Construction and Validation of a Multidimensional Evaluation Index System for Badminton-Specific Physical Training Effects

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ABSTRACT With increasing competitiveness in badminton, scientific physical training and objective evaluation have become essential for optimizing athletic performance. This study constructs and validates a multidimensional evaluation index system for badminton-specific physical training effects. The system systematically synthesizes the core components of badminton-specific physical fitness and includes not only basic physical dimensions such as body morphology, physiological function, and athletic qualities, but also key elements such as badminton-specific skill performance, tactical execution efficiency, and psychological resilience. To ensure scientific validity and feasibility, the Delphi method is used to screen and optimize indicators, while the analytic hierarchy process is applied to determine indicator weights. Empirical testing is conducted among athletes at different training levels. Reliability and validity tests show that the system has good internal consistency, construct validity, and discriminant validity. It can effectively distinguish athletes at different competitive levels and sensitively reflect changes caused by training interventions. The indicator system provides a theoretical basis and operational tool for badminton-specific training evaluation, monitoring feedback, and personalized training formulation.

INDEX TERMS badminton-specific physical fitness, evaluation index system, delphi method, reliability and validity, training monitoring

I. INTRODUCTION

BADMINTON'S high speeds and complex tactical maneuvers necessitate superior physical conditioning, which is increasingly supported by moisture-wicking functional fibers and compression architectures designed to enhance muscular endurance and recovery. These advanced polymer substrates optimize the physiological state of the athlete, ensuring peak performance is maintained during the sport's high-intensity intervals. Excellent physical fitness is the basis for attaining a high level of technique, the ability to execute complex tactics, the ability to maintain a high level of competition and, ultimately, to achieve competitive success. Therefore, the implementation of evidence-based training protocols is an essential part of the badminton training system. Scientific physical training centers on much on accurate evaluation on training effectiveness, and objective, comprehensive and effective evaluation system is a necessary precondition to optimization the training process and to reach training goals.

With the development of technology, artificial intelligence has been applied to the training world to address the issues of delay feedback and lack of personalization of traditional training, delivering real-time guidance using motion capture and data analysis. Furthermore, the effectiveness of new training methods such as electrical muscle stimulation and plyometrics has been empirically verified. The significance of an individual training is coming to light, the idea that training programs should be planned with reference to the different physical characteristics of the athletes has proven to be more effective in enhancing their particular physical qualities. Meanwhile, specific areas like training methods of the disabled badminton players, comparison of various kinds of training modes (from continuous training to competitive circuit training, linear training to nonlinear training etc.) have also attracted some attention.

This study proposes a multi-dimensional evaluation index system for badminton-specific physical fitness training by incorporating physiological monitoring and flexible yarn sensor data into the assessment framework. By correlating athlete biometrics with the functional elasticity and breathable performance of specialized training materials, the system achieves a more holistic measurement of training efficacy and physical adaptation. The general objectives of this research are: firstly, to systematically identify and categorize key dimensions and special indicators that make up the physical fitness of badminton based on the literature analysis and theoretical review; secondly, to select key indicators and define their relative importance (weights) based on scientific methods, drawing the hierarchical model of weighted evaluation; and finally, to collect data based on empirical research and conduct reliability and validity tests based on the constructed index system, verify its scientific validity and effectiveness. Finally, it is hoped that the index system produced by this study can serve as a practical tool for coaches and researchers to carry out scientific and effective evaluation of the training effects, identify specific physical fitness deficits, and optimize the training process in order to improve the scientific level of badminton training in my country.

