin affinity.

The determination of thickness parameters is based on the core requirements of each scenario (impact protection weight 0.55 for contact sports, breathability weight 0.40 for endurance sports, motion flexibility weight 0.40 for flexibility sports) and multiple sets of orthogonal experimental verification. The orthogonal experiment design takes functional layer thickness (0.5/0.6/0.8mm), cushioning layer thickness (2.0/2.5/3.5mm), and comfort layer thickness (0.3/0.4mm) as factors, with 18 experimental combinations. The optimal thickness combination for each scenario is selected based on comprehensive scores of protective performance, sports adaptability, and comfort.

D. SPORTS PROTECTIVE GEAR DESIGN ADAPTATION METHOD

1) Protective Gear Structural Parameter Design

Based on ergonomic adaptation principles, key structural parameters are designed as follows:

1. Dimensional Parameters: Length, width, circumference, and other dimensions are determined using anthropometric data (GB/T 10000-1988), employing graded sizing (S, M, L, XL) to accommodate diverse body types;
2. Contour Parameters: Design the protective gear's curved contours and cutting lines based on digital human motion models to ensure static fit and dynamic adaptation;
3. Fastening Parameters: Employ a combination of hook-and-loop fasteners and elastic straps with an adjustable structure to accommodate bodily deformation during different athletic states.

2) Adaptability Evaluation Model Construction

Establish a three-dimensional adaptability evaluation model linking "material properties - protective gear structure - athletic scenarios":

$$A = \alpha A_m + \beta A_s + \gamma A_{sc} \quad (1)$$

Where A represents the comprehensive adaptability score (0-100 points), A_m denotes the material property adaptability score, A_s indicates the protective gear structure adaptability score, and A_{sc} signifies the movement scenario adaptability score; $\alpha = 0.4$, $\beta = 0.3$, $\gamma = 0.3$ are the weighting coefficients.

Scores for each dimension are calculated as follows:

1. Material property adaptation score A_m : Calculated via weighted sum based on the mapping relationship between protective requirements and material properties;
2. Protective gear structural adaptation score A_s : Measured through motion capture experiments assessing joint movement restriction, combined with fit evaluation;
3. Sports scenario adaptation score A_{sc} : Evaluated through field testing in diverse scenarios, assessing protective efficacy, comfort, and sports compatibility.

E. DATASET CONSTRUCTION

A multidimensional dataset (SPD-2024) was constructed by integrating "experimental test data + user feedback data + market product data":

1. Experimental test data: Through material performance testing and sports biomechanical experiments, 120 sets of textile material characteristic data (mechanical properties, comfort properties) and 80 sets of sports injury risk data were collected;
2. User Feedback Data: Through user surveys and trial tests, 1,200 user requirement entries and 500 protective gear usage feedback entries were collected;
3. Market Product Data: Data on 200 products from leading domestic and international sports protective gear brands (Nike, Adidas, Li-Ning, Anta, etc.) was scraped, including material parameters, structural design, protection levels, and user reviews.

The dataset was partitioned into training (2,240 entries), validation (320 entries), and test (640 entries) sets at a 7:1:2 ratio for training and validating the protective requirement mapping model and adaptability evaluation model.

To standardize the definition of protection levels in the SPD-2024 dataset, Table B presents the quantitative indicators and classification logic. The five protection levels are divided based on sports injury risk intensity (low, medium-low, medium, medium-high, high), with reference to ISO 13287-2022 and GB/T 29510-2013 standards, and optimized according to actual sports scenario requirements. The grading statistical basis is derived from sports injury data of 180 subjects and performance analysis of 200 market products.

IV. EXPERIMENTAL DESIGN AND RESULTS ANALYSIS

A. EXPERIMENTAL ENVIRONMENT AND EQUIPMENT

1) Hardware Equipment

1. Material Performance Testing Equipment: Drop Weight Impact Tester (Instron 9450), Martindale Abrasion Tester (SDL Atlas), Air Permeability Tester (YG461E), Electronic Fabric Tensile Tester (Instron 5965), Moisture Absorption and Sweat Evaporation Tester (SW-12A);
2. Sports Biomechanics Testing Equipment: Vicon Motion Capture System (12 cameras), Kistler 3D Force Sensor (9287B), Surface Electromyography System (Delsys Trigno);

3. Ergonomic Testing Equipment: 3D Human Body Scanner (Artec Eva), Contact Pressure Tester (Tekscan Flexi-force);
4. Environmental Simulation Equipment: Constant Temperature and Humidity Chamber (YG601), High/Low Temperature Test Chamber (GDW-100).

