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Multidisciplinary aspects and performance in racket sports, volume II

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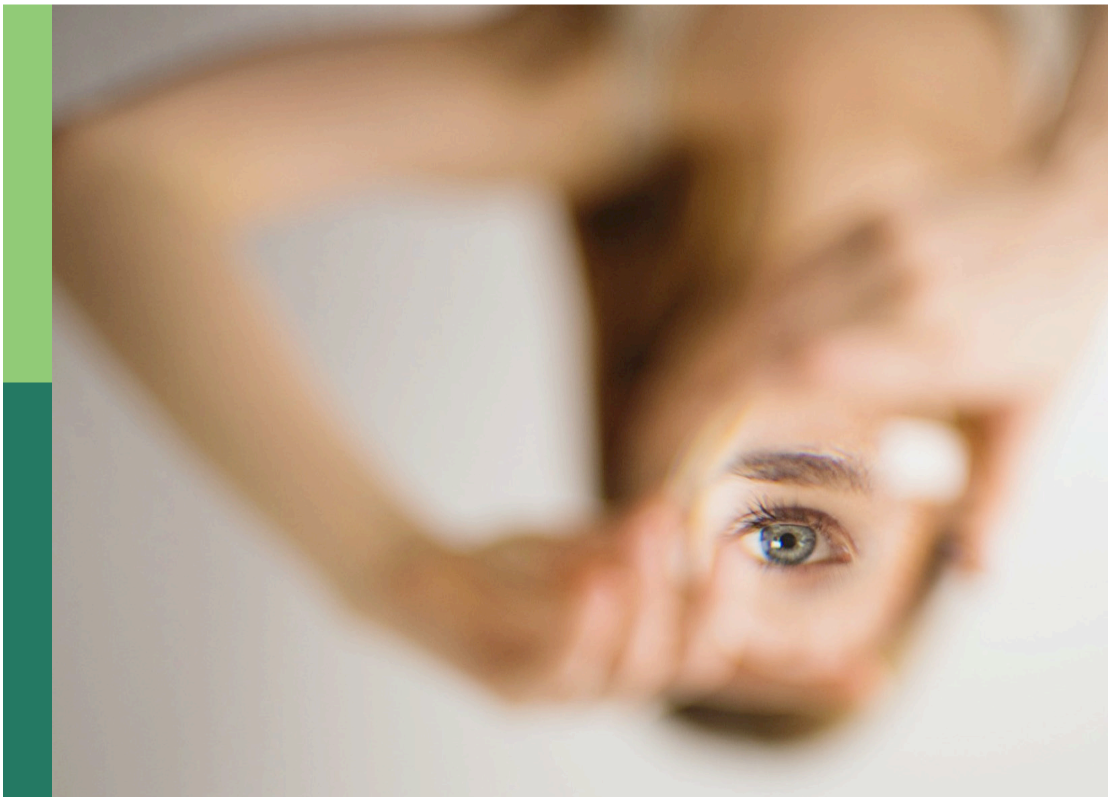

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Multidisciplinary aspects and performance in racket sports, volume II

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Editorial: Multidisciplinary aspects and performance in racket sports, volume II

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KEYWORDS

racket sports, performance, psychology, skill acquisition, training, coaching

Editorial on the Research Topic
Multidisciplinary aspects and performance in racket sports, volume II

Racket sports continue to captivate athletes, coaches, researchers, and practitioners around the world, driven by their unique combination of dynamic physical demands, technical skill, tactical decision-making, and psychological performance. Building on the contributions of prior research, this second volume of the Research Topic *"Multidisciplinary aspects and performance in racket sports, volume II"* offers new perspectives and deepens our understanding of the diverse factors that influence performance, development, and wellbeing across multiple racket disciplines.

One prominent theme in this volume is the psychological dimension of racket sports, encompassing both the enhancement of wellbeing and the management of competitive stress. Sun et al. explore the positive impact of tennis on university students, showing how participation can reduce depressive symptoms and promote prosocial behavior, with social support playing a mediating role. In the competitive sphere, Conde-Ripoll et al. examine pre- and post-competition anxiety and self-confidence in elite male padel players, revealing links to technical and tactical performance and offering guidance for psychological preparation. Complementing this focus on performance under pressure, Mizuno and Masaki investigate the effects of left-hand contraction on tennis serve performance, suggesting a simple and practical strategy to reduce choking risk and enhance execution during high-pressure moments.

Skill acquisition and pedagogical innovation are equally central to this Research Topic. Morales-Campo et al. introduce Touchtennis as an engaging alternative for physical education, aiming to broaden participation and enhance accessibility among schoolchildren. In a related study, Ortega-Zayas et al. develop and validate a questionnaire designed to assess the quality of table tennis instruction in educational settings, offering educators a practical assessment tool. Expanding on these themes, Piquer-Piquer et al. present a scoping review on equipment modifications for novice tennis players. Their synthesis highlights how scaled equipment supports skill development, supports performance and enhances enjoyment—while also addressing biomechanical and coaching considerations.

Technical skill development and anticipation training are further examined as key elements for success in racket sports. Triolet and Benguigui investigate the efficacy of opponent-specific, implicit anticipation training in expert tennis players, demonstrating improvements in predictive accuracy. At the developmental level, Diler et al. propose a structured tool to assess groundstroke technique in preadolescent players, providing coaches with objective criteria to guide early technical training.

Physical conditioning and performance assessment remain critical to optimizing athletic potential. Wang and Xu evaluate the effects of different frequencies of upper limb plyometric training on strength, power, and serve velocity in young male tennis players, offering evidence-based recommendations for training design. In a broader context, Morais et al. assess the impact of a 6-week court-based training program on the International Tennis Number (ITN) and various physical fitness indicators in youth players, identifying key predictors of the ITN relevant for talent identification and progression. Additionally, Winata et al. present a systematic review of match-play data in badminton, highlighting specific demands across the five competitive categories—insights that are crucial for guiding training and evaluation approaches.

In summary, the contributions in *"Multidisciplinary aspects and performance in racket sports, volume II"* reflect the growing complexity and breadth of this field. Spanning psychology, pedagogy, biomechanics, motor learning, and physical conditioning, these studies offer relevant insights and tools for researchers, practitioners, educators, and coaches. We are confident that this Research Topic will not only inform current practices but also inspire continued exploration and innovation in the dynamic world of racket sports.

Author contributions

RM-G: Writing – review & editing, Writing – original draft. BS-A: Writing – review & editing, Writing – original draft. GV: Writing – review & editing, Writing – original draft. JR-L: Writing – review & editing, Writing – original draft.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Tool to assess the groundstroke technique of preadolescent tennis players

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Objective: In this study, we develop a tool that can be used by tennis coaches to evaluate the groundstroke (forehand and backhand) technique of preadolescent tennis players.

Methods: The participants of the study were 60 children (30 males and 30 females) aged 10–12 years, with at least two years of training in tennis. The Groundstroke Correction Checklist (GCC) was translated into Turkish by using a blind procedure. The Turkish translation was then evaluated by 15 coaches of the Turkish Tennis Federation who had at least a level-3 coaching license and more than five years of coaching experience. The technical components related to technique in the checklist were labeled as unimportant, important, and very important. Following this, the GCC was converted into a Groundstroke Technique Assessment Test Tool (GTATT) by a selection committee consisting of three experts, and its reliability and validity were assessed by using it in the field. Spearman's correlation was used to analyze the correlation (test-*r* test) between the technical evaluation scores assigned to the players by the tennis coaches based on the GTATT in the first and second weeks. Intra- and inter-rater reliability was used to analyze the overall scores of technical evaluations in the first and second weeks to assess the reliability of the scale used. We determined each player's number of years of playing experience (TPY), technical evaluation (TE), international tennis-level test score (ITN), I-cord classification order (ICCO), and the number of games won (GW) in a tournament organized among themselves and evaluated the correlations among these parameters by using Spearman's correlation analysis.

Conclusion: A statistically high and significant correlation was observed between the technical evaluations of the players' forehand and backhand groundstrokes by the tennis coaches by using the GTATT in the first and second weeks ($r > .90$, $p < .01$). The analysis of the intra- and inter-rater reliability of the GTATT yielded excellent agreement between the technical observations of the three coaches of the players' forehand and backhand strokes in the first and second weeks.

KEYWORDS
tennis, technique, groundstroke, performance assessment, test reliability

1 Introduction

It is believed that technical evaluation based on objective criteria and tools of measurement can enable players to improve the quality of their strokes in training, and the improved technique has an indirect positive effect on their performance in competitions. Such an evaluation also makes it possible to measure and assess the technical development of players.

Tennis is a globally popular sport that is played by millions of people at different levels of skill (1). As in many other sports, the interactions among the technical, anthropometric, physiological, tactical, and psychological characteristics tennis players have an important influence on their performance and success (2).

