

Causal – Hierarchical Network of Sport-Specific Physical Fitness in Chinese Male University Tennis Athletes: Policy Insights from a Delphi–fuzzy DEMATEL–ISM Analysis

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Abstract

Background: Tennis is a high-intensity, intermittent sport that requires the integrated development of physical components including speed, power, agility, coordination, and endurance for competitive success. Existing physical fitness evaluation frameworks rely mainly on expert consensus and static statistical analyses. Both approaches fail to reveal the dynamic causal hierarchies and interdependencies among these components. This gap in methodology impedes the design of training intervention protocols based on systematic optimization. This study aims to (1) identify the major physical fitness components of Chinese male university tennis athletes based on a Delphi consensus process, and (2) quantify their causal hierarchy using an integrated fuzzy DEMATEL–ISM approach.

Methods: The study was conducted in two phases: (1) establishment of an evaluation framework through a three-round Delphi survey of 23 experts; and (2) quantification and confirmation of the causal hierarchy among the components using a fuzzy DEMATEL–ISM approach, based on the judgments from eight experts.

Results: Five primary components were identified. The fuzzy DEMATEL–ISM analysis demonstrated that coordination (cause degree = 1.94; influencing degree = 8.84) and agility (cause degree = 0.87;

influencing degree = 8.89) were considered foundational drivers, speed (centrality = 17.05) and power (centrality = 17.00) as dependent hubs (negative cause degrees) and endurance (centrality = 11.31) as an independent outcome. A two-tier hierarchy was confirmed based on the ISM results, with agility and coordination driving speed, power, and endurance.

Conclusion: A causal–hierarchical network of tennis-specific physical fitness was established, identifying coordination and agility as the foundational drivers. Priority should be given to these foundational drivers in training programs before targeting speed and power improvements, while endurance can be addressed independently. A novel paradigm was provided by the integrated Delphi-fuzzy DEMATEL–ISM methodology for analyzing complex athletic performance.

Keywords: Tennis-specific physical fitness, Training optimization, indicator hierarchy, causal analysis, Delphi, Fuzzy DEMATEL, Interpretive Structural Modeling(ISM)

Introduction

In the sport of tennis, physical fitness acts as the keystone for optimal competitive performance and long-term athlete development. (Xiao et al., 2022; Li et al., 2011; Sun, 2002). As a high-intensity intermittent sport, tennis demands a well-developed mix of aerobic and anaerobic capacities to sustain prolonged matches (Fernandez-Fernandez et al., 2023; Kilit & Arslan, 2019; Brito et al., 2024; Reid et al., 2008). Sport-specific physical fitness, including speed, endurance, agility, flexibility, and power, not only underpins competitive success, but also mitigates injury risks and promotes long-term athletic development (Ulbricht et al., 2016; Fernandez-Fernandez et al., 2014; Tian, 2017). In China, university tennis athletes make up a large proportion of the sport participants. Therefore, the study mainly focuses on the sport-specific physical fitness of Chinese male tennis university athletes, on the grounds that precise evaluation of these factors is vital in monitoring physical status, identifying individual deficits, and designing evidence-based training protocols to optimize the athletes' potential (Fernandez-Fernandez et al., 2014; Henriques-Neto et al., 2022).

Even though the Delphi method has been shown to be valuable for establishing initial frameworks for physical-fitness evaluation of tennis and other sports (Li & Wang, 2023; Xiao et al., 2021; Ke, 2014), notable methodology limitations persist.

Existing studies often focus on static correlations and qualitative consensus. Quantitative analyses are scarce to find out the interrelationships, causal influences, and hierarchical structures among components. When examined using conventional factor analysis and regression models, the dynamic, nonlinear interactions among foundational components and higher-level performance are poorly understood. These limitations impede the identification of driving factors and their pathways of influence, and further hinder the optimization of training protocols. The application

of integrated techniques capable of modeling the complex influence structures in tennis-specific physical fitness evaluation remains limited.

To address these methodology bottlenecks, this study aimed to develop and apply a Delphi–fuzzy DEMATEL–ISM framework for evaluating the physical-fitness of Chinese male university tennis athletes. Grounded in complex systems theory, we hypothesized the fitness components exhibit a discernible hierarchy, where foundational components act as major drivers, consequently influencing performance outcomes through indirect pathways. The objectives included: (1) to identify the key sport-specific components of Chinese male university tennis athletes using the Delphi method. and (2) to quantitatively analyze the interrelationships among the components, to identify cause-and-effect groups and to construct a multi-level hierarchical structure through the integrated application of fuzzy set theory (addressing expert judgment uncertainty), DEMATEL (revealing causal relationships and influence degrees), and ISM (establishing the hierarchical model). This methodological integration allows for a more detailed and data-driven deconstruction of the fitness system's architecture.

The innovations of this study were as follows: An integrated approach of Delphi–fuzzy DEMATEL–ISM was applied to the evaluation of tennis-specific physical fitness for the first time, moving beyond descriptive statistics and static correlations to model the complex interdependencies within the fitness construct. By revealing the hierarchical influencing pathways and foundational drivers, the study provided a solid theoretical basis and a toolkit for the optimization of training protocols. Prioritizing the foundational components while strategically enhancing performance outcomes and individually improving endurance based on its level in the hierarchy offers a pathway to significantly elevate training efficiency and competitive performance.