2) Software Environment

1. Data Processing Software: MATLAB 2023b, SPSS 26.0, Origin 2023;
2. Modeling and Design Software: SolidWorks 2023, Rhino 7.0, Grasshopper;
3. Simulation and Analysis Software: ANSYS 2023 R2, ADAMS 2023.

B. COMPARATIVE DESIGN SCHEMES

To validate the superiority of the research outcomes, three comparative schemes were selected:

1. Traditional Scheme: Utilizes conventional textile materials (unoptimized) and traditional structural design employed in mainstream sports protective gear;
2. Single Optimization Scheme A: Optimizes only textile material properties (without considering design adapt-

ability);

3. Single Optimization Scheme B: Optimized solely for design adaptability (using standard textile materials);

All comparison schemes were tested under identical experimental conditions as the proposed scheme to ensure experimental fairness.

C. EVALUATION METRIC SYSTEM

Evaluation metrics were established across three core dimensions:

1. Protective Performance: Impact absorption efficiency (%), tear strength (N), abrasion resistance cycles (times);
2. Athletic Adaptability: Joint Movement Angle Restriction Rate (%), Increased Energy Expenditure Rate (%), Performance Impact Score (1-10 points);
3. Comfort Experience: Air Permeability (L/(m²·s)), Moisture Absorption & Wicking Rate (g/h), Contact Pressure (kPa), Wear Comfort Score (1-10 points).

D. EXPERIMENTAL RESULTS AND ANALYSIS

- 1) Optimized Textile Material Properties

Table 3 shows the comparison of core properties before and after optimization:

TABLE 3. Comparison of core properties before and after optimization

Property Indicator	Before Optimization (Conventional Material)	After Optimization (Proposed Scheme)	Improvement Rate
Impact Absorption Efficiency (%)	48.2 ± 3.5	63.9 ± 2.8	+32.6%
Tear Strength (N)	12.3 ± 1.2	18.7 ± 1.5	+52.0%
Abrasion Resistance (Times)	18500 ± 1200	29800 ± 1500	+61.1%
Elastic Recovery Rate (%)	82.5 ± 2.3	91.3 ± 1.8	+10.7%
Air Permeability (L/(m ² ·s))	98.6 ± 5.2	182.5 ± 6.8	+85.1%
Moisture Absorption and Perspiration Rate (g/h)	0.52 ± 0.08	0.97 ± 0.12	+86.5%
Mass per Unit Area (g/m ²)	320 ± 15	285 ± 12	-10.9%
Contact Pressure (kPa)	2.3 ± 0.3	1.7 ± 0.2	-26.1%

Table 1 demonstrates that the optimized textile material achieved significant improvements across all performance metrics:

1. In protective performance: impact absorption efficiency increased by 32.6%, tear strength by 52.0%, and abrasion resistance cycles by 61.1%, meeting high-risk sports protection requirements;
2. In comfort performance: air permeability increased by 85.1%, moisture absorption and sweat wicking rate by 86.5%, and contact pressure decreased by 26.1%, effectively enhancing long-term wear comfort;
3. In terms of lightweight performance, the mass per unit area decreased by 10.9%, while elastic recovery rate

increased by 10.7%, balancing athletic adaptability and service life.

This advancement stems from the synergistic optimization of “fiber modification-structural design-composite process”: nano-SiO₂ particle doping enhanced fiber mechanical properties, three-dimensional weaving structures optimized impact absorption and breathability, and multi-layer composite processes achieved balanced improvements across multiple performance metrics.

- 2) Design Adaptability Results for Sports Protective Gear
- Adaptability scores for sports protective gear designs across six typical athletic scenarios are shown in Table 4:

TABLE 4.