Tennis has a competitive identity. The technical and tactical capacity of the player are among the most important factors influencing the outcome of matches. The totality of technical and tactical actions, together with the competitive ability of the players, influence the result (3). Forehand and backhand strokes are the most common shots played in tennis competitions (4), and are the two most important strokes after the service stroke (5).

The relevant literature has shown that it is possible to attain the desired movement patterns and ensure skill development in sport by ignoring the influence of developments in motor learning based on changes in the coordination of movement on the resulting performance and/or subjective evaluations of the patterns of movement (6). However, it is important for coaches to easily conduct accurate technical evaluations to create the desired movement patterns.

A combination of technical and tactical skills is more likely than other factors to help distinguish between players with different levels of performance (7). In tennis, a player can enhance their tactical diversity with a technique that is simple, effective, and economical by using the appropriate biomechanical principles. In terms of biomechanics, the inefficient movements and positioning of various joints can adversely affect the speed, direction, and rotation of the ball, and may also increase the risk of injury to the player (8). Technique in tennis is generally characterized by the quality of the stroke. The critical elements that determine the quality of the stroke are the ball speed, and the accuracy and rate of success of the stroke (9). The constant interplay between technical and tactical skills is critical to earning each point in a match. We can consider technique as a functional tool for achieving a tactical goal. For example, a player who chooses to move their opponent out of the court as a tactical goal needs to hit the ball with the appropriate speed, precision, and angle. Moreover, a player playing against an opponent who is aggressively hitting deep balls toward the back line can gain the time they need to recover by throwing high and deep balls. In such cases, the techniques that the player uses in their tactical decisions come to the fore (10).

As in other sports, technique is the basis for player development in tennis, and all the coach's efforts will be futile if the player does not internalize the correct technique. Incorrect neural and movement-related patterns are stored in the brain if the technical training procedures are incorrectly applied, and severely limit the player's subsequent development of their desired optimum speed. For instance, incorrect patterns can affect the player's batting speed and accuracy (11).

Technical training should be an important part of the training cycle for junior players (6–12 years old), which in turn should be built on sound foundations when they are 5–10 years old. As players get older, the technical aspect of their training diminishes, such that more minor adjustments and interventions are required. When they are 12–16 years old, their technique should be improved through deliberate practice. In other words, their technique should be reinforced through conscious practice (1).

A tool with proven reliability and validity for the technical evaluation of the forehand and backhand, which are the most frequently used groundstrokes in a tennis match, has not been proposed in the literature to the best of our knowledge. It is thought that technical evaluation based on objective criteria and tools of measurement can enable players to enhance the quality of their strokes in training, and this has an indirect positive effect on their performance in competition. It also offers the possibility of measuring and evaluating the technical development of players. Furthermore, using common criteria to assess the player's movements while hitting the ball can transform such a technical evaluation from being grounded in subjective criteria to being based on more objective features. In light of this, we develop a test tool in this study that can be used by tennis coaches to evaluate the groundstroke (forehand and backhand) technique of players as this constitutes the basic technical skill in the game. We think that our tool can enable tennis coaches to easily, quickly, and accurately evaluate the groundstroke technique of player on the court without requiring additional equipment or materials.

2 Materials and methods

2.1 Participants

The criteria for the inclusion of the subjects in our experiments were a minimum of two years of experience playing tennis, active participation in tennis training, absence of health problems, and no medication use. Participation in the study was voluntary.

Sixty tennis players (30 males and 30 females) (age 11.47 ± 0.89 years; body height 143.97 ± 8.68 cm; weight 40.85 ± 6.49 kg) with at least two years of tennis training and an average experience of 3.50 ± 0.82 years voluntarily participated in the study. All participants were training four to six times a week at the time of the experiment. The test–retest reliability of the Groundstroke Technique Assessment Test Tool was assessed on these 60 tennis players. We also recruited 15 coaches who met the following criteria: at least a level-3 coaching certificate from the Turkish Tennis Federation (TTF), professional experience of 18.66 ± 3.47 years, with an average age of 44.73 ± 6.15 years, record of service as a national team coach.

2.2 Procedures

All parents/guardians were informed of the experimental procedures as well as the associated risks prior to providing their written consent. The study was approved by the Akdeniz University Clinical Research Ethics Committee (No. 70904504/276). All procedures were performed in accordance with the Declaration of Helsinki (1964).

The Groundstroke Technique Assessment Test Tool (GTATT) was developed in the following three phase:

Phase 1: The International Tennis Federation's (ITF) groundstroke correction checklist (GCC) (10) was translated into Turkish by two tennis coaches who had an advanced knowledge of English. The final Turkish version of the tool was subsequently translated back into English by a native English speaker. The translation involved a blind procedure. The translated checklist (GC) was then compared with the original version, and the two were determined to have very similar meanings.

Phase 2: The translated version of the GCC was sent to the coaches via email. They were asked to mark the parameters on the observation evaluation form that they considered the most important for the groundstrokes of 10–12-year-old players by using the following options: unimportant, important, and very important.

Phase 3: According to the evaluations provided by the 15 coaches, the items marked as very important and important among the parameters of the forehand and backhand strokes were examined by a selection committee comprising three experts.

The most commonly marked items by the coaches and those developed by the selection committee were identified according to the results of the review and were used to create the GTATT (Table 1).

Before using the GTATT, which consisted of 12 stages, the coaches read the criteria for technical evaluation (Table 2) and then took their places on the field.

Previous studies have used a five-point scale to assess the technique of children in tennis (12). The five-point Likert scale is a widely used tool in the social sciences to capture attitudes, opinions, and perceptions. It contains a series of statements or questions that respondents are asked to rate on a five-point scale ranging from "totally agree" to "strongly disagree.

Warming up:

The players warmed up for 10 min in the traditional manner used during training, consisting of 5 min of low-paced running and 5 min of dynamic stretching. Then, two players warmed up by rallying, first from the service line and then from the base line, within the 5-min warm-up period implemented by the TTF for official matches.

TABLE 1 Grading scale for the groundstroke technique assessment test tool.

Grading scale for the groundstroke technique assessment test tool			
Player's given name and surname:			
Age:			
Trainer's given name and surname:			
Date:			
Forehand:	Backhand:	Rating	
Evaluation topic	Weak	Middle	Good
(1) Racket grip			
(2) Ready position			
(3) Split step			
(4) Shoulder rotation			
(5) Footwork			
(6) Racket reversal			
(7) Bending the racket head and wrist under the ball			
(8) Ball meeting point			
(9) Racket speed			
(10) Rhythm and path of the racket			
(11) Balance during the stroke			
(12) Footwork and recovery			

Technical evaluation protocol:

The GTATT was applied on the tennis court for the 10–12-year-old players by three coaches, each with at least 10 years of professional experience as a level-3 trainer. The technical evaluation was conducted on a hard-floor indoor tennis court with the regular dimensions as determined by the ITF.

The balls were fed to the players from the opposite side of the court by using the SAM P1 ball-throwing machine. ITF-approved tennis balls, fresh from a pressurized box, were used for the evaluation. The duration between forehand and backhand strokes was set to 2 s, the speed to two units, and the amount of spin in the forward direction to four units for the ball thrower. The balls were thrown at a moderate velocity (40 $km.h^{-1}$).

Previous studies have reported that the rally pace (mean duration of flight of the ball between opponents) in tennis matches varies depending on the playing surface. The historical rally pace is the highest in the Australian Open (1.22 s), significantly higher than that in the French Open (1.35 s). The rally pace in Wimbledon is 1.27 s for the men's tournament (13). We set the rally pace to 2 s in order to avoiding affecting the players' technique as they hit the ball.

The players started hitting the balls thrown by the ball machine from behind the base line on the court to a designated 90 cm^2 area. Each player was then asked to hit the balls toward a marked 3 m area in front of the baseline. This instruction was given only to motivate the players to focus on a specific area, rather than resort to random hits. Each player played forehand and backhand strokes in the same manner toward the marked area until all three coaches had filled out the GTATT and declared that they had completed their observations. The evaluation then ended. The coaches observed the players from positions of their own choosing so that they could not see one another's evaluations. We ensured that there was no contact between the coaches during the evaluation. The speed and accuracy with which the balls were hit were not considered in the GTATT.

Implementation of international tennis level (ITN) test:

The international tennis number (ITN) manual on-court assessment test was introduced by the ITF to rate the skill of players. The test involves measurements of the accuracy and depth of the groundstroke, service accuracy, depth of the volley, and the mobility of the player. We used only the depth–power (groundstroke depth assessment) and accuracy–power (groundstroke precision assessment) sections of the ITN test in this study (14).

2.3 Test of groundstroke depth

The manner in which this test was performed is shown in Figure 1, where "*P*" represents the player and "*F*" the feeder. To evaluate the test, 10 top feeds were made toward the area marked with "*x x*" in the figure in front of the breakthrough balls of *F* (*P*). The player was required to hit five balls using the

TABLE 2 Criteria used for technical evaluation.