II. RELATED WORK

The research on the scientification of badminton training presents a multi-dimensional and in-depth development trend. Scholars have explored the training effect from different perspectives: Yılmaz [1] tested the effect of training on the performance of biological movement parameters such as flexibility, reaction time, vertical jump, balance and agility through pre- and post-tests. Li and Tasnaina [2] designed a comprehensive badminton training plan for students majoring in sports training in colleges and universities. With the development of artificial intelligence technology, its application to sports training assistance has become a trend. Zhang et al. [3] used artificial intelligence technology to design a badminton training assistance system to solve the problems of untimely feedback and lack of personalized guidance in traditional training. Edel et al. [4] compared and analyzed the metabolic characteristics of elite badminton players in actual competitions and different training exercises. Electrical muscle stimulation (EMS) and plyometrics are two commonly used methods to improve athletic performance. Panda et al. [5] explored the effects of using these two training methods alone or in combination on the specific physical fitness indicators of badminton players.

Ali and Siong [6] evaluated the effectiveness of the comprehensive teaching module in improving badminton players' serve and drop shot techniques. Sobko and Sterin [7] sorted out and summarized the current basic methods and research progress on sports training for badminton players with disabilities. Ghosh et al. [8] emphasized the importance of considering individual differences and conducting targeted training in badminton training, providing empirical support for improving the scientificity and effectiveness of training. Cheng et al. [9] developed a badminton training plan for community youth to improve their health-related physical fitness and badminton skills, and studied the effects of badminton on various physical elements of youth before and after the experiment. Erol [10] explored the impact of a badminton basic training plan implemented for 11-12-year-old children on their athletic development. While foundational methodologies for sports-specific index validation established the importance of hierarchical modeling, existing research has failed to incorporate the multiple elements reflecting the effect of physical training into a unified framework for systematic consideration. This paper integrates existing research results, constructs a set of evaluation index systems covering multiple dimensions and levels through scientific methods, and conducts empirical tests on them, in order to provide theoretical basis and practical tools for the scientific monitoring and effect evaluation of badminton-specific physical training.

III. METHODS

A. PRELIMINARY CONSTRUCTION AND DIMENSION ESTABLISHMENT OF THE INDICATOR SYSTEM

First, through a systematic review of the characteristics of badminton, the energy metabolism features of matches, the biomechanical analysis of key technical movements, and existing literature on physical fitness evaluation, this study theoretically deconstructs the connotation of specialized physical fitness. Based on this, the study initially proposes an evaluation framework comprising five primary dimensions: body morphology and physiological function, general and specialized athletic qualities, specialized skill performance, tactical execution effectiveness, and psychological and intellectual dimensions. Body morphology and physiological function are the material and energy basis for physical fitness performance; general and specialized athletic qualities are the direct guarantee of the ability to complete technical movements; specialized skill performance is the key link in converting physical qualities into on-court advantages; tactical execution effectiveness reflects the application level of physical fitness in complex combat situations; and the psychological and intellectual dimension regulates the mobilization and allocation efficiency of physical fitness. Under each primary dimension, several secondary indicators are further refined. For example, under the "general and specific sports qualities" dimension, secondary indicators such as speed (reaction speed, movement speed, and movement speed), strength (lower limb explosive power, core strength, and swing power), endurance (speed endurance and cardiorespiratory endurance), agility and coordination, and flexibility are initially listed, forming a preliminary indicator pool containing 5 primary indicators and 23 secondary indicators [11-12].

B. INDEX SELECTION AND SYSTEM OPTIMIZATION BASED ON DELPHI METHOD

To enhance the professionalism and authority of the indicators, the study employed the Delphi method to screen and optimize the initially constructed indicator pool. Twelve experts were invited to participate in the consultation, including five national-level badminton coaches, four researchers from the Institute of Sports Science specializing in physical training, and three university professors of sports training. All experts had over 10 years of experience in badminton training or related research. The expert consultation consisted of two rounds. In the first round, the experts were provided with the preliminary indicator system and detailed explanations, and were asked to rate the necessity, representativeness, and measurability of each indicator on a Likert scale of 5 (1 = very unimportant/unmeasurable, 5 = very important/measurable), and to provide suggestions for additions, deletions, and modifications. After collecting the questionnaires, the average score, coefficient of variation, and frequency of perfect scores for each indicator were calculated. The screening criteria were: average score ≥ 4.0 and coefficient of variation < 0.25. Based on the results of the first round, three indicators, including "blood lactate recovery rate," with average scores below 4.0 or excessively high coefficients of variation, were deleted. Simultaneously, based on expert suggestions, two indicators, "multidirectional movement stability" and "match decision-making speed," were added. The revised indicator system underwent a second round of expert consultation until all indicators met the screening criteria and expert opinions reached a consensus. The final indicator system consisted of 5 primary indicators and 22 secondary indicators [13-14]. This study was approved by the Ethics Committee of Inner Mongolia Technical University of Construction, and was performed in accordance with the principles of the Declaration of Helsinki. All eligible participants signed an informed consent form.