Sports Scenario	Evaluation Dimension	Traditional Scheme	Single Optimization A	Single Optimization B	Proposed Scheme	Improvement Rate of Proposed Scheme (vs Traditional)
Basketball (Contact)	Protective Performance (Score)	65.3 ± 4.2	82.5 ± 3.8	68.7 ± 4.0	89.6 ± 3.1	+37.2%
	Sports Adaptability (Score)	72.5 ± 3.6	75.8 ± 3.2	83.6 ± 3.5	88.9 ± 2.7	+22.6%
	Comfort Experience (Score)	68.2 ± 4.5	78.3 ± 3.9	75.6 ± 4.1	86.7 ± 3.3	+27.1%
	Comprehensive Adaptability (Score)	68.0 ± 3.8	78.8 ± 3.4	76.0 ± 3.6	88.4 ± 2.9	+29.9%
Running (Endurance)	Protective Performance (Score)	62.8 ± 3.9	80.4 ± 3.5	66.3 ± 3.7	87.2 ± 2.8	+38.8%
	Sports Adaptability (Score)	75.6 ± 3.3	78.9 ± 3.0	85.2 ± 3.2	90.5 ± 2.5	+19.7%
	Comfort Experience (Score)	65.3 ± 4.2	82.7 ± 3.6	73.5 ± 3.9	89.4 ± 3.0	+36.9%
	Comprehensive Adaptability (Score)	67.2 ± 3.6	80.7 ± 3.2	75.0 ± 3.4	89.0 ± 2.6	+32.4%
Yoga (Flexibility)	Protective Performance (Score)	58.6 ± 4.0	76.3 ± 3.7	63.5 ± 3.8	83.5 ± 2.9	+42.5%
	Sports Adaptability (Score)	70.3 ± 3.5	73.5 ± 3.1	86.8 ± 3.3	92.3 ± 2.4	+31.3%
	Comfort Experience (Score)	72.5 ± 4.1	80.6 ± 3.8	81.2 ± 3.7	88.6 ± 3.1	+22.2%
	Comprehensive Adaptability (Score)	67.1 ± 3.7	76.8 ± 3.3	77.2 ± 3.5	88.1 ± 2.7	+31.3%

Table 2 demonstrates that the proposed design exhibits optimal comprehensive adaptability across all scenarios:

1. Overall adaptability scores improved by 29.9%-32.4% compared to traditional designs, 9.6%-13.3% over single-optimization Design A, and 12.1%-17.2% over single-optimization Design B;
2. In contact sports (basketball), protective performance showed the most significant increase (+37.2%), demonstrating the optimized material's superior impact protection;
3. In endurance sports (running), comfort experience im-

proved most significantly (+36.9%), benefiting from optimized breathability and sweat-wicking properties;

4. In flexibility sports (yoga), athletic adaptability improved most significantly (+31.3%), validating the dynamic adaptation between the protective gear structure and human movement.

3) Field Trial Validation Results

A 4-week field trial was conducted with 180 volunteers (30 per sport category, including 6 professional athletes and 24 amateur enthusiasts). Results are summarized in Table 5:

TABLE 5.

Evaluation Indicator	Traditional Protective Gear	Proposed Protective Gear	Difference Rate	Satisfaction (1-10 Score)	
				Traditional Protective Gear	Proposed Protective Gear
Injury Protection Effect (Effectiveness %)	62.3	89.7	+44.0%	—	—
Impact on Sports Performance (No Impact %)	58.7	86.2	+46.8%	—	—
Long-term Wearing Comfort (%)	52.5	83.6	+59.2%	6.3 ± 1.5	8.7 ± 1.2
Durability of Protective Gear (No Damage %)	75.8	92.3	+21.8%	—	—
Overall Satisfaction (Score)	—	—	—	6.5 ± 1.4	8.9 ± 1.0

Field trial findings indicate:

1. Injury protection efficacy: The protective gear achieved an 89.7% injury prevention rate, representing a 44.0% improvement over traditional gear and effectively reducing sports injury risks;
2. Regarding impact on athletic performance, the protective gear achieved an 86.2% non-impact rate, a 46.8% improvement over traditional gear, demonstrating that enhanced design adaptability effectively minimizes restrictions on athletic performance;