<table>
<tr><th></th><th>Forehand groundstroke</th><th>Backhand groundstroke</th></tr>
<tr><td>1</td><td>Eastern forehand
Semi-western
Western</td><td>Single hand (Eastern Backhand, Continental)
Double hand
(Right-hand continental; left-hand eastern forehand)
(Right-hand eastern forehand; left-hand eastern forehand)</td></tr>
<tr><td>2</td><td colspan="2">1-The center of gravity of the body is at the level of and inside the soles of the feet.
2-Head and shoulders are aligned so that they are straight.
3-The upper body bends slightly forward at the waist. The knees are energized by being slightly bent.
4-Feet spread out to shoulder level. Body weight is kept on the toes, staying in front. The center of gravity is lower and more anterior than normal.</td></tr>
<tr><td>3</td><td colspan="2">As the opponent hits the ball, a forward rise is attained by bending the knee joints and lifting the ankles off the ground.</td></tr>
<tr><td>4</td><td colspan="2">1-The unit spin can start as soon as the turn preparation jump (split step) is completed.
2-An outward lunge is made by using the foot closest to the ball. This move also initiates the backward racket movement through the rotation of the hips and shoulders.
3-The racket arm is used to push the body backward in a unit spin.
4-It is important not to move the head and shoulders forward or step backward with the front foot.</td></tr>
<tr><td>5</td><td colspan="2">1-The unit spin can start immediately after a split step with two feet.
2-Stepping out is performed by using the foot closest to the ball. The direction of this fast, lateral movement and step should be diagonal and forward with respect to the incoming ball.
3-Again, this movement initiates the backward movement of the racket through the rotation of the hips and shoulders.
4-The racket arm is used to push the back during the unit spin. Do not move forward with the head and shoulders or step back with the front foot. The player is as fast as their speed in the first step.</td></tr>
<tr><td>6</td><td>Eastern Forehand
1-The racket handle is positioned under the head of the racket, and its face is positioned more freely upward. As the racket is moved backward in a circle, the racket head also moves backward. The body weight is transferred to the back foot.
Semi-Western Forehand
1-In general, preparation starts with the elbow.
2-As the opponent hits the ball, rotate around the front foot and continue by raising the elbow (backward movement), rotating the shoulders in a coordinated manner.
3-The left hand can be used to pull the racket back and contribute to shoulder rotation.</td><td>Double-hand backhand
1-Shoulder rotations occur automatically when the racket is pulled backward with both hands.
2-The hips and upper body turn back in the phase before the front step is taken. The player transfers linear momentum with the step forward.
3-The racket is lifted behind the body. The rotation of the hips begins.
One-hand backhand
1-The player rotates from the ready position, as the hand and racket are in one place as the ball approaches.
2-Either of two methods can be used when approaching the end of the racket retrieval phase. First, the racket is lifted to shoulder height, rotated, the hand is taken back, and the position is assumed. Second, the shoulder is rotated (in a half-U shape) and, immediately afterward, the hand is raised and the back swing curve is performed.</td></tr>
<tr><td>7</td><td colspan="2">According to the height of the incoming ball, the racket and the wrist are lowered below its level before it is hit, and the movement is assisted by bending the knees.</td></tr>
<tr><td>8</td><td>The racket is expected to meet the ball in front of and to the side of the body. The contact point with Western grips is higher and closer to the body than with Eastern and semi-Western grips.</td><td>The racket is expected to meet the ball in front of and to the side of the body. The contact point with Western grips is higher and closer to the body than with Eastern and semi-Western grips. During the stroke, the ball is struck in front of the front foot.</td></tr>
<tr><td>9</td><td colspan="2">The racket speed is as high as possible at the point of contact, and is adjusted for the purpose of the stroke.</td></tr>
<tr><td>10</td><td colspan="2">Once the acceleration phase of the racket has begun, it is necessary to move it along the right path. The path of the racket immediately before and after hitting the ball is a straight line.</td></tr>
<tr><td>11</td><td colspan="2">Good balance during the stroke requires that the head be upright and still, and the head and upper body move. It is also helpful to keep the arm at a comfortable distance from the body during the forward swing to maintain control over the head of the racket when hitting the ball, and to hit the ball without leaving the line of flight.</td></tr>
<tr><td>12</td><td colspan="2">The body weight is shifted forward, and the arm is moved forward toward the target in a relaxed state. During the pursuit, there is a gradual deceleration of the body parts. At the same time, if the stroke has a sufficiently high linear acceleration, the back leg moves to prepare the movement for the next stroke by assuming a position with the foot in front.</td></tr>
</table>

forehand stroke and the other five by using the backhand stroke. The player received zero points when a ball's first bounce lands anywhere outside the normal singles playing area.

(1) The player was awarded one to four points depending on the first region in which the ball fell.
(2) According to the region in which the ball fell, the player was awarded zero points if the ball fell in their own half of the tennis court.

Power Area = 1 Bonus Point—When a ball lands anywhere within the singles court area and the second bounce lands between the baseline and Bonus line, 1 Bonus point is awarded.

Power Area = Double Points—When a ball lands anywhere within the singles court area and the second bounce lands beyond the Bonus line, double points are awarded.

Each player could earn a maximum of 90 points in this part of the test (Figure 1).

2.4 Test of groundstroke accuracy

The ball machine F alternately threw six balls, to either side of the player for them to play the forehand and backhand strokes, respectively, to the areas denoted by "*x*" in Figure 2. The player throws six more balls alternately, one in front of the hand and one in the back of the hand, towards the places indicated by the letters "*x x*" in front of him. The player throws these balls diagonally.

The player received zero points if the ball went out of bounds or was caught in the net and was otherwise awarded one to three points depending on where the ball first landed.

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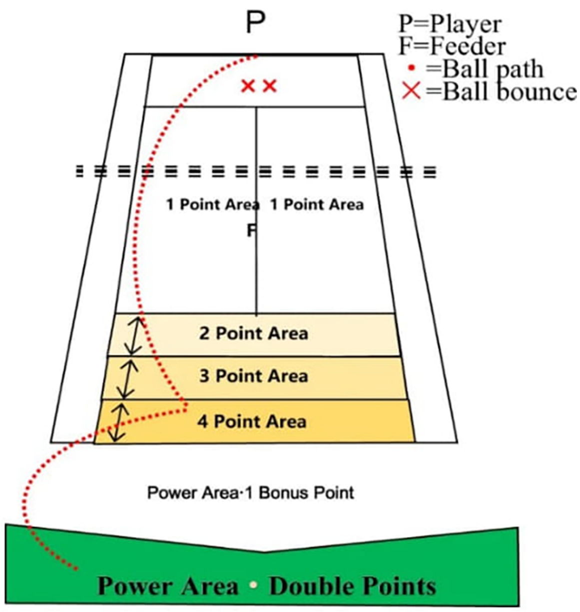

FIGURE 1
Test of groundstroke depth. (Available online at: https://tenis.i-kort.ttf.org.tr/home.seam)

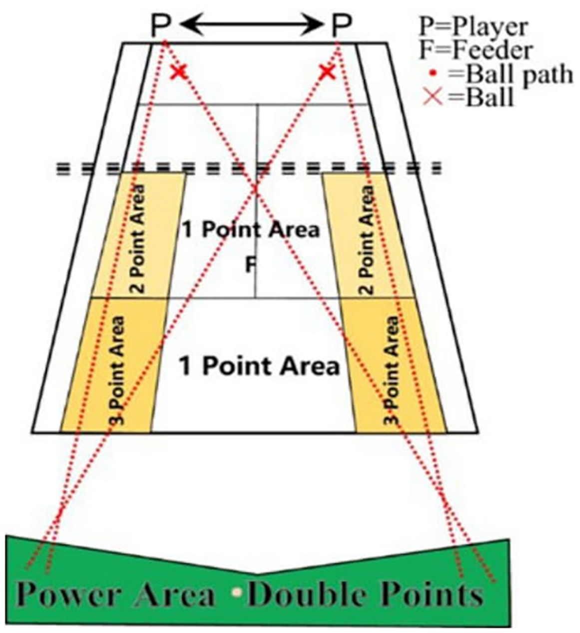

FIGURE 2
Test of groundstroke accuracy. (Available online at: https://tenis.i-kort.ttf.org.tr/home.seam)

The player was awarded zero points if the ball landed in their half of the court.

Power Area = 1 Bonus Point—When a ball lands anywhere within the singles court area and the second bounce lands between the Baseline and Bonus line, 1 bonus point is awarded.

Power Area = Double Points—When a ball lands anywhere within the singles court area and the second bounce lands beyond the Bonus line, double points are awarded. Each player could earn a maximum of 84 points in this part of the experiment (Figure 2).