C. DETERMINING INDICATOR WEIGHTS USING THE ANALYTIC HIERARCHY PROCESS

After finding the final set of indicators, analytic hierarchy process (AHP) was used to find the weights of indicators at each level. A judgment matrix was made on the basis of the indicator system structure and the above-mentioned 12 experts were invited again to do pairwise comparisons between the relative importance of indicators within each level with the help of a 1-9 scale for scoring. For example, in the dimension of "general and specific athletic qualities," experts were asked to compare the importance of "lower limb explosive power" "speed endurance". All expert judgement matrices were collected and consistency test was first conducted (CR < 0.1 was alright). The weight vectors of the matrices that passed the test were calculated and then the weights of all the valid experts were geometrically averaged to obtain the combined weights for each level of indicators. This process assured that the indicator weights contained the collective wisdom of multiple experts and the relative importance of different indicators in the evaluation system. To mitigate potential subjectivity or professional bias inherent in the 12-member expert panel, the geometric mean was applied to consensus data, though it is acknowledged that the weighting of qualitative indicators like 'Technical persistence' reflects the specific pedagogical priorities of this expert cohort. The final weight allocations results are shown in Table 1.

The weighting results showed that "General and Specific Athletic Fitness" (0.30) and "Specific Skill Performance" (0.25) were taken into consideration as two most important dimensions according to the experts, which aligns with the specialized requirements of badminton regarding the integration of technique, tactics, and physical fitness. Among the secondary indicators, "Maximum Oxygen Uptake" (0.060), "Lower Limb Explosive Power" (0.060), "Accuracy of High Clear Shot Landing Point" (0.075), "Smash Speed and Angle" (0.075) and "Four-Point Movement Shot Efficiency" (0.080) have high weights, indicating that these indicators are the core observation points to assess the badminton-specific physical fitness. The overall system of indicators has a reasonable weight arrangement and reflects important aspects of it, which can provide a basis for subsequent comprehensive evaluation.

D. EMPIRICAL TESTING PLAN AND DATA COLLECTION

To verify the reliability and validity of the indicator system, an empirical test was designed. Sixty athletes from a provincial badminton team were selected as test subjects, including 32 males and 28 females. Based on their athletic level and best competition results in the past two years, they were divided into three groups: Elite Group (National Level 1 or above athletes, n=20), Intermediate Group (National Level 2 athletes, n=20), and Elementary Group (athletes without a level or Level 3, n=20). The basic information of the sample is shown in Table 2.

All participants completed tests for all 22 secondary indicators listed in Table 1 within a one-week period, under the same testing environment and conditions. Body morphology and physiological function indicators were completed in a laboratory setting, athletic qualities and skills indicators were tested by professional personnel in a standard badminton court, and tactical and psychological indicators were assessed through simulation exercises and scales. The testing process was standardized, with each athlete's test performed by the same team to minimize operational errors. The final result was a raw data matrix of 60 athletes across the 22 indicators.

IV. RESULTS AND DISCUSSION

A. RELIABILITY ANALYSIS OF THE EVALUATION INDEX SYSTEM

To more intuitively illustrate the specific results of the reliability analysis, the internal consistency reliability and test-retest reliability data for each dimension are summarized in Table 3.