4) Stability and Reliability Testing

Stability and reliability tests were conducted on the optimized materials and protective gear products from this study, yielding the following results:

1. Material Stability: After 6 months in a constant temperature and humidity environment (25°C, 65% humidity), all material performance metrics showed a decay rate ≤ 5%. Following 50 washes, the impact absorption efficiency decay rate was only 3.2%, and the breathability decay rate was 4.1%, meeting long-term usage requirements;
2. Protective Gear Reliability: After 10,000 simulated dynamic deformation cycles, the gear exhibited no damage or deformation, with protective performance degradation ≤ 4.5%. Performance remained stable across temperatures ranging from −10°C to 40°C, adapting to diverse

climatic conditions for athletic activities.

V. DISCUSSION

A. CORE MECHANISMS OF MATERIAL PROPERTY OPTIMIZATION

The proposed integrated optimization approach—"fiber modification-structural design-composite process"—relies on synergistic enhancement across multiple scales and dimensions:

1. At the micro-scale, nano-SiO₂ particles uniformly disperse within PCL/PU blended fibers, enhancing mechanical properties and impact absorption through particle reinforcement; Plasma treatment modifies the fiber surface, increasing roughness and hydrophilicity to improve moisture absorption and wicking performance;
2. At the mesoscale, the three-dimensional woven structure creates a gradient porosity through yarn interlacing. The dense surface layer provides abrasion resistance, the loose middle layer achieves impact cushioning, and the inner skin-friendly layer enhances comfort. These layers synergistically balance multiple functionalities;
3. At the macroscale, the three-layer composite process organically integrates material protective properties, athletic adaptability, and comfort through the rational combination of functional, cushioning, and comfort layers, overcoming the limitations of single-structure designs in meeting multiple demands.

Experimental validation demonstrates that this synergistic optimization mechanism achieves 15%-25% greater performance gains compared to single-optimization approaches (e.g., fiber modification alone or structural design alone), providing a novel technical pathway for optimizing athletic protective materials.

B. KEY FACTORS INFLUENCING DESIGN ADAPTABILITY

Enhancing the adaptability of sports protective gear design primarily relies on three critical factors:

1. **Precise Requirement Decomposition:** Protection needs vary significantly across different sports scenarios. For instance, contact sports prioritize impact protection, endurance sports emphasize comfort enhancement, and flexible sports require strengthened motion adaptability. Precise requirement decomposition is the prerequisite for adaptability design.
2. **Ergonomic Data Support:** Utilizing motion capture and 3D scanning data to design protective gear structures ensures contours closely follow human curves and elastic properties precisely match joint ranges of motion, minimizing movement restrictions;
3. **Material-Structure Synergy:** Protective gear design must fully consider material mechanical properties and elastic characteristics. For instance, highly elastic materials may employ minimalist structural designs, while stiffer materials require segmented structures to avoid conflicts between material properties and structural design.

C. RESEARCH LIMITATIONS AND FUTURE DIRECTIONS

1) Limitations

1. **Material optimization:** Uniform dispersion of nanoparticles remains an area for improvement. Agglomeration during mass production may compromise material performance stability.
2. **Design adaptability:** Current research primarily targets healthy individuals, neglecting the needs of special populations (e.g., injury/illness rehabilitation patients, persons with disabilities). Adaptability scope requires expansion.
3. **In terms of scenario coverage,** research is limited to six typical sports categories, with insufficient investigation into protective gear adaptability under extreme environmental conditions (e.g., high temperature and humidity, extreme cold).

2) Future Improvement Directions

1. **Material Optimization:** Employ combined ultrasonic dispersion and surface modification techniques to enhance nanoparticle dispersion uniformity; explore the application of smart responsive fibers (e.g., thermosensitive, hygroscopic fibers) in sports protective gear to achieve dynamic adjustment of protective performance;
2. **Design Adaptation:** Conduct biomechanical studies on special populations to establish a differentiated protective gear design adaptation system; develop smart

protective gear integrating wearable sensor technology for real-time monitoring of athletic performance and protective efficacy;

3. **Scenario Expansion:** Investigate performance changes of textile materials in extreme environments to optimize gear environmental adaptability; extend research to additional sports (e.g., skiing, rock climbing, rugby) to enhance the universality of findings.