I-cord classification order (ICCO) score:

The players are ranked in this age category according to their performance in national and international tournaments in the preceding 52 weeks. We obtained the general classification from the TTF's official website (15).

Games won (GW):

To determine their competitive performance, we asked 30 players in the 10-, 11-, and 12-year age categories to play in groups of five in accordance with the instructions of the TTF for competitive tournaments for two short (four-game) sets. Male and female players competed separately. In case each player won a set each, a 10-point match was played as a tiebreaker. The groups of five players each were determined by draw for players in each age category. New balls were used for these matches. At the end of the competition, the total number of games won by each player in all their matches was calculated.

2.5 Statistical analyses

The number of players required to obtain a significant effect was calculated by using Gpower 3.1.9.4 (16). The appropriate sample size was determined to be 67 for a 5% margin of error and an 80% confidence interval, with the correlation coefficient $r = 0.3$. As mentioned above, our experiment involved 60 players.

To determine the homogeneity of the data obtained in this study, we used the Kolmogorov–Smirnov test, which is a test of the normal distribution (because the number of subjects was greater than 50). All data were analyzed by using the SPSS 25 package. Descriptive statistical values, such as the arithmetic mean and standard deviation ($\bar{x} \pm SD$), were calculated for all variables. A margin of error of $\alpha = .05$ was used in all statistical procedures. Data on the descriptive characteristics of the participants were presented as the arithmetic mean ± standard deviation (Mean ± SS).

To assess test-retest reliability, Spearman's correlation or intraclass correlation coefficient (ICC) was calculated (17, 18). Spearman's correlation coefficient was applied for the correlation analysis (test–retest) between the technical evaluation scores of the tennis coaches in the study in the first and second weeks. Differing from Spearman's correlation coefficient interpretation, intra- and inter-rater reliability was performed. Results were analyzed ICC 2-way mixed effects model to determine intra- and inter- rater reliability of the Groundstroke Technique Assessment Test Tool. ICC values of less than 0.4, between 0.4 and 0.59, between 0.60 and 0.74, and above 0.74 are indicator of poor, fair, good, and excellent agreement respectively.

The relations between the following parameters, obtained from the male and female tennis players, were determined by using Spearman's correlation analysis: the player's years of playing (TPY), technical evaluation (TE), international tennis-level test score (ITN), I-cord classification order (ICCO), and number of games won (GW). The values of r were evaluated as follows in terms of correlation: $r < 0.50$ = weak, $r > 0.50$ = moderate, $r > 0.75$ = good, and $r > 0.90$ = high (19).

3 Results

Table 3 shows test points of the players participating in the study.

Table 4 shows that according to Spearman's rho (r) correlation analysis, a statistically positive, high, and significant correlation was found between the first- and second-week technical observations of the three observer coaches for the forehand and backhand strokes.

Table 5 shows that the analysis of the intra- and inter-rater reliability of the GTATT yielded excellent agreement between the technical observations of the three coaches of the players' forehand and backhand strokes in the first and second weeks.

According to Table 6, a positive and moderately significant correlation was observed between GDA and TE ($^{**}p < .001$, $r > .50$). Further, there was a moderately significant positive correlation between GPA and TE ($^{**}p < .001$, $r > .50$), and a positive and significant correlation between ITN and TE ($^{**}p < .001$, $r > .75$). There was a negative and significant correlation between ICCO and TE ($^{**}p < .01$, $r > .75$). A positive and moderately significant correlation was identified between GW and TE ($^{**}p < .001$, $r > .50$).

Table 7 shows a positive and moderately significant correlation between GDA and TE ($^{**}p < .001$, $r > .50$), and a weakly significant positive correlation between GPA and TE ($^{*}p < .05$, $r < .50$). A negative and moderately significant correlation was observed between ITN and TE ($^{**}p < .001$, $r > .50$). A negative and moderately significant relation was identified between ICCO and TE ($^{**}p < .01$, $r > .50$). Moreover, a positive and moderately significant relation was found between GW and TE ($^{**}p < .01$, $r > .50$).

4 Discussion

We have developed a test tool that can be used by tennis coaches to evaluate the groundstroke (forehand and backhand) technique of preadolescent tennis players. It is difficult to analyze the technique of

TABLE 3 Test points of participants.

Variables	Min.	Max.	Mean (SD)
TPY (years)	2.00	6.00	3.50 (0.77)
TE (points)	23.33	36.00	31.09 (3.09)
GDA (points)	24.00	74.00	43.65 (10.62)
GPA (points)	26.00	69.00	51.18 (10.58)
ITN (points)	31.00	131.00	94.35 (17.70)
ICCO (points)	190.00	2,364.00	985.73 (528.36)
GW (points)	8.00	33.00	22.20 (7.97)

TPY, years of playing tennis; TE, technical evaluation; GDA, groundstroke depth assessment; GPA, groundstroke precision assessment; ITN, international tennis-level test score; ICCO, I-cord classification order; GW, games won.

TABLE 4 Spearman's correlation analysis of observer coaches' ($n = 60$) technical observation of players' ground strokes in the first and second weeks.

Variable rho (p)	FH1W1C	FH2W1C	BH1W1C	BH2W1C	FH1W2C	FH2W2C	BH1W2C	BH2W2C	FH1W3C	FH2W3C	BH1W3C
FH2W1C	.94** (.001)**	–									
BH1W1C	.94** (.001)**	.96** (.001)**	–								
BH2W1C	.92** (.001)**	.96** (.001)**	.97** (.001)**	–							
FH1W2C	.91** (.001)**	.95** (.001)**	.95** (.001)**	.95** (.001)**	–						
FH2W2C	.85** (.001)**	.91** (.001)**	.88** (.001)**	.88** (.001)**	.90** (.001)**	–					
BH1W2C	.90** (.001)**	.92** (.001)**	.94** (.001)**	.91** (.001)**	.92** (.001)**	.87** (.001)**	–				
BH2W2C	.88** (.001)**	.88** (.001)**	.91** (.001)**	.90** (.001)**	.91** (.001)**	.83** (.001)**	.95** (.001)**	–			
FH1W3C	.88** (.001)**	.90** (.001)**	.90** (.001)**	.90** (.001)**	.90** (.001)**	.82** (.001)**	.90** (.001)**	.90** (.001)**	–		
FH2W3C	.83** (.001)**	.90** (.001)**	.90** (.001)**	.90** (.001)**	.90** (.001)**	.84** (.001)**	.90** (.001)**	.90** (.001)**	.97** (.001)**	–	
BH1W3C	.88** (.00)**	.91** (.001)**	.91** (.001)**	.90** (.001)**	.92** (.001)**	.83** (.001)**	.92** (.001)**	.90** (.001)**	.94** (.001)**	.94** (.001)**	–
BH2W3C	.90** (.001)**	.92** (.001)**	.94** (.001)**	.92** (.00)**	.91** (.001)**	.83** (.001)**	.93** (.001)**	.91** (.001)**	.93** (.001)**	.94** (.001)**	.97** (.001)**

FH, forehand; BH, backhand; 1W, first week; 2W, second week; 3W, third week; 1C, first coach; 2C, second coach; 3C, third coach.
** Correlation is significant at the 0.01 level.

TABLE 5 Intra- and inter-rater reliability of the technical observation tool according to scores.

Intra-rater reliability	ICC	95% CI
FH1W1C- FH2W1C	0.98	0.97–0.99
BH1W1C- BH2W1C	0.99	0.99–0.99
FH1W2C- FH2W2C	0.99	0.98–0.99
BH1W2C- BH2W2C	0.99	0.98–0.99
FH1W3C- FH2W3C	0.99	0.98–0.99
BH1W3C- BH2W3C	0.99	0.98–0.99
Inter-rater reliability		
FH 1W1-2-3C	0.97	0.95–0.98
FH 2W1-2-3C	0.97	0.96–0.98
BH 1W1-2-3C	0.98	0.97–0.99
BH 2W1-2-3C	0.98	0.97–0.99

FH, forehand; BH, backhand; 1W, first week; 2W, second week; 3W, third week; 1C, first coach; 2C, second coach; 3C, third coach; ICC, intra-class correlation coefficient (interpretation: <0.40 poor; 0.40–0.59 fair; 0.60–0.74 good; >0.74 excellent). CI, confidence interval.

TABLE 6 Results of the analysis of correlations between the variables of male athletes.