Material and Methods

The study combined a literature review with an integrated qualitative and quantitative approach. The Delphi method synthesized expert consensus through iterative anonymous questionnaires (Niederberger et al., 2025; Jandhyala, 2020; Trevelyan & Robinson, 2015). Fuzzy logic was introduced to conventional DEMATEL (Decision-Making Trial and Evaluation Laboratory) framework to address the uncertainty in causal relationship mapping (Hu et al., 2025; Ebrahimi et al., 2024; Kuzu, 2023; Zhang et al., 2025; Irfan et al., 2024; Wang et al., 2024; Bakar et al., 2023; Tran et al 2020), building on traditional DEMATEL frameworks (Ferrazzi et al., 2025; Si et al., 2018; Gabus & Fontela, 1972). ISM (Interpretive Structural Modeling) constructed hierarchical models through direct graphs (Huang et al., 2024; Wan et al., 2021; Shakerian et al., 2019; Yuan

et al., 2019). This three-method integration quantifies factor interactions and establishes causal hierarchies in complex systems.

Participants

Twenty-three experts were recruited from departments of sports science and tennis programs at Chinese universities (Banning,2024). 17 were tennis specialists and 6 were coaches. Eight experts proceeded to the second phase (fuzzy DEMATEL phase), in order to ensure methodology consistency and expertise continuity. The sample size ($n>5$) has met the criterion of the fuzzy DEMATEL analysis (Li et al., 2024; Wang et al., 2024).

Consistent inclusion criteria were applied for both Delphi and Fuzzy DEMATEL phases. The inclusion criteria were as follows: (a) professional experience in sports training, physical education, or sports science; (b) a minimum of 10 years of relevant work experience; (c) academic title- for tennis specialists: associate professor or above; for coaches: lecturer or above; (d) age between 30 and 65 years; (e) willingness to participate and provide informed, constructive feedback. The exclusion criteria included: (a) unwillingness to participate; (b) lack of practical experience in sports performance or physical fitness; (c) withdrawal during the survey process.

The target population for this evaluation framework was Chinese male university tennis athletes aged 18-24 with National Level-2 certificate or above.

All procedures involving human participants were conducted in accordance with the ethical standards of the institutional and/or national research committee and the 1964 Helsinki Declaration and its later amendments. Ethical approval for this study was granted by the Ethics Committee of Mahasarakham University (Certificate No. 677-609/2024).

Study Design

The study comprised two phases. In phase one, the indicators influencing the sport-specific physical fitness of Chinese male university tennis athletes were screened via the Delphi method. In phase two, a quantified structural model was determined using the fuzzy DEMATEL–ISM approach. Through this two-phase, three-method analytical framework, the causal-hierarchical relationships among factors influencing the sport-specific physical fitness in Chinese male university tennis athletes were elucidated (Figure 1).

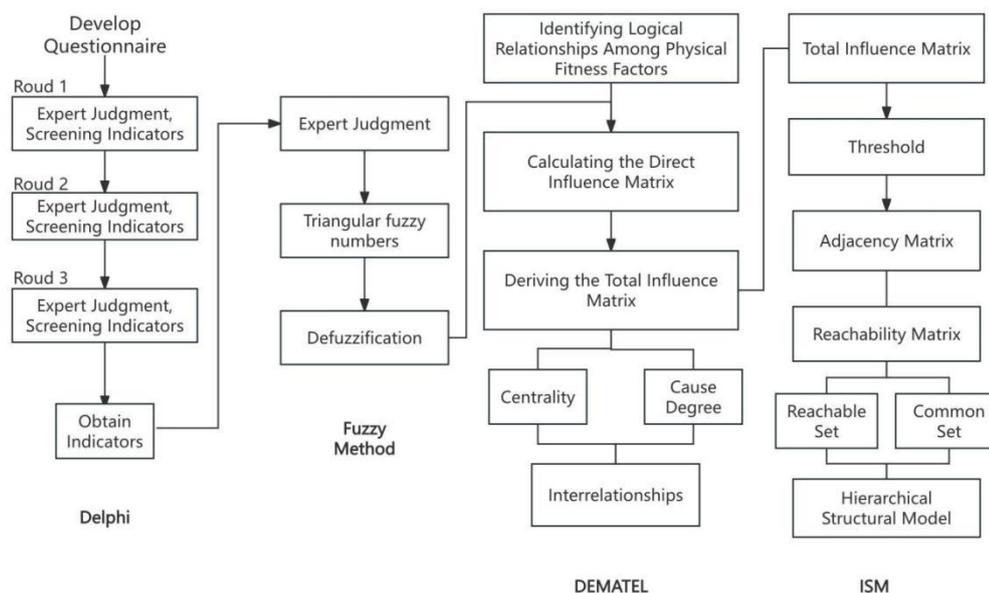


Figure 1 Study Framework

Questionnaire Design

During the first phase, a comprehensive literature review across PubMed, ScienceDirect, Web of Science, Google Scholar, CNKI, and Pub Scholar identified 7 primary and 35 secondary indicators (Table 1). Experts were asked to independently evaluate these indicators via a 5-point Likert scale questionnaire administered electronically via the Questionnaire Star platform or in person. To ensure validity and reliability, expert engagement coefficient, authority coefficient ($Cr \geq 0.7$), and coordination coefficient (Kendall's W with $p < 0.05$) (McPherson et al., 2018) were calculated. Indicators were prioritized using a threshold method based on the full-mark ratio (K_j), arithmetic mean (M_j), and coefficient of variation (V_j). Thresholds were defined as $TK = \text{mean}(K) - SD(K)$, $TM = \text{mean}(M) - SD(M)$, and $TV = \text{mean}(V) + SD(V)$. Indicators with $K_j \geq TK$, $M_j \geq TM$, and $V_j \leq TV$ were favored. To avoid discarding key items, only indicators failing two or three criteria ($K_j < TK$ and $M_j < TM$ and $V_j > TV$) were eliminated; those failing a single criterion were retained based on expert consensus. The process was conducted in accordance with five core construction principles: scientific validity, applicability, independence, comprehensiveness, and feasibility (Sun et al., 2022).