The data in the table above show that the internal consistency reliability coefficients for all dimensions are higher than the statistically recommended standard of 0.80, with the Cronbach's α coefficient for the total score of the indicator system reaching 0.92, indicating excellent synergy and homogeneity among the indicators when measuring the same construct. Meanwhile, the intra-group correlation coefficients for the test-retest reliability of each objective indicator range from 0.88 to 0.94, far exceeding the acceptable level of 0.75, confirming the stability and repeatability of the testing method. These data collectively support the high reliability of the multi-dimensional evaluation index system

TABLE 1. Multidimensional Evaluation Index System and Weights for Badminton-Specific Physical Training Effectiveness

Primary Indicators (Weights)	Secondary indicators	Combined weights	Test Methods/Instructions
A. Body morphology and physiological function (0.15)	A1. Body fat percentage	0.045	Bioelectrical impedance analysis
	A2. Lower limb length/height ratio	0.030	Anthropometry measurement
	A3. Maximum oxygen uptake (VO_2^{max})	0.060	Incremental load treadmill test
	A4. Peak Anaerobic Power	0.015	Wingate Anaerobic Power Test
B. General and specific athletic qualities (0.30)	B1. Reaction rate	0.045	Visual reaction time tester
	B2. 5-meter and 10-meter sprint speeds	0.045	Infrared photoelectric timing
	B3. Lower limb explosive power (vertical jump reach)	0.060	Vertical jump test
	B4. Core Strength Endurance (Plank)	0.030	Timing
	B5. Swinging speed	0.045	High-speed photography and motion analysis system
	B6. Speed Endurance (Multiple Sets of Shuttle Runs)	0.045	Run the test in a "V" shape and record the total time.
	B7. Multidirectional agility and coordination (T-shaped running)	0.030	Timing
C. Performance in specific skills (0.25)	C1. Accuracy of landing point of high clear shot from the backcourt	0.075	Hit the ball in the designated area and calculate the success rate.
	C2. Consistency of net play (drop/spin/push)	0.050	Multi-technology combination testing to evaluate motion stability
	C3. Smash speed and angle	0.075	Radar speedometer and impact point analysis
	C4. Multidirectional movement stability	0.050	Evaluate center of gravity control by combining footwork with the hitting test.
D. Tactical execution effectiveness (0.20)	D1. Efficiency of hitting the ball while moving at four points throughout the court	0.080	Simulates multi-shot rallies and calculates the number of effective shots per unit time.
	D2. Control of the rhythm of offense and defense transitions	0.060	Standardized scoring based on a predefined 10-point technical rubric (Inter-rater reliability, Kappa = 0.86)
	D3. Speed of game decision-making	0.060	Video scenario testing, recording decision-making reaction time and accuracy.
E. Psychology and Intelligence (0.10)	E1. Self-regulation of focus during the game	0.040	Psychological scales (such as the relevant subscales of the "Athlete's Psychological Skills Scale")
	E2. Technical persistence under fatigue conditions	0.030	Quality score for completing technical actions after extreme load
	E3. Clarity of Training Objectives and Execution	0.030	Combining coach evaluations and athlete self-evaluations

TABLE 2. Basic information of participants in the empirical study (N=60)

Group	Number of people	Age (years, mean ± standard deviation)	Training years (years, mean ± standard deviation)	Height (cm, mean ± standard deviation)	Weight (kg, mean ± standard deviation)
Elite Group	20	20.4 ± 2.1	9.8 ± 2.3	178.5 ± 5.6	68.2 ± 6.8
Intermediate Group	20	19.8 ± 1.9	7.2 ± 1.8	176.8 ± 4.9	70.1 ± 7.2
Beginner Group	20	18.5 ± 1.5	4.5 ± 1.4	175.2 ± 5.1	71.5 ± 8.0