Variables	TPY	GDA	GPA	ITN	ICCO	GW
GDA (points)	.44	–				
	(.01)**	–				
GPA (points)	.29	.53	–			
	(.12)	(.001)**	–			
ITN (points)	.43	.87	.87	–		
	(.01)**	(.001)**	(.001)**	–		
ICCO (points)	-.26	-.70	-.72	-.80	–	
	(.16)	(.001)**	(.001)**	(.001)**	–	
GW (points)	.44	0.80	0.55	.77	-.57	–
	(.09)	(.001)**	(.03)*	(.001)**	(.02)*	–
TE (points)	.29	.69	.61	.75	-.86	.68
	(.11)	(.001)**	(.001)**	(.001)**	(.001)**	(.001)**

*$p < .05$.
**$p < .01$.
TPY: Years of playing. TE: Technical evaluation. GDA: Groundstroke depth assessment. GPA: Groundstroke precision assessment. ITN: International tennis-level test score. ICCO: I-cord classification order. GW: Games won.

TABLE 7 Results of the analysis of correlations between the variables of female athletes.

Variables	TPY	GDA	GPA	ITN	ICCO	GW
GDA (points)	.15	–				
	(.40)	–				
GPA (points)	.25	.53	–			
	(.17)	(.78)	–			
ITN (points)	.30	.71	.66	–		
	(.10)	(.001)**	(.001)**	–		
ICCO (points)	-.61	-.51	-.52	-.70	–	
	(.001)**	(.001)**	(.001)**	(.001)**	–	
GW (points)	.35	.47	.89	.30	-.59	–
	(.09)	(.001)**	(.03)*	(.27)	(.02)*	–
TE (points)	.45	.64	.36	.70	-.72	.70
	(.01)	(.001)**	(.04)*	(.001)**	(.001)**	(.001)**

*$p < .05$.
**$p < .01$.

players at forehand and backhand strokes, which are the most commonly used shots in tennis, without video recordings, especially in a competitive environment. The players' stroke technique during a match is influenced by the opponent's choice of stroke, the speed of arrival of the ball, its direction, height, the type of tactical application, and other factors. For example, a player who normally steps forward and turns to the side to play a stroke may, during a match or training, hit a forehand stroke across without executing all parts of the stroke (e.g., by not taking the racket back far enough, or by not executing the post-swing action) due to a change in the speed or direction of the incoming ball. Therefore, instantaneous observations and evaluations of hits may not always yield reliable results. Considering the influence of personal style and practice in the application of technique, there will likely be limitations and difficulties in scientific studies in this area. In this study, we provided appropriate conditions to observe the pure technique of tennis players in an isolated environment, in which they were unaffected by the opponent and the relevant decision-making mechanisms. Observational processes, which are an important information-gathering tool in sport in general, retain their importance despite multiple and rapid developments in technology.

Observational methods are among the most commonly used by researchers for matching and notational analysis (20). The results of the GTATT showed that the observations of the three coaches, who had observed the players over two weeks and assessed their technique by using our tool, were significantly correlated.

We can thus conclude that the proposed GTATT is highly reliable and can be used by tennis coaches in the field. The observers who participated in our experiment were coaches with at least 10 years of professional experience in the TTF and had a level-3 training license (senior coach) for coaching 10–12-year-old children. Their professional experience undoubtedly contributed to the high and significant correlation among their observations. We also found that the values of the parameters of the male and female tennis players differed only in terms of the ICCO.

We think that the above difference was obtained because there are more players in the male division than in the female division. Šlosar et al. (12) developed a valid and reliable scale of assessment called the "Tennis Rating Score for Child Tennis Players" (TRSC) to evaluate the technique of players aged 6–12 years for three basic tennis strokes: the forehand, backhand, and service. They made video recordings of 60 players (30 frames per second) practicing these three strokes (21 forehand shots, 22 backhand shots, and 17 services). They were then evaluated on days 1 and 7 by five tennis coaches by using the TRSC. The tennis coaches developed an initial TRSC list consisting of 20 items. The final selection by 15 experts reduced the number of items to 15, to be scored on a five-point scale. While this is different from our 12-item tool developed here, we noted certain similarities between items in our list and that formulated by Šlosar et al. (preparation for the shot, acceleration of the racket, contact point, and finishing).

Myers et al. (21) used the Observational Tennis Serve Analysis (OTSA) tool in their research on 33 non-professional tennis players (18 men, 15 women and eight observer coaches). Developed by the

OTSA Women's Tennis Association in collaboration with the Kentucky Shoulder Center (Lexington, KY). It is a field-based tool that can be used to assess the mechanics of the tennis serve and offers the possibility to visually assess the mechanics of the service without requiring expensive laboratory equipment. The OTSA was evaluated by expert coaches, who examined the mechanics of the serve by using a video recording system. A concordance analysis between the raters was conducted one day apart. The interval between evaluations was one day (seven days in our study). The average values of kappa of the eight observers were moderate and high for all nine components of the OTSA. Their kappa values were in moderate agreement or better for eight of the nine components.

Torres-Luque et al. (20) analyzed all shots played in three matches at the 2014 Tennis Masters Cup in a study, in which they designed and validated a tool for the observational measurement of technical–tactical actions in singles tennis. Similarly to our study, the measurement tool was developed in five stages. Different expert groups were used to design and validity studies of the tool and test its validity. A total of four observers and 23 experts participated in this process. The design of the tool consisted of five phases: (a) review of the scientific literature and definitions of the variables provided by experts, (b) pilot observation study, (c) qualitative and quantitative evaluations of the tool by experts, (d) review and validation of the tool by experts (content validity), and (e) observational training and reliability assessment. In the context of the validity of the content of the tool, the value of Aiken's V was 0.94 and the reliability score was 0.81 according to the minimum values of V. The value of V was used as a criterion to determine whether a given item on the scale was statistically significant. Its value varied from zero to one, where values close to one indicated high content validity. The results showed that their designed tool provided valid and objective information on the technical–tactical movements of the players and their performance in singles tennis. Although our GTATT tool can be used to observe and evaluate players' technique in an isolated environment, the tool designed by Torres-Luque et al. can be used to assess both their technical and tactical choices by considering the entire game and can be used to evaluate the differences between winners and losers in a more holistic manner.

Studies conducted in recent years have also shown that there is a strong relationship between players' rankings and their performance in terms of playing the groundstroke. Research has shown that the accuracy of the velocity of the groundstroke significantly influences the performance of junior tennis players (22). Vergauwen et al. (23) assessed quality of the forehand groundstrokes of players in rally patterns in professional, low-, and intermediate-level tennis play while considering ball velocity– precision of ball placement (VP) and velocity–precision–success (VPS) index was calculated to reveal interactive effects. The validity and sensitivity of the ForeGround procedure in the target population were determined by verifying whether test scores reflected minor differences in tennis experience. They found that more experienced players scored significantly higher than beginner-level players in terms of the rate of success, ball velocity, and precision of ball placement as well as on the velocity–precision VP and the VPS indices. Our GTATT does not consider the speed and accuracy with which the player hits the ball. It can be used in combination with tracking and analysis software, like swingvision (which is available on cellphones), and videos. The GTATT is a useful tool when video recording is not available because it allows coaches to evaluate the quality of players' groundstrokes. Moreover, the use of tracking software that can use videos to provide feedback to players can help coaches fill out the 12 items on the GTATT.

Our study has certain limitations. We were unable to perform experiments on players aged 12–14 years, for which range of ages technical development is also very important, because we were unable to find an adequate number of participants. Moreover, we did not assess the anxiety of the subjects in our experiments before, during, and after the test to determine whether this had an effect on their stroke technique. Video recordings were not used by the observers/evaluators. In addition, we did not consider such parameters as the ball speed and the accuracy of the stroke in the GTATT. Future research in the area should use the GTATT in conjunction with tracking and analysis software, such as swing vision. Moreover, experiments should be performed on elite tennis players, with trainers with higher credentials and more experience recruited as observers. Finally, our measurement tool should be expanded to cover other strokes and forms of technique in tennis.

5 Conclusions

The GTATT developed in this study can be used by tennis coaches as a valid and reliable tool to assess the groundstroke technique of 10–12-year-old tennis players. The results of our experiments showed that improving the precision of their groundstrokes can help young tennis players improve their ranking and achieve competitive success, where this is consistent with the findings of previous studies. In addition, in this study, it was determined that there was a relationship between the technical abilities of young tennis players and their sensitivity, classification and competition success. This information can help tennis coaches plan effective training sessions for young players.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Akdeniz University Sports Sciences Ethics Committee. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin. Written informed consent was obtained from the individual(s), and minor(s)' legal guardian/next of kin, for the publication of any potentially identifiable images or data included in this article.

Author contributions

HD: Conceptualization, Data curation, Investigation, Resources, Visualization, Writing – original draft. AŞ: Conceptualization, Formal Analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. KE: Formal Analysis, Investigation, Methodology, Validation, Visualization, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Effects of left-hand contraction on tennis serve performance

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Introduction: The tennis serve is commonly executed in high-pressure scenarios, often leading to performance decline; a condition commonly referred to as choking under pressure. One suggested effective method to avert choking involves contracting the left hand. We examined the effects of left-hand contraction on tennis serve performance using a wearable grasping material (polyurethane foam) which can be incorporated into sportswear.