Table 1 Preliminary Screening Indicators

Primary Indicators	Secondary Indicators	
Strength	1. Pull-ups	4. Bench Press
	2. Push-ups	5. Barbell Clean and Jerk
	3. Standing Long Jump	6. Vertical Jump

Power	1. Continuous Incline Barbell Press	3. Medicine Ball Throw with Forehand Closed Stance
	2. Overhead Medicine Ball Throw	4. Medicine Ball Throw with Backhand Closed Stance
	Crossover Change-of-Direction Run	4. 10 Meter Sprint
Speed	Hexagonal reaction ball	5. 28 Meter Sprint
	4x10 Meter Sprint	6. 20 Meter Sprint
		7. 30 Meter Sprint
Endurance	1. 400-Meter Sprint	4. Beep Test
	2. 1500-Meter Run	5. Plank
	3. Wall-Sit Test	
Agility	1. Singles Baseline Shuttle Run	3. Spider Test
	2. Burpee Test	4. Two-Foot Hexagonal Jump
Flexibility	1. Sit and Reach	3. Horizontal splits
	2. Vertical Split	
Coordination	1. 30s Double-Under Jump Rope Test	4. Tennis Ball Throw
	2. Single-Leg Stand with Eyes Closed	5. Turn left foot and run forward
	3. Hand-Eye Coordination Test	6. Turn right foot and run forward

In the second phase, the causal relationships among the five primary sport-specific physical fitness indicators (identified through the Delphi process) were investigated using the integrated fuzzy DEMATEL–ISM approach. The expert evaluation questionnaire was administered either via the Questionnaire Star platform or in person, wherein the experts rated inter-indicator influences of these indicators on a 5-point scale (0 = no influence; 4 = very strong influence). These scores formed the initial direct influence matrix (A), serving as the foundational input for constructing the fuzzy decision model.

Fuzzy DEMATEL-ISM Model Construction

To ensure the reliability of the experts' feedback, the internal consistency of ratings from eight experts was tested using Cronbach's alpha coefficient. Following this, the fuzzy DEMATEL approach was employed to transform qualitative expert judgments into quantifiable data. Considering the inherent subjectivity in experts' evaluations, triangular Fuzzy numbers were introduced to address the uncertainty. The Converting Fuzzy Data into Crisp Scores (CFCS) method (Wu et al., 2007) was then applied to defuzzify the data and produce the defuzzified direct influence matrix Z, which served as the foundation for subsequent causal and hierarchical analysis.

Step 1: Based on a predefined linguistic scale, expert judgments were converted into triangular fuzzy numbers, as shown in Table 2.

Table 2 Expert Ratings and Triangular Fuzzy Number Conversion

Expert Evaluation	Influence Value	Triangular Fuzzy Number
No Influence	0	(0, 0, 0.25)
Weak Influence	1	(0, 0.25, 0.5)
Moderate Influence	2	(0.25, 0.5, 0.75)
Strong Influence	3	(0.5, 0.75, 1.0)
Very strong influence	4	(0.75, 1.0, 1.0)

Step 2: Defuzzification via the CFCS method.

① Standardization

$$xl_{ij}^k = (l_{ij}^k - \min l_{ij}^k) / \Delta_{\min}^{\max} \quad (1)$$

$$xm_{ij}^k = (m_{ij}^k - \min l_{ij}^k) / \Delta_{\min}^{\max} \quad (2)$$

$$xr_{ij}^k = (r_{ij}^k - \min l_{ij}^k) / \Delta_{\min}^{\max} \quad (3)$$

where $\Delta_{\min}^{\max} = \max r_{ij}^k - \min l_{ij}^k$.

② Compute left- and right-side standardized values.

$$xls_{ij}^k = xm_{ij}^k / (1 + xm_{ij}^k - xl_{ij}^k) \quad (4)$$

$$xrs_{ij}^k = xr_{ij}^k / (1 + xr_{ij}^k - xm_{ij}^k) \quad (5)$$

③ Compute the total standardized value.

$$x_{ij}^k = [xls_{ij}^k(1 - xls_{ij}^k) + xrs_{ij}^k xrs_{ij}^k] / [1 - xls_{ij}^k + xrs_{ij}^k] \quad (6)$$

④ Obtain the defuzzified value of the k -th expert's evaluation.

$$z_{ij}^k = \min l_{ij}^k + x_{ij}^k \Delta_{\min}^{\max} \quad (7)$$

⑤ Aggregate across experts to obtain the defuzzified direct-influence matrix.