D. INDUSTRY APPLICATION RECOMMENDATIONS

1. **Textile Enterprises:** Develop a series of sports protective materials based on the material optimization solutions proposed herein. Introduce differentiated materials (e.g., high-protection, high-comfort, high-adaptability) tailored to specific sports scenarios to meet diverse market demands.
2. **Protective Gear Manufacturers:** Establish a standardized R&D process encompassing “needs analysis → material selection → structural design → adaptability testing.” Utilize the adaptability evaluation model developed herein to guide product design and enhance competitiveness.
3. **Standards Development Bodies:** Reference the quantitative evaluation system for protective requirements and material performance metrics outlined in this paper to refine standards for sports protective gear. Clarify protection level requirements and material performance specifications for different sports scenarios.
4. **Sports Organizations:** Apply the protective gear developed herein to athlete training and competitions, continuously optimize products based on practical feedback, and promote them to the general fitness population to reduce sports injury rates.

VI. CONCLUSIONS

Based on core sports protection needs, this study optimized textile material properties and investigated the design adaptability of protective gear. It established a comprehensive technical system encompassing “protection needs analysis – material property optimization – protective gear design adaptation – experimental validation and evaluation.” Key findings include:

1. Established a multidimensional evaluation system for sports protection requirements, clarifying protection levels, athletic adaptability, and comfort experience needs across different sports scenarios (contact sports, endurance sports, flexibility sports), and created a quantitative mapping matrix between protection requirements and textile material properties;
2. Proposed a three-pronged material property optimization approach integrating “fiber modification - structural design - composite processing.” Optimized textiles achieved a 32.6% increase in impact absorption efficiency, an 85.1% improvement in air permeability, and a 91.3% elastic recovery rate, synergistically enhancing protective performance, comfort, and sports adaptability;

3. Developed a three-dimensional adaptability evaluation model linking material properties, protective gear structure, and sports scenarios. The designed sports protective gear achieved a 29.9%-32.4% improvement in comprehensive adaptability scores across six typical sports scenarios compared to traditional gear;
4. Field testing validated that the developed sports protective gear achieved an injury prevention effectiveness rate of 89.7%, a rate of no impact on athletic performance of 86.2%, and an overall user satisfaction score of 8.9 (out of 10), representing significant improvements over conventional protective gear.

AUTHOR CONTRIBUTIONS

Gang Duan designed, collected and analyzed the data, and drafted the manuscript. Gang Duan conducted the study, critically revised the manuscript for important intellectual content, and gave final approval of the version to be published. Gang Duan participated fully in the work, take public responsibility for appropriate portions of the content, and agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

CONFLICTS OF INTEREST

The author declares no conflict of interest.

FUNDING

This research received no external funding.

HUMAN RESEARCH SUBJECTS

This study was approved by the Ethics Committee of SHANDONG HUAYU UNIVERSITY OF TECHNOLOGY, and was performed in accordance with the principles of the Declaration of Helsinki. All eligible participants signed an informed consent form.

ACKNOWLEDGEMENTS

Not applicable.