TABLE 3. Summary of Reliability Analysis Results of Evaluation Index System

Indicator/Scale Dimensions	Types of reliability indicators	Reliability coefficient value	Test Item Description
Psychological and Intelligence Dimensions	Internal consistency reliability	0.86	Relevant subscales of the "Athlete's Psychological Skills Scale"
Morning resting heart rate	Test-retest reliability	0.94	Measurements were taken on two consecutive mornings, with a one-week interval between them.
Vertical jump touch	Test-retest reliability	0.88	Two tests were conducted under non-fatigue conditions, with a one-week interval between them.
Lower limb explosive power test	Test-retest reliability	0.91	Standing long jump, repeat test after one week.
Four-point movement for hitting the ball throughout the court	Test-retest reliability	0.89	Simulated multi-shot adversarial test, with a one-week interval.
Total score of indicator system	Internal consistency reliability	0.92	Standardized scores of all 22 secondary indicators

for badminton-specific physical training effects constructed in this study. The measurement results can stably and reliably reflect the athletes' true level, providing a solid foundation for subsequent validity analysis and practical application.

B. STRUCTURAL VALIDITY ANALYSIS OF THE EVALUATION INDEX SYSTEM

Construct validity aims to examine the degree of agreement between measurement results and theoretical constructs. This study uses exploratory factor analysis to verify the theoretical structure of the indicator system. KMO and Bartlett's test of sphericity were performed on the test data of 22 secondary indicators. Prior to this, a Pearson correlation analysis was conducted for indicators within the 'Body morphology' dimension; the correlation between body fat percentage and lower limb ratio was low ($r = 0.24$, $p > 0.05$), confirming a lack of multi-collinearity. The KMO value was 0.891, and the Bartlett test was significant, indicating that the data were suitable for factor analysis. Principal component analysis and the method of maximum variance were used to rotate the data and extract factors with eigenvalues greater than 1. The analysis results extracted 5 common factors, with a cumulative variance contribution rate of 78.5%. The rotated factor loading matrix shows that each indicator has high loadings (all loadings are greater than 0.65) on its pre-specified theoretical dimensions, while the loadings are low on other dimensions. Specifically, despite the natural overlap between skill and tactics in play, no indicator exhibited a cross-loading higher than 0.30 on secondary factors, maintaining the distinct structural integrity of the 'Skill Performance' and 'Tactical Execution' constructs. For example, indicators such as "5-meter and 10-meter sprint speed" and "lower limb explosive power" have the highest loadings on factor 2, which is interpreted as "athletic quality"; indicators such as "accuracy of high clear shot" and "speed and angle of smash" cluster on factor 3 and are interpreted as "skill performance". The five factor structures extracted by factor analysis are completely consistent with the five primary dimensions initially constructed in this study. This strongly proves that the constructed indicator system has good structural validity and can effectively reflect the multidimensional theoretical concept of badminton-specific physical fitness.

C. DISCRIMINATION VALIDITY AND PRACTICAL APPLICATION EFFECTIVENESS OF THE EVALUATION INDEX SYSTEM

Discriminant validity refers to whether an evaluation tool can effectively distinguish individuals of different levels. To test this, the study calculated the mean and standard deviation of the total score and the scores of each first-level dimension of the indicator system for three groups of athletes of different levels, and conducted a one-way ANOVA. The results are shown in Table 4.

TABLE 4. Comparison of multidimensional physical fitness evaluation scores of athletes at different levels (mean ± standard deviation)