$$z_{ij} = \frac{1}{8} (z_{ij}^1 + z_{ij}^2 + \dots + z_{ij}^8) \quad (8)$$

Step 3: Normalize the defuzzified matrix Z . Using the row-maximum method, we summed each row and divided each element by the maximum row sum to obtain the normalized influence matrix.

$$B = \frac{x_{ij}}{\max(\sum_{j=1}^n x_{ij})} \quad (9)$$

Step 4: Compute the total (comprehensive) influence matrix T (Table 9):

$$T = B(I - B)^{-1} \quad (10)$$

Step 5: Compute the influencing degree (D_i) (row sum of T) and affected degree (C_i) (column sum of T) for each factor:

$$D_i = \sum_{j=1}^n x_{ij}, (i = 1, 2, \dots, n) \quad (11)$$

$$C_i = \sum_{j=1}^n x_{ji}, (i = 1, 2, \dots, n) \quad (12)$$

Step 6: Derive centrality (M_i) and cause degree (R_i) for each factor:

Centrality (M_i): Sum of D_i and C_i , indicating the overall importance of factor i :

If $R_i > 0$, factor i is a casual factor (actively influences others).

If $R_i < 0$, factor i is an outcome factor (passively influenced by others).

$$M_i = D_i + C_i \quad (13)$$

$$R_i = D_i - C_i \quad (14)$$

Step 7: Draw the causal-relationship diagram.

Step 8: Derive the adjacency matrix A from T using a threshold λ with equation 15 where $\lambda = \bar{x} + s$, with \bar{x} as the mean and s as the standard deviations (Sheykhan et al., 2024).

$$\begin{cases} a_{ij} = 1, t_{ij} \geq \lambda \\ a_{ij} = 0, t_{ij} < \lambda \end{cases} \quad (15)$$

Step 9: Compute the reachability matrix L using the adjacency matrix A with equation 16 where I is the identity matrix.

$$L = (T + I)^{n+1} = (T + I)^n \neq (T + I)^{n-1} \neq (T + I) \quad (16)$$

Step 10: Construct the ISM hierarchical model.

Firstly, obtain the reachable set $R(s_i)$, antecedent set $A(s_i)$, and common set $C(s_i)$ from the reachability matrix L .

$$R(s_i) = \{s_i \in S | s_{ij} = 1\} \quad (17)$$

$$A(s_i) = \{s_i \in S | s_{ji} = 1\} \quad (18)$$

$$C(s_i) = R(s_i) \cap A(s_i) \quad (19)$$

Secondly, following a results-oriented extraction, arrange factors level by level (top to bottom) and draw the hierarchical topology diagram (Singh et al., 2024).

Statistical Analysis

All data were managed using WPS Office 7.0. Statistical procedures included: (1) Internal consistency validation was tested via SPSSAU v24.0 (Cronbach's $\alpha > 0.6$ across both phases); (2) Delphi expert consensus metrics were computed using IBM SPSS Statistics 29.0, including engagement coefficient, authority coefficient (Cr), coordination coefficient (Kendall's W). And indicator screening statistics were also done with IBM SPSS Statistics 29.0, including full-mark ratio, coefficient of variation (CV), arithmetic mean (M); (3) MATLAB R2025b was used for matrix operations and structural modeling during the fuzzy DEMATEL–ISM phase.

Results

1. Indicator Screening via Delphi Method

This phase lasted eight weeks from November 1, 2024 to December 27, 2024. Three rounds of experts survey were conducted. 25 questionnaires were distributed in the first round, of which 23 were retrieved. The response rate was 92%, and valid response rate was 100%. In the second and third rounds, 23 questionnaires were distributed in each round, with all 23 retrieved. The response rate was 100%. The panel showed extremely high engagement, meeting the requirements for questionnaire validity. After analyzing the expert survey results of the third-round questionnaire, the calculated expert credibility level was 0.934, indicating a high level of expert authority. The Kendall's Coefficient of Concordance (W) values for the three rounds of expert questionnaires all exceeded 0.5, satisfying the consistency requirement for expert consensus; $P < 0.05$, indicating statistical significance. Detailed results are presented in Tables 3-6.

Table 3 Kendall's Coefficient of Concordance (W) Test

Round	Indicator Level	Kendall's Coefficient of Concordance (<i>W</i>)	P-value
1	Primary	0.632	<0.001
	Secondary	0.667	<0.001
2	Primary	0.604	<0.001
	Secondary	0.578	<0.001
3	Primary	0.684	<0.001
	Secondary	0.603	<0.001

Table 4. Expert Consensus for Primary Indicators

Item	Mean	Mean	Mean	SD	SD	SD	CV	CV	CV	FMR	FMR	FMR
	(R1)	(R2)	(R2)	(R1)	(R2)	(R3)	(R1)	(R2)	(R3)	(R1)	(R2)	(R3)
Strength	3.304	1.076	-	0.559	3.391	-	0.169	0.317	-	0.043	0.217	-
Power	4.957	0.288	4.913	0.209	4.913	0.288	0.042	0.059	0.059	0.957	0.913	0.913
Speed	4.870	0.825	4.174	0.344	4.043	0.778	0.071	0.204	0.186	0.870	0.348	0.391
Endurance	3.783	0.815	3.826	0.736	3.870	0.650	0.195	0.211	0.170	0.174	0.261	0.130
Agility	4.087	0.656	4.087	0.848	4.609	0.733	0.208	0.142	0.179	0.391	0.696	0.304
Flexibility	2.957	-	-	1.261	-	-	0.426	-	-	0.130	-	-
Coordination	4.870	0.518	4.870	0.344	4.783	0.344	0.071	0.108	0.071	0.870	0.826	0.870

Note: SD, Standard Deviation; CV, Coefficient of Variation; FMR, Full Score Frequency.