REFERENCES

- [1] L. Torsus, T. Plamus, K. Kabun, et al., "Revaluation of Estonian local sheep wool - impact of different wool types on textile material properties," *Proceedings of the Estonian Academy of Sciences*, vol. 75, no. 1, pp. 15-33, 2026, doi: 10.3176/PROC.2026.1.02.
- [2] M. I. Egorov, "Prediction and Assessment of the Operational Properties of Polymer Textile Materials," *Fibre Chemistry*, vol. 57, no. 2, pp. 1-4, 2025, doi: 10.1007/S10692-025-10621-7.
- [3] I. V. Vagner, "Operational and Deformation Properties of Aramid Textile Materials for Alpinistic and Mine-Rescue Purposes Under Variable Temperature Conditions," *Fibre Chemistry*, vol. 57, no. 2, pp. 1-5, 2025, doi: 10.1007/S10692-025-10611-9.
- [4] B. Julián, J. Claramunt, M. Ardanuy, et al., "Influence of long-fibre content on the reinforcement capacity of nonwovens obtained from recycled textile waste for application in cement composites," *Case Studies in Construction Materials*, vol. 23, e05083, 2025, doi: 10.1016/J.CSCM.2025.E05083.
- [5] G. A. Makarov, V. A. Demidov, A. A. Kozlov, "Digital Methods for Predicting the Operating Properties of Aramid Textile Materials," *Fibre Chemistry*, vol. 57, no. 1, pp. 1-3, 2025, doi: 10.1007/S10692-025-10604-8.
- [6] T. Tasopoulos, O. Naka, I. Rachiotis, et al., "Clinical-based design of additively manufactured custom sports mouthguards using intraoral scanner integrated splint software," *Digital Dentistry Journal*, vol. 3, no. 1, 100073, 2026, doi: 10.1016/J.DDJ.2026.100073.
- [7] V. L. C. Boyneburgk, P. H. Heim, "Effect of Changing Climatic Conditions on Properties of Wood Textile Composites," *Materials*, vol. 18, no. 12, 2764, 2025, doi: 10.3390/MA18122764.
- [8] E. Irzmańska, J. M. Kowalska, A. Boczkowska, et al., "Thermal Analysis of Polyurethane Coatings Modified with Graphene and Modification Influence on Mechanical Properties of Hybrid Textile Materials Dedicated to Personal Protective Equipment," *Coatings*, vol. 15, no. 6, 705, 2025, doi: 10.3390/COATINGS15060705.
- [9] A. M. Abtey, F. Boussu, I. Cristian, et al., "Experimental investigation on dynamic stab resistance of high-performance multi-layer textile materials," *Defence Technology*, 47-14, 2025, doi: 10.1016/J.DT.2025.01.010.
- [10] Y. Yu, R. Zhang, L. Cheng, et al., "Huo Cao: a unique collectively utilized natural textile material and its structure and properties," *The Journal of The Textile Institute*, vol. 116, no. 3, pp. 380-388, 2025, doi: 10.1080/00405000.2024.2337169.
- [11] I. Prasetyo, K. A. Nisa, G. Gunawan, et al., "Influential properties on sound-absorption behavior of textile material-based multi-layer composite," *Textile Research Journal*, vol. 95, no. 3-4, pp. 337-354, 2025, doi: 10.1177/00405175241260434.
- [12] P. Li, L. Liu, J. Sun, et al., "Application of Thermodynamic Methods in Enhancing the Antibacterial Performance of Textile Materials," *International Journal of Heat and Technology*, vol. 42, no. 6, 2024, doi: 10.18280/IJHT.420615.
- [13] R. Abidinejad, H. Baniasadi, M. Fazeli, et al., "High-fiber content composites produced from mixed textile waste: Balancing cotton and polyester fibers for improved composite performance," *International Journal of Biological Macromolecules*, vol. 292, 139227, 2024, doi: 10.1016/J.IJBIOMAC.2024.139227.
- [14] E. S. Keating, D. J. Boer, G. Catsoulis, et al., "Co-designing Approaches to Sustainable Exercise Care for People with Metabolic Dysfunction-associated Steatotic Liver Disease," *Journal of Clinical and Translational Hepatology*, vol. 13, no. 9, pp. 707-722, 2025, doi: 10.14218/JCTH.2025.00155.
- [15] J. Price, A. Rushton, N. Ives, et al., "Co-designed neck exercise (EPIC-Neck) vs usual exercise care for people with chronic non-specific neck pain: protocol for a randomised feasibility study with process evaluation," *Pilot and Feasibility Studies*, vol. 11, no. 1, 26, 2025, doi: 10.1186/S40814-025-01608-6.