Materials and methods: We assigned 40 right-handed skilled tennis players to either the contraction group ($n = 20$) or the no-contraction group ($n = 20$). They were instructed to perform a second-serve task during the pre-test and pressure test. The participants in the contraction group squeezed the grasping material for 20 s before executing the task in the pressure test. We measured performance, including total scores, the number of maximum score achievements, landing positions, and kinematic indices (i.e., ball speed, racket speed, and impact height).

Results: Although neither group demonstrated deteriorated performance on the pressure test, the contraction group experienced an increased number of maximum score achievements under the pressure situation compared with the pre-test ($p = 0.021$).

Discussion: Our results suggest that when under pressure, left-hand contraction may improve performance during tennis serves.

KEYWORDS

left-hand contraction, choking under pressure, clutch, tennis serve, wearable grasping material

1 Introduction

Serving stands out as one of the paramount skills in tennis, exerting a direct impact on match results (Whiteside et al., 2013; Kovalchik and Reid, 2017). Notably, the second-serve takes center stage in tense moments, serving as a pivotal strategy to prevent double faults (Weinberg, 2005). Athletes are required to exhibit superior performance in competitive situations. However, psychological pressure—due to a competitive situation, the presence of an audience, reward/punishment contingency, and ego relevance—often deteriorates performance (Baumeister and Showers, 1986). One phenomenon associated with diminished performance is "choking under pressure" (Baumeister, 1984). Although several relaxation techniques (including autogenic training, progressive muscle relaxation, and biofeedback) have been proposed as potential solutions to choking, the acquisition of these techniques requires long-term regular practice and debriefing (e.g., Stetter and Kupper, 2002). Hence, it is vital to develop more effective and easier methods to prevent choking.

By recording electroencephalograms (EEGs), prior studies have demonstrated that experts in closed-skill sports (e.g., golf, rifle shooting, and archery) tend to inhibit neuronal activity in the left hemisphere (indexed as increased alpha power) while stabilizing activation in the right hemisphere prior to performing critical movements (Hatfield et al., 1984; Salazar et al., 1990; Crews and Landers, 1993). The left hemisphere is primarily associated with verbal analysis, whereas the right hemisphere is associated with visuospatial processing (De Renzi, 1982). Notably, verbal-analytical engagement during motor preparation is thought to be indicative of conscious processing of movement (Zhu et al., 2011). Therefore, the left hemispheric inhibition during motor preparation may suggest pre-attentive (i.e., automated) motor control, which is typical of expert performance (e.g., Haufler et al., 2000); meanwhile, the left hemispheric activation disrupts smooth movements (Zhu et al., 2011; Gallicchio et al., 2016), resulting in choking. Given that unilateral muscle contraction of the left hand can activate the right hemisphere while relatively deactivating the activity of the left hemisphere (Harmon-Jones, 2006; Hirao and Masaki, 2019), the left-hand contraction preceding a crucial movement may help to prevent choking.

Indeed, Beckmann et al. (2013) reported that repetitive left-hand contraction could prevent choking in a variety of sports-related skills, including the penalty kick of indoor soccer, the taekwondo kicks, and badminton serves. They found that the left-hand contractions immediately before a critical movement effectively prevented choking under pressure. Conversely, contractions of the right hand prior to tasks have been linked to choking (Beckmann et al., 2013). Subsequent studies have replicated these findings. Gröpel and Beckmann (2017, Study 1) successfully prevented choking during gymnastics matches (i.e., German university championships) by employing left-hand contractions. Additionally, Beckmann et al. (2021) discovered that grasping a tennis ball with the left hand maintained serve performance in competitive situations involving highly skilled tennis players.

Moreover, left-hand contractions have been shown to enhance athletic performance under pressure in various sports such as taekwondo kicking (Beckmann et al., 2013, Study 2), gymnastics (Gröpel and Beckmann, 2017, Study 2), and bowling (Mesagno et al., 2019, Study 2). These instances of improved performance under pressure are commonly referred to as "clutch" phenomena (Otten, 2009), characterized by enhanced performance when athletes perceive pressure-induced anxiety as a challenge (i.e., positive perception) rather than a threat (i.e., negative perception) (Blascovich et al., 1999; Cheng et al., 2009). These findings strengthen the effectiveness of the left-hand contraction for achieving high performance under pressure.

Psychophysiological research has provided valuable insights into how the left-hand contraction influences brain states during the preparation of movements. Deeny et al. (2003) found that highly skilled marksmen exhibited weak EEG connectivity between the left temporal region (T7) and the frontal region (Fz) during the aiming phase. Weak connectivity (i.e., desynchronization) of EEGs may indicate a reduction in the cortico-cortical communications between the left hemisphere (which is responsible for verbal-analytical processing) and the frontal region, which is involved in motor planning (Deeny et al., 2003; Gallicchio et al., 2016). These results indicate that verbal-cognitive (i.e., conscious) motor processing should be inhibited to achieve automated movement execution.

Lo et al. (2019) observed strong T7-Fz connectivity along with performance deterioration in dart throwing, suggesting an elevation in conscious processing under pressure. Hoskens et al. (2020) revealed a reduction in T7-Fz connectivity after the left-hand contraction in a golf putting task, implying that the left-hand contraction may prevent choking by suppressing verbal analysis in the left hemisphere, which involves the conscious processing of movement.

Although the abovementioned studies by Beckmann et al. used a soft ball for the left-hand contraction, they ambiguously described the ball material and grasping manners, making it difficult to conduct follow-up studies. Furthermore, it is difficult to practice ball grasping in competitive situations without interference from subsequent movements. To address this issue, Masaki (2022, mandatory report of a research grant) attempted to incorporate polyethylene foam into sportswear to accomplish left-handed grasping before performing a critical action, even in a competitive situation. Although he did not observe any obvious effect of left-handed grasping on performance scores in the first level of analysis, the kinematic data remained unanalyzed. Given that subtle decreases in performance due to pressure induction tend to manifest only in kinematic indices (Tanaka and Sekiya, 2010), kinematics should be examined in studies on choking prevention. To clarify whether wearable grasping materials can have a beneficial effect on real-game performance, we reanalyzed the kinematic data of Masaki (2022), expanding earlier results and adding new findings.

Compared to beginner-level tennis serves, those of experts are characterized by faster ball speeds, higher impact heights, and earlier peak activities of electromyograms (EMGs) in the leg extensor muscles during the serving phase (Girard et al., 2005). Intermuscular coordination that enables adequate energy transfer may indicate the efficiency of a tennis serve (Girard et al., 2005). Additionally, high spatial resolution analysis has provided precise distribution of ball landing positions, confirming that elite tennis players can serve a ball closer to a target position than recreational players (Hernández-Davó et al., 2019).

Psychological pressure may impair coordinated movements. Both decreased amplitude and speed of action have been observed under pressure conditions (e.g., golf putting, Tanaka and Sekiya, 2010; table tennis, Sekiya and Tanaka, 2019). These findings suggest that kinematic variables are vulnerable to psychological pressure. Therefore, it is important to measure kinematics to thoroughly evaluate motor impairment due to pressure (Sekiya and Tanaka, 2019). Additionally, kinematic change may result in high variability in landing positions. The heightened variability in error distribution under pressure (Ellis and Ward, 2022) can be assessed using two-dimensional coordinate analysis, a method that examines performance consistency (Hancock et al., 1995).

The aim of this study was to investigate the impact of left-hand contraction on tennis serve performance, utilizing a practical method involving grasping a material for sportswear. Kinematic variables such as ball and racket speed and impact height were measured. Our hypothesis posited that left-hand contraction would maintain serve performance, including scores and landing positions, even under pressure, despite an increase in state anxiety and potential deterioration in serve qualities. We also anticipated that the left-hand contraction would conserve appropriate kinematics (i.e., the high speed of served balls and racket movements, and high impact heights) in a pressure situation. Conversely, we expected performance deterioration under pressure in the control condition (i.e., no left-hand contraction), which would disrupt these kinematic variables.

2 Materials and methods

We report a secondary analysis of the preliminary analysis conducted by the last author. A portion of the results were published in an extremely limited and mandatory report written in Japanese to complete a research grant (Masaki, 2022). In the preliminary analysis, we only analyzed performance scores and subjective anxiety ratings.

In this study, we explored the number of successes, landing positions, and kinematics. The outcomes of the secondary analysis are worth reporting and are statistically significant.