Table 5. Expert Consensus for Secondary Indicators

Item	Mean	Mean	Mean	SD	SD	SD	CV	CV	CV	FMR	FMR	FMR
	(R1)	(R2)	(R3)									
1. Pull-ups	3.826	3.652	-	1.029	0.714	-	0.269	0.196	-	0.304	0.130	-
2. Push-ups	3.391	3.565	-	1.270	0.788	-	0.374	0.221	-	0.261	0.174	-
3. Standing long jump	3.783	3.696	-	1.204	0.974	-	0.318	0.264	-	0.391	0.304	-
4. Bench press	3.217	-	-	1.166	-	-	0.362	-	-	0.174	-	-
5. Barbell clean and jerk	3.087	-	-	1.083	-	-	0.351	-	-	0.130	-	-
6. Vertical jump	3.261	-	-	1.054	-	-	0.323	-	-	0.174	-	-

7. Continuous incline barbell press machine	3.261	-	-	1.096	-	-	0.336	-	-	0.174	-	-
8. Overhead medicine ball throw	4.870	4.826	4.957	0.458	0.388	0.209	0.094	0.080	0.042	0.913	0.826	0.957
9. Forehand closed medicine ball throw	4.957	4.783	4.957	0.209	0.422	0.209	0.042	0.088	0.042	0.957	0.783	0.957
10. Backhand standing closed medicine ball throw	4.957	4.957	4.913	0.209	0.209	0.288	0.042	0.042	0.059	0.957	0.957	0.913
11. Crossover Change-of-Direction Run	4.870	3.696	-	0.344	1.063	-	0.071	0.288	-	0.870	0.304	-
12. Hexagonal reaction ball	4.957	4.957	4.043	0.209	0.209	0.825	0.042	0.042	0.204	0.957	0.957	0.348
13. 4x10-meter shuttle run	4.739	4.913	4.826	0.541	0.288	0.388	0.114	0.059	0.080	0.783	0.913	0.826
14. 28-meter sprint	3.261	-	-	1.137	-	-	0.349	-	-	0.174	-	-
15. 10-meter sprint	3.652	3.739	-	1.301	0.810	-	0.356	0.217	-	0.391	0.217	-
16. 20-meter sprint	4.696	4.913	4.957	0.635	0.288	0.209	0.135	0.059	0.042	0.783	0.913	0.957
17. 30-meter sprint	3.174	-	-	1.029	-	-	0.324	-	-	0.087	-	-
18. 400-meter sprint	3.696	3.739	-	1.105	1.287	-	0.299	0.344	-	0.304	0.478	-
19. 1500-meter run	3.087	-	-	1.083	-	-	0.351	-	-	0.130	-	-
20. Beep test	4.696	4.826	3.957	0.822	0.491	0.878	0.175	0.102	0.222	0.870	0.870	0.348
21. Plank	4.739	4.783	3.870	0.619	0.600	0.694	0.131	0.125	0.179	0.826	0.870	0.174
22. Wall sit test	4.783	4.826	3.870	0.518	0.388	0.757	0.108	0.080	0.196	0.826	0.826	0.217
23. Singles Baseline Shuttle Run	4.565	3.957	3.870	0.788	0.767	0.757	0.173	0.194	0.196	0.696	0.261	0.217
24. Burpee test	3.174	-	-	1.029	-	-	0.324	-	-	0.087	-	-
25. Spider test	4.696	3.870	4.957	0.635	0.815	0.209	0.135	0.211	0.042	0.783	0.261	0.957
26.Hexagon Jump with Both Feet	4.609	4.870	3.913	0.839	0.458	0.848	0.182	0.094	0.217	0.783	0.913	0.304

27. Sit and reach	3.217	-	-	1.204	-	-	0.374	-	-	0.174	-	-
28. Horizontal splits	2.826	-	-	0.937	-	-	0.331	-	-	0.043	-	-
29. Vertical split	3.261	-	-	1.054	-	-	0.323	-	-	0.174	-	-
30. 30s Double Unders Jump Rope Test	4.696	4.000	3.870	0.470	0.853	0.869	0.100	0.213	0.225	0.696	0.348	0.304
31. One-leg stance with eyes closed	4.696	4.870	3.957	0.559	0.344	0.767	0.119	0.071	0.194	0.739	0.870	0.261
32. Hand-eye coordination test	4.130	4.130	4.870	1.058	0.815	0.344	0.256	0.197	0.071	0.522	0.391	0.870
33. Tennis ball throw	2.913	-	-	1.083	-	-	0.372	-	-	0.130	-	-
34. Turn left foot and run forward	4.130	3.739	-	1.058	0.810	-	0.256	0.217	-	0.522	0.217	-
35. Turn right foot and run forward	4.391	3.696	-	0.839	0.822	-	0.191	0.222	-	0.565	0.217	-

Note: SD, Standard Deviation; CV, Coefficient of Variation; FMR, Full Score Frequency.