- [16] M. Turner, R. Zaman, B. Ertl, et al., "64 - The use of lattice design to tune the mechanical properties of 3D-printed sports mouthguards," *Dental Materials*, vol. 41, no. S1, e31, 2025, doi: 10.1016/J.DENTAL.2025.01.078.
- [17] E. Paraskevopoulos, S. Penthroudaki, M. Papandreou, "Exploring the Discriminant Validity of the Modified Arm Care Screen (MACS), Designed for Overhead Athletes, in Detecting Musculoskeletal Risk Factors in the General Population," *Biomechanics*, vol. 4, no. 4, pp. 642-652, 2024, doi: 10.3390/BIOMECHANICS4040046.
- [18] A. M. Maialen, G. Gaizka, B. Pengbo, et al., "Design, motion-planning, and manufacturing of custom-shaped tools for five-axis super abrasive machining of a turbomachinery blade type component," *The International Journal of Advanced Manufacturing Technology*, vol. 133, no. 1-2, pp. 655-669, 2024, doi: 10.1007/S00170-024-13774-7.
- [19] T. M. Rahaman, H. S. M. Khan, "Applications of green nano textile materials for environmental sustainability and functional performance: Past, present and future perspectives," *Nano-Structures & Nano-Objects*, vol. 40, 101332, 2024, doi: 10.1016/J.NANOSO.2024.101332.
- [20] E. K. Batal, S. Douhi, A. Eddiai, et al., "Design and Performance Analysis of a Low-Profile Dual-Band Antenna with Low Specific Absorption Rate Using Textile Materials for Wearable and RF Energy Harvesting Applications," *Journal of Electronic Materials*, vol. 53, no. 12, pp. 1-13, 2024, doi: 10.1007/S11664-024-11455-5.
- [21] O. Jingang, "Mechanical Movement in Stamping Die Design Based on Computer Analysis," *Journal of Physics: Conference Series*, vol. 2303, no. 1, 2022, doi: 10.1088/1742-6596/2303/1/012038.
- [22] M. Frydrysiak, Z. Pawliczak, "Design and Testing of 3D Textile Materials with Vibro-Insulating Properties, Applicable in the Construction of Vibroisolating Seats for Machine and Device Operators," *Fibres & Textiles in Eastern Europe*, vol. 32, no. 3, pp. 57-68, 2024, doi: 10.2478/FTEE-2024-0020.
- [23] M. Arya, M. Skrifvars, P. Khalili, "Performance and Life Cycle Assessment of Composites Reinforced with Natural Fibers and End-of-Life Textiles," *Journal of Composites Science*, vol. 8, no. 6, 196, 2024, doi: 10.3390/JCS8060196.
- [24] T. Asaulyuk, O. Semeshko, Y. Sariybekova, et al., "Effect of ZnO nanoparticles synthesized by the improved method on the antibacterial properties of cotton textile materials," *Eastern-European Journal of Enterprise Technologies*, vol. 1, no. 12, pp. 27-34, 2024, doi: 10.15587/1729-4061.2024.297066.
- [25] M. Koleva, D. Angelova, D. Zheleva, "METHODS FOR THE SYNTHESIS OF TiO2 NANO-PARTICLES. PROPERTIES OF TEXTILE MATERIALS TREATED WITH TiO2 NANOPARTICLES," *Journal of Chemical Technology and Metallurgy*, vol. 59, no. 2, 2024, doi: 10.59957/JCTM.V59.I2.2024.7.
- [26] I. Ra'no, V. Nailya, K. Islom, et al., "Fire retardants giving special properties to fibers and textile materials based on them," *E3S Web of Conferences*, vol. 486, 05021, 2024, doi: 10.1051/E3SCONF/202448605021.
- [27] S. K. R. N., "Performance analysis of textile materials with electric and transverse magnetic modes for modified Yee algorithm," *European Journal of Materials*, vol. 3, no. 1, 2023, doi: 10.1080/26889277.2023.2232384.
- [28] M. R. Cristy, F. M. T. Maria, "Design and Evaluation of Demonstration Tools for Newton's Law of Motion," *American Journal of Educational Research*, vol. 5, no. 2, pp. 155-160, 2017, doi: 10.12691/education-5-2-8.
- [29] H. G. Qin, D. Lu, P. S. Sun, et al., "A Kinematic Approach to Locating Error Analysis for Fixture Design," *Key Engineering Materials*, vol. 431-432, pp. 74-77, 2010, doi: 10.4028/www.scientific.net/KEM.431-432.74.
- [30] H. F. Wang, Q. Liu, M. H. Wang, "Clamp Equipment Design and Motion Analysis with ANSYS for Large Cylindrical Segment," *Applied Mechanics and Materials*, vol. 197, pp. 110-113, 2012, doi: 10.4028/www.scientific.net/AMM.197.110.