2.1 Participants

We recruited 40 skilled tennis players (M = 20.0 yrs, SD = 1.2) from a university tennis team. All participants had more than 3 years of tennis experience, with the majority having competed in intercollegiate tournaments. Participants were randomly assigned to either the contraction group (11 males and nine females) or the no-contraction group (12 males and eight females). Each group comprised 17 intercollegiate-level and 3 regional-level players. They were right-handed, as assessed by the Edinburgh Handedness Inventory (M = +92.7, SD = 16.9; Oldfield, 1971). With a sample size powered at 0.80 to detect significance at an alpha level of 0.05, G*Power (Faul et al., 2007) determined a required sample size of 34 for a repeated measures analysis of variance (f = 0.25), corresponding to a small to medium effect size (Cohen, 1992). This study was approved from the local ethics committee (approval number: 2020–077).

2.2 Experimental task

The participants were instructed to serve a ball from a predetermined position (i.e., 1 m to the right of the center mark), targeting the wide corner of the deuce service court. We quantified serving scores based on the ball landing position, as classified by the lines drawn on the court (Figure 1). We established scoring zones across the entire service court. Following assessment by a skilled tennis player, we adjusted the scoring zones to align with difficulty levels, as proficient serves typically target the near side-line in the wide corner. The participants were told to "perform second serves as if they were in a real match, aiming for maximum accuracy to achieve the highest possible score." We presumed that the second serve would be executed under pressure because its failure would result in losing a point in real tennis competitions as a double fault (Weinberg, 2005). The tasks were performed using their own rackets. Faults received a score of 0 points. If a let occurred, an additional serve was provided, adhering to official tennis rules. Serving motions were recorded using a high-speed camera positioned 9 m away that captured the right sagittal plane. The courts were recorded at a height of 3 m.

2.3 Procedure

The participants attended a 30-min session. After receiving instructions for the experiment, they completed the serving task, which comprised 25 servers. This consisted of 5 serves in the practice session, 10 on the pre-test, and 10 on the pressure test. Before each test, we assessed state anxiety (Figure 2).

On the pre-test, participants in both groups served balls without hand contractions. On the pressure test, participants in the contraction

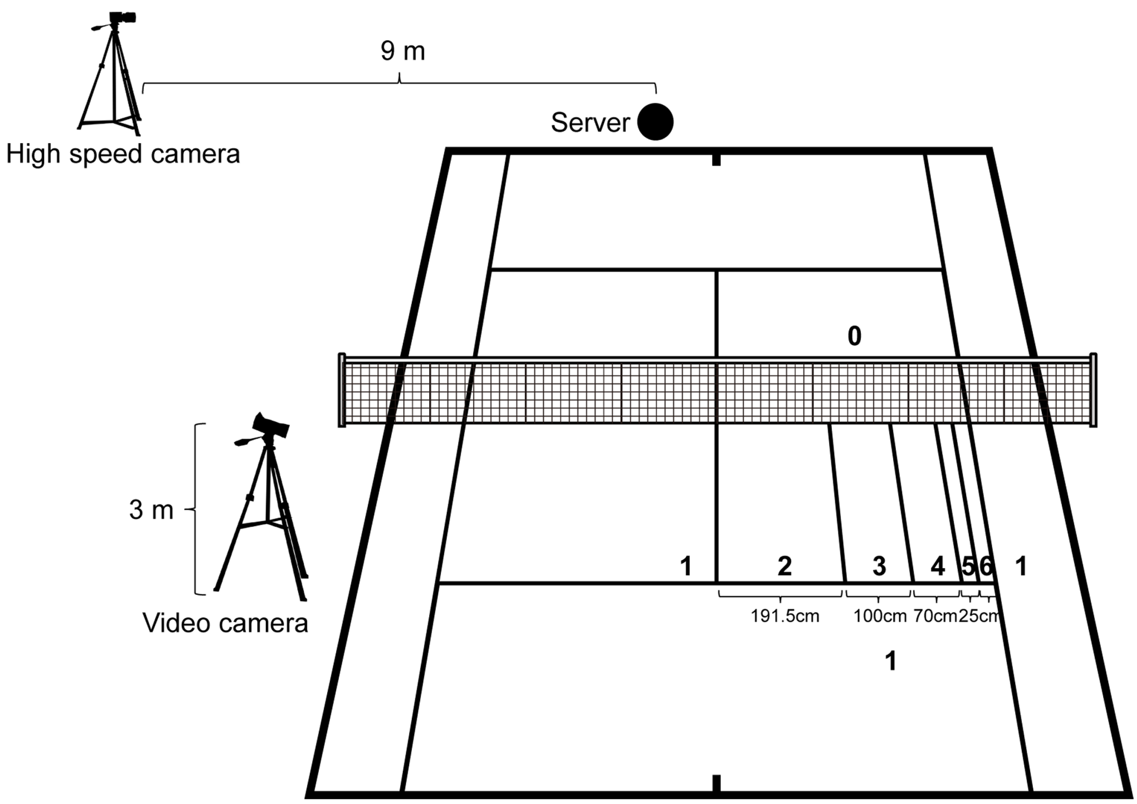

FIGURE 1
The experimental setup. The numbers denote the point in question.

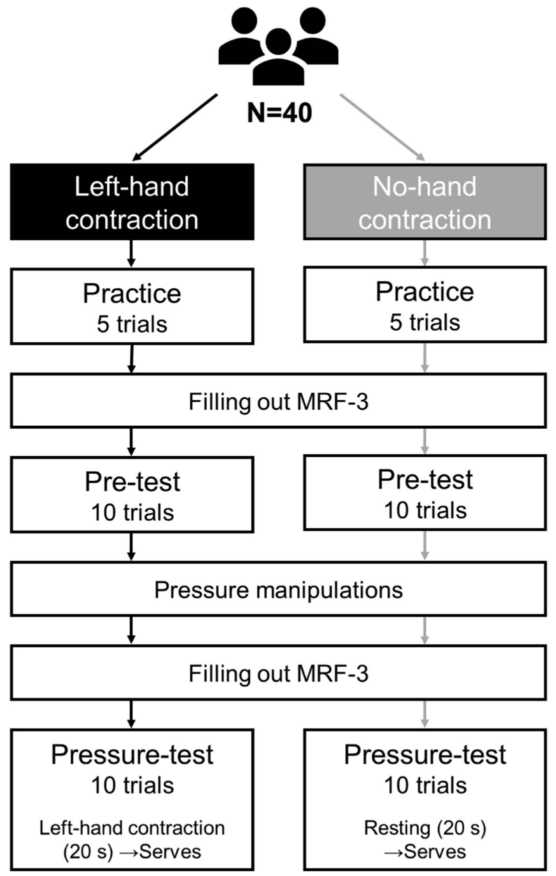

FIGURE 2
Study protocol.

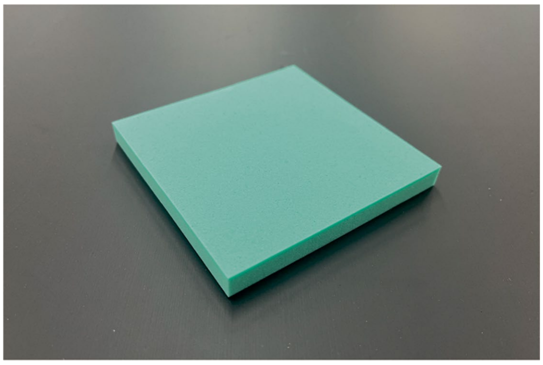

FIGURE 3
Grasping material (expanded polyethylene foam).

group served a ball immediately after contracting their left hand by grasping a material called "expanded polyethylene foam" (0.1 m × 0.1 m × 0.01 m, density 30 kg/m^3, compressive stress 50 kPa, P0030, manufactured by Fuji Gomu Co., Japan, Figure 3). This material was embedded in a flat pocket that could be sewn into the sportswear. They repeatedly grasped the material with their left hand for 20 s immediately before serving. Participants in the no-contraction group did not grasp the material during the same period (20 s). We set the grasping pace at 60 beats per minute (bpm) and recorded the sounds using a metronome.

Before the pressure test, the participants were told the following, which was effective for inducing state anxiety as in previous studies (Cooke et al., 2014; Lo et al., 2019): (a) the serving motion would be recorded with two cameras; (b) performance outcomes would be evaluated by the head coach of the tennis club; (c) performance results would be disclosed to all tennis club members; (d) if the participants performed significantly worse than others, they would be asked to participate in another experiment later; and (e) the reward money would be decreased by 300 yen per serve based on the results (down from a maximum of 3,000 yen). In (e), if the score was 5 or 6, the reward would be maintained. However, if the score were 4 or less, the reward would be reduced to 300 yen per serve (down from 3,000 yen). Therefore, the maximum reward would be 3,000 yen and the minimum 0 yen. The experimenter announced the score results and the amount earned aloud. All participants were debriefed after the experiment.

2.4 Measures

2.4.1 Psychological anxiety

We gaged cognitive and somatic state anxiety using the Mental Readiness Form-3 (MRF-3; Krane, 1994). Each item was scored on an 11-point Likert scale ranging from 1 (*not worried*) to 11 (*worried*) for cognitive anxiety, and from 1 (*not tense*) to 11 (*tense*) for somatic anxiety.