Table 6. Selection Criteria for Indicators

Indicator Level	Item	Mean (R1)	Mean (R1)	Mean (R1)	SD (R1)	SD (R2)	SD (R3)	TV (R1)	TV (R2)	TV (R3)
Primary	Arithmetic Mean	4.118	4.268	4.374	0.812	0.596	0.490	3.306	3.672	3.741
	Coefficient of Variation (CV)	0.169	0.174	0.133	0.132	0.091	0.063	0.300	0.265	0.245
	Full-Mark Ratio(%)	0.491	0.543	0.522	0.397	0.305	0.351	0.094	0.239	0.246
Secondary	Arithmetic Mean	4.007	4.304	4.386	0.746	0.563	0.520	3.261	3.741	3.866
	Coefficient of Variation (CV)	0.232	0.158	0.134	0.116	0.087	0.079	0.347	0.245	0.213
	Full-Mark Ratio(%)	0.496	0.565	0.574	0.321	0.319	0.339	0.175	0.246	0.235

Note: SD, Standard Deviation; TV, Threshold Value.

Based on the three rounds of Delphi expert questionnaires, five primary indicators and fifteen secondary indicators affecting the sport-specific physical fitness of male university tennis athletes in China were ultimately derived. The results are shown in Table 7.

Table 7 Sport-specific Physical Fitness Indicators of Chinese male university tennis athletes

Primary Indicators	Secondary Indicators
Power	1. Overhead Medicine Ball Throw
	2. Medicine Ball Throw with Forehand Closed Stance
	3. Medicine Ball Throw with Backhand Closed Stance
Speed	1. Hexagonal Reaction Ball Test
	2. 4×10-Meter Shuttle Run
	3. 20-Meter Sprint
Endurance	1. Beep Test
	2. Plank
	3. Wall-Sit Test
Agility	1. Singles Baseline Shuttle Run
	2. Two-Foot Hexagonal Jump
	3. Spider Test
Coordination	1. 30s Double-Under Jump Rope Test
	2. Hand-Eye Coordination Test
	3. Single-Leg Stance with Eyes Closed

2. Analysis of Influencing Factors on Sport-specific Physical Fitness of Chinese male university tennis athletes via Fuzzy DEMATEL–ISM

This phase lasted four weeks from March 1, 2025 to April 1, 2025. A total of 8 expert questionnaires were distributed, with all 8 returned. The response rate was 100%. The experts showed extremely high engagement, meeting the requirements for questionnaire validity. The internal consistency of scores from the 8 experts yielded a Cronbach's α coefficient of 0.899 (>0.8), confirming high reliability ((Bürk & Sival, 2018).

Each expert's evaluation matrix was defuzzified using equations 1–7, and the comprehensive defuzzified scores of the eight experts were calculated using equation 8 to obtain the direct influence matrix Z , as shown in Table 8.

Table 8 Defuzzified Crisp Direct-Influence Matrix

	Speed	Power	Endurance	Agility	Coordination
Speed	0.03	0.79	0.47	0.62	0.44
Power	0.76	0.03	0.46	0.62	0.47
Endurance	0.44	0.35	0.04	0.35	0.32
Agility	0.76	0.79	0.32	0.03	0.70
Coordination	0.73	0.73	0.38	0.73	0.03

Using equations 9–10 to derive the total (comprehensive) Influence Matrix *T* as shown in Table 9.

Table 9 Total (comprehensive) Influence Matrix *T*

	Speed	Power	Endurance	Agility	Coordination
Speed	1.693	1.917	1.254	1.678	1.425
Power	1.906	1.687	1.247	1.673	1.428
Endurance	1.276	1.251	0.754	1.120	0.971
Agility	2.111	2.117	1.340	1.673	1.644
Coordination	2.094	2.093	1.349	1.876	1.433

Using equations 11–14, the influencing degree, affected degree, centrality, and cause degree for the 16 factors were calculated, as shown in Table 10.

Table 10 Ranking of Influencing Degree, Affected Degree, Centrality, and Cause Degree for Each Factor

Factor	Influencing Degree	Rank	Affected Degree	Rank	Centrality	Rank	Cause Degree	Factor Attribute
Speed	7.9665	3	9.079	1	17.0455	1	-1.1125	Result factor
Power	7.9397	4	9.0638	2	17.0035	2	-1.1241	Result factor
Endurance	5.3705	5	5.9441	5	11.3146	5	-0.5736	Result factor
Agility	8.8856	1	8.0191	3	16.9047	3	0.8665	Causal Factor
Coordination	8.844	2	6.9003	4	15.7443	4	1.9437	Causal Factor

Using the centrality as the horizontal axis and the cause degree as the vertical axis, with $O(13.803,0)$ (where 13.803 is the mean centrality) as the origin, all factors were plotted in the Cartesian plane to obtain the causal relationship diagram of each factor.