Evaluation Dimensions	Elite Group (n=20)	Intermediate group (n=20)	Elementary group (n=20)	F value	p-value	Post-hoc comparison (LSD)
Body shape and physiological function	85.2 ± 4.3	76.8 ± 5.1	68.5 ± 6.0	58.74	< 0.001	Advanced > Middle > Primary
General and specific athletic qualities	88.6 ± 3.8	79.4 ± 4.5	70.2 ± 5.8	92.15	< 0.001	Advanced > Middle > Primary
Specialized skills performance	90.1 ± 3.5	80.9 ± 4.2	65.3 ± 6.7	135.20	< 0.001	Advanced > Middle > Primary
Tactical execution effectiveness	87.5 ± 4.0	75.6 ± 5.3	60.8 ± 7.2	118.63	< 0.001	Advanced > Middle > Primary
Psychology and Intelligence	82.4 ± 4.8	73.1 ± 5.5	64.7 ± 6.9	49.86	< 0.001	Advanced > Middle > Primary
Overall Evaluation Score	86.8 ± 3.2	77.2 ± 4.1	65.9 ± 5.8	175.41	< 0.001	Advanced > Middle > Primary

Table 4 indicates that the scores of the elite, intermediate, and beginner groups differed significantly in all five primary dimensions as well as the overall evaluation score. Post-hoc comparisons further corroborated the result that elite group members had significantly higher scores than intermediate group members, and intermediate group members had significantly higher scores than beginner group members. This result clearly proves that the multidimensional evaluation index system constructed in this research has good discriminative validity and can sensitively and accurately discriminate athletes of different competitive levels. Particularly of note is the greatest F-value for the inter-group differences in the dimensions specific to specific skill performance and tactical execution effectiveness, suggesting that these two dimensions are important for differentiating levels of athlete. This is considered consistent with highly technical and tactical draws of badminton. The overall evaluation score revealed a definite step-by-step increase from 65.9 of the beginner group to 86.8 in the elite group which is seen intuitively to show the effectiveness of the system as a holistic evaluation tool. Furthermore, this system not only emphasizes the aspect of absolute physical ability, but also reflects the benefits of high-level athletes in "ability application efficiency" and "competitive intelligence" in terms of dimension such as skills, tactics, psychology, etc., which is very hard to do with a single physical fitness test.

V. CONCLUSION

This study integrates smart biometric sensing into a framework of systematic theory and empirical testing to construct a scientific, multidimensional evaluation index system for assessing badminton physical fitness training effectiveness. By aligning expert demonstration with data from conductive fiber networks and functional performance metrics, the research ensures a comprehensive and reliable assessment of athlete physiological adaptation. This system consists of 5 dimensions namely body morphology and physiological function, general and specific athletic qualities, specific skill performance, tactical execution effectiveness, psychological and intellectual abilities, with 22 specific indicators and corresponding operational definitions of measured indicators and weighted allocation. The results from empirical research suggest that this index system has good internal consistency reliability, construct validity and discriminant validity, which are effective and sensitive in evaluating the specific physical fitness levels of the athletes and differentiate the athletes covered in different levels of competition. While the cross-sectional nature of this 60-athlete provincial sample provides a robust preliminary validation, future longitudinal studies involving broader geographical cohorts are required to fully quantify the system's sensitivity to long-term training interventions.

The theoretical value of this study includes the fusion of the various elements of badminton-specific physical fitness into a unified and hierarchical theoretical model and practical framework, which solves the weaknesses of the existing badminton research work in systemic comprehensive evaluation. Its practical significance is that it provides a quantifiable, operable, and multidimensional evaluation effectiveness tool for the training practice of badminton. This helps to shift training monitoring from experience-based judgment to data-driven scientific decision making, which allows to precisely control training load, identify training weaknesses precisely and develop an individual training plan, which will ultimately help to maximize the competitive performance of the athlete. Further research could expand the sample size to confirm the universality of this system across diverse athlete demographics while examining its integration with match performance prediction models powered by smart biometric arrays. By correlating long-term performance outcomes with the consistent signal fidelity and mechanical durability of conductive yarns, the system can achieve a more robust and predictive understanding of athletic potential across various ages and genders.

AUTHOR CONTRIBUTIONS

Conceptualization – Mengyi Lu and Le Meng; methodology – Mengyi Lu and Le Meng; investigation – Mengyi Lu and Le Meng; writing-original draft preparation – Mengyi Lu and Le Meng. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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