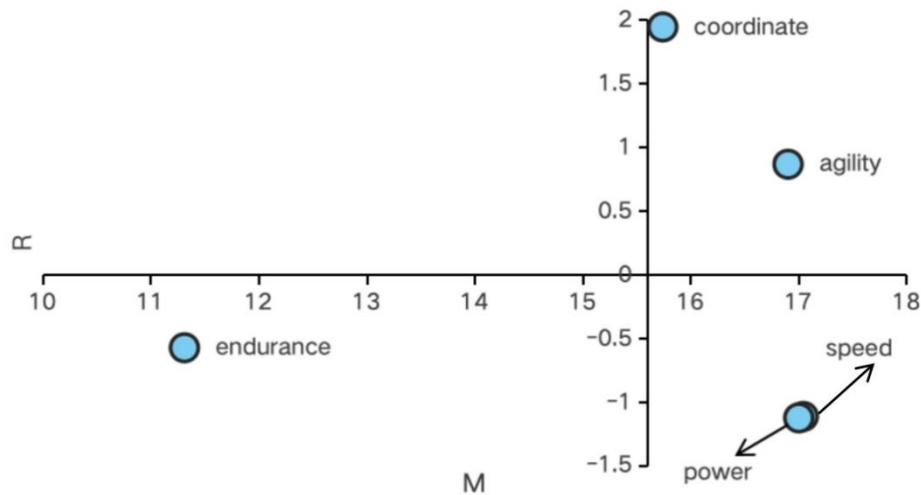


Figure 2 The causal relationship diagram

As shown in Table 10 and Figure 2, agility demonstrated the highest influencing degree (8.8856, Rank 1), followed by coordination (8.844, Rank 2). Endurance exhibited the lowest influencing degree (5.3705, Rank 5). Both agility and coordination were identified as causal factors, displaying the highest positive cause degrees (1.9437 and 0.8665, respectively). In contrast, speed, power, and endurance were classified as result factors, each having negative cause degrees (-1.1125, -1.1241, and -0.5736, respectively). Speed had the highest centrality (17.0455, Rank 1), followed by power (17.0035, Rank 2), while endurance had the lowest centrality (11.3146, Rank 5). Regarding affected degree, speed (9.079, Rank 1) and power (9.0638, Rank 2) ranked the highest, whereas endurance had the lowest affected degree (5.9441, Rank 5).

Table 11 Adjacency Matrix A

	Speed	Power	Endurance	Agility	Coordination
Speed	0	0	0	0	0
Power	0	0	0	0	0
Endurance	0	0	0	0	0
Agility	1	1	0	0	0
Coordination	1	1	0	0	0

The adjacency matrix A is derived from the total (comprehensive) influence matrix T using equation 15, where $\lambda=1.932$, as shown in Table 11.

Using equation 16 to derive the reachability matrix L, as shown in Table 12.

Table 12 Reachability Matrix L

	Speed	Power	Endurance	Agility	Coordination
Speed	1	0	0	0	0
Power	0	1	0	0	0
Endurance	0	0	1	0	0
Agility	1	1	0	1	0
Coordination	1	1	0	0	1

Using equations 17-19 to derive the hierarchical sorting of influencing factors, as shown in Table 13.

Table 13 Hierarchical Sorting Table of Influencing Factors

Influencing factors	Reachable set	Antecedent set	Common set
Speed	1	1、4、5	1
Power	2	2、4、5	2
Endurance	3	3	3
Agility	1、2、4	4	4
Coordination	1、2、5	5	5

In the above table, 1-5 represent speed, power, endurance, agility, and coordination respectively.

Construct the ISM Hierarchical Topology Map, as shown in Figure 3.

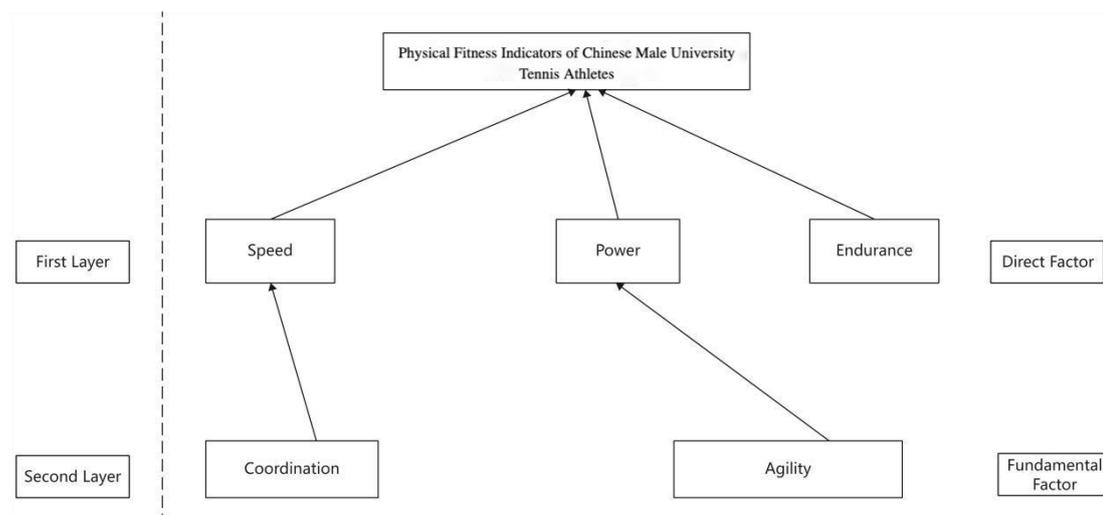


Figure 3 ISM hierarchical topology map

Figure 3 illustrates a two-layer structural model of sport-specific physical fitness indicators for Chinese male university tennis athletes. The first layer comprises speed, power, and endurance, which function as result factors. The second layer includes coordination and agility, both identified as causal factors. Coordination primarily influences speed, while agility exerts a direct effect on power. Endurance appears relatively independent, exhibiting minimal causal relationships with other indicators.

Discussion

The current study systematically elucidated the causal hierarchy of sport-specific physical fitness in Chinese male university tennis athletes via a Delphi–fuzzy DEMATEL–ISM approach. Through three rounds of Delphi expert survey, we established a structured evaluation framework comprising 5 primary and 15 secondary indicators. Fuzzy DEMATEL–ISM was subsequently used to reveal the multi-layered causal structure within the primary indicators. This approach has moved beyond conventional methods, providing reliable guidance for training priority optimization.

The structural analysis reveals coordination (cause degree = 1.94) and agility (cause degree = 0.87) as fundamental drivers of the physical fitness system in Chinese male university tennis athletes. Their high influencing degrees (8.844 and 8.8856, respectively) confirm their dominant role in propagating dynamic changes through kinetic chain integration and neuromuscular control. This aligns with tennis-specific demands characterized by multi-directional reactivity and adaptive motor responses (Predoiu, 2015; Pereira et al., 2018). In contrast, speed and power emerge as pivotal outcome hubs with the highest centrality values (17.05 and 17.00), yet negative cause degrees (-1.11 and -1.12). This indicates their dependence on more driving factors (e.g., coordination-agility inputs) rather than acting as primary initiators of systemic change. Endurance exhibits the lowest centrality (11.31) and cause degree (-0.57), functioning as a relatively independent outcome factor (ISM Layer 1). While

essential for match sustainability (Fernandez-Fernandez et al., 2009; Davey et al., 2002), its relative isolation within the network suggests that targeted endurance training may be optimized independently of complex neuromuscular coordination drills—though integrated programming remains preferable for competition-specific adaptations.

These findings are in accordance with existing researches. Specifically, the results demonstrate that improving coordination indirectly enhances speed performance (Whitacre et al., 2024; Larson et al., 2024; Van Waerbeke et al., 2023), while improving agility indirectly enhances power performance (Hermassi et al., 2018; Sekulic et al., 2013; Rota et al., 2012). This supports our hypothesis that foundational driving factors exert synergistic effects through indirect pathways. In prior studies, consistent findings suggest power, speed, endurance, agility, and coordination are key tennis performance factors (Ke, 2014; Tian, 2017; Xiao et al., 2021; Xiao et al., 2022). However, they were often treated as relatively independent factors and solely analyzed using factor analysis. This study quantifies the inter influences and hierarchical dependencies among these factors. This deeper understanding provides a theoretical foundation and practical implications for designing physical training protocols for tennis athletes.

There are some methodology innovations in this study. We initially applied the Delphi–fuzzy DEMATEL–ISM framework on the evaluation of sport-specific fitness in tennis athletes. This has allowed us to overcome the limitations in static correlation analysis, to quantify the complex interdependencies within the fitness network, and to establish the first causal-hierarchical model of male tennis athletes in universities. In detail, coordination and agility were identified as foundational drivers with highest influence centrality, speed and power as dependent core hubs shaped by these foundations, and endurance as a relatively independent outcome factor. Based on these findings, agility and coordination should be given priority in training optimization. Speed and power should be enhanced consequently, and endurance should be tailored to individual tactical demands. This hierarchical insight enables precise resource allocation toward foundational components, which in turn maximize benefits. And it has offered coaches a system-optimized toolkit for designing personalized programs for strategically performance enhancement.

The study has a few limitations. First, the target group for the evaluation framework was limited to male university tennis athletes aged between 18–24. Expanded studies for female players, younger/junior athletes, senior professionals, or players from different cultural/regional training backgrounds are needed. Second, the study only reflects the current training paradigms and performance demands. Evolving tactics, equipment, or training methodologies might alter these relationships over time. Environmental factors were not explicitly considered. Third, despite the fact that subjectivity was handled through Delphi and fuzzy DEMATEL, the weighting and relationships of preliminary factors relied heavily on expert judgment. In future studies, objective performance data and biomechanical indicators could be adopted. Additionally, the study utilized traditional field-based physical tests. Integration of wearable devices and motion capture may provide more detailed data on the complex interactions between fitness components during actual tennis movements, enhancing the

model's accuracy and real-time applicability. Finally, The model identifies causal relationships based on expert judgments and structural modeling. Longitudinal intervention studies are needed to empirically test the causality implied by the model.

In future studies, the model should be validated across diverse populations including female athletes, adolescents, athletes of different nationalities, and professionals. Biomechanical data should be integrated for deeper insights. Longitudinal intervention studies are needed to testify causal pathways and refine training priorities. Future work should also explore integrating wearable sensors and AI to dynamically optimize the physical fitness hierarchical model, and investigate the interplay between technical–tactical skills and the physical fitness hierarchy.

Conclusion

Through the cross-disciplinary Delphi–fuzzy DEMATEL–ISM approach, the study establishes the first quantified causal-hierarchical model in tennis-specific physical fitness with enhanced scientific validity and operational consistency based on expert consensus. This creates an opportunity to address long-standing theoretical and practical challenges in athletic performance systems by revealing coordination and agility as foundational driving factors, while identifying the dependent nature of speed and power and relative independence of endurance. The study provides coaches with a novel paradigm and practical toolkit for designing optimal training programs that strategically prioritize foundational capacities, thereby advancing evidence-based training methodologies for university tennis athletes.

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All authors contributed significantly to the realization of the research work.

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Conflict of interest

The authors declare no conflict of interest.

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