2.4.2 Serving scores

We quantified each serve outcome based on the area launched into the service box on the opposite side (Figure 1). We also counted the total number of achievements in the highest-ranked area (i.e., 6 points) that the participant served.

2.4.3 Landing positions

The tennis court was video-recorded from a height of 3 m using a video camera (SONY FDR-AX60) at 120 frame-per-second (fps). We applied a direct 2D linear transformation (Abdel-Aziz et al., 1971) to the offline image data using Frame DIAS V (DKH, Japan) to obtain the ball landing positions. We calibrated the court with 70 points (10 on the x-axis and 7 on the y-axis) at 1-m intervals, and we defined the interaction between the center-service line and the net as the origin. We set the 2D coordinates as the x-axis for the centerline direction and the y-axis for the net direction. The error between the calibration and measured points was less than 0.01 m on both the x- and y-axes. After excluding net trials, we calculated the variable error (VE) for the x- and y-axes and the bivariate variable error (BVE) across tests to evaluate the participant's variability in the landing positions (Hancock et al., 1995). We completed this using the following Equations (1–3), where the coordinates of each trial are X_i and Y_i, and the mean coordinates are X_c and Y_c:

$$VEx = \left[\frac{1}{n} \sum_{i=1}^{n} \left(X_i - X_c \right)^2 \right]^{1/2} \tag{1}$$

$$VEy = \left[\frac{1}{n} \sum_{i=1}^{n} \left(Y_i - Y_c \right)^2 \right]^{1/2} \tag{2}$$

$$BVE = \left[\frac{1}{n} \sum_{i=1}^{n} (X_i - X_c)^2 + (Y_i - Y_c)^2 \right]^{1/2} \quad (3)$$

2.4.4 Serving kinematics

We recorded the serving motion from the right sagittal plane 9 meters away using a high-speed camera (NAC Image Technology, MEMORECAM Q2m) at 250 fps. A marker was attached to the top of each racket. We performed the offline analysis using MOVIAS Neo ver. 3.0 (NAC Image Technology) by manually digitizing the markers and balls. We set the 2D coordinates as the x-axis for the net direction and the y-axis for the vertical direction. We calculated the ball speed, racket speed, and impact height. Based on the vertical and horizontal coordinates of the ball center after the impact, we defined the ball speed as the average of the resultant velocity in five frames after impact. Similarly, the racket speed was the average of the resultant velocities of the marker in the five frames before impact. We defined the impact height as the y-axis coordinate of the ball at impact when the floor was set to zero.

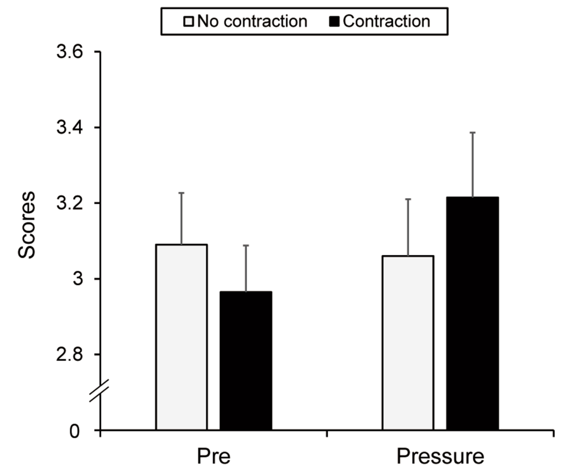

FIGURE 4
The scores of the tennis serve in the no-contraction and contraction groups on the pre- and pressure tests. The error bars indicate standard errors.

2.5 Statistical analysis

We subjected all measurements—including psychological states, serve performance (i.e., scores, the number of point 6 achievements, VE, and BVE), and kinematics (i.e., ball speed, racket speed, and impact height)—to two-way mixed-design analysis of variance (ANOVA) with a group factor (no-contraction/contraction) and a repeated measures factor of the test (pre–/pressure). When we found an interaction, we conducted multiple comparison tests by applying the Bonferroni correction. The effect size was expressed as partial eta squared (η_p^2). We performed statistical analyses using SPSS Statistics ver. 28 (IBM Corp. NY, Armonk, United States), with a significance level of 5%.

3 Results

3.1 Psychological scales

A two-way ANOVA confirmed an increase in somatic anxiety during the pressure test ($M=5.38$, $SD=2.40$) compared to the pre-test ($M=3.45$, $SD=2.40$) [F (1, 38) = 23.912, $p<0.001$, $\eta_p^2=0.442$]. The interaction between group and test was also significant [$F(1, 38)=4.392$, $p=0.043$, $\eta_p^2=0.442$]. Simple main effect analyses demonstrated that somatic anxiety increased from the pre- to the pressure test and was significant for the contraction group ($p<0.001$) and marginally significant for the no-contraction group ($p=0.055$). Cognitive anxiety did not differ between the two tests [$F(1, 38)=2.533$, $p=0.120$, $\eta_p^2=0.062$] or groups [$F(1, 38)=1.561$, $p=0.219$, $\eta_p^2=0.039$].[1]

3.2 Performance

Figure 4 outlines the performance scores. A two-way ANOVA revealed no effects of group [$F(1, 38)=0.008$, $p=0.929$, $\eta_p^2=0.000$] or test [$F(1, 38)=0.720$, $p=0.401$, $\eta_p^2=0.019$]. The interaction between group and test was not significant [$F(1, 38)=1.167$, $p=0.287$, $\eta_p^2=0.030$].

Figure 5 presents the number of maximum scores achieved. Neither a main effect of group [$F(1, 38)=0.310$, $p=0.581$, $\eta_p^2=0.008$] nor test [$F(1, 38)=1.724$, $p=0.197$, $\eta_p^2=0.043$] was found. However, the interaction between group and test was significant [$F(1, 38)=4.414$, $p=0.042$, $\eta_p^2=0.104$]. Simple main effect analyses demonstrated no group difference in the pre-test ($p=0.159$). However, the contraction group improved the number of maximum score achievements in the pressure test ($M=1.25$ times, $SD=0.94$) compared to the pre-test ($M=0.6$ times, $SD=0.49$) ($p=0.021$). The no-contraction group did not demonstrate any improvement in the number of maximum scores (pre-test, $M=0.9$ times, $SD=0.76$; pressure test, $M=0.75$ times, $SD=0.94$, $p=0.581$).[2]

Table 1 presents the VE and BVE results. For VE (x), a two-way ANOVA revealed neither a main effect of group [$F(1, 38)=2.720$, $p=0.107$, $\eta_p^2=0.067$] nor test [$F(1, 38)=0.002$, $p=0.968$, $\eta_p^2=0.000$]. There was no interaction [$F(1, 38)=1.056$, $p=0.311$, $\eta_p^2=0.027$]. For VE (y), a two-way ANOVA indicated neither a main effect of group [$F(1, 38)=0.016$, $p=0.901$, $\eta_p^2=0.000$] nor test [$F(1, 38)=0.135$, $p=0.715$, $\eta_p^2=0.004$]. There was no interaction between group and test [$F(1, 38)=0.151$, $p=0.700$, $\eta_p^2=0.004$]. For BVE, neither an effect of group [$F(1, 38)=1.959$, $p=0.170$, $\eta_p^2=0.049$] nor test [F(1,

1 We also conducted Wilcoxon signed-rank tests, which revealed a significant increase in somatic anxiety during the pressure test compared to the pre-test for both the contraction group (Z = 3.292, p < 0.001, r = 0.521) and the no-contraction group (Z = 2.042, p = 0.041, r = 0.322). However, cognitive anxiety did not differ between the tests for either the contraction group (Z = 1.207, p = 0.227, r = 0.036) or the no-contraction group (Z = 0.708, p = 0.479, r = 0.112).

2 We also applied the Wilcoxon signed-rank test, which revealed that the number of maximum score achievements increased from the pre-test to the pressure-test in the contraction group (Z = 2.440, p = 0.015, r = 0.386). However, it did not change in the no-contraction group (Z = −0.441, p = 0.659, r = −0.07).

38) = 0.009, p = 0.923, η_p^2 = 0.000] was found. There was no interaction [F(1, 38) = 1.307, p = 0.260, η_p^2 = 0.033].

3.3 Kinematics

The kinematics data are summarized in Table 1. Both the ball and racket speeds were greater on the pressure test than on the pre-test [ball speed, F(1, 38) = 33.489, p < 0.001, η_p^2 = 0.468; racket speed, F(1, 38) = 6.763, p = 0.013, η_p^2 = 0.151]. These did not differ between the two groups [ball speed, F(1, 38) = 0.171, p = 0.681, η_p^2 = 0.004; racket speed, F(1, 38) = 0.137, p = 0.713, η_p^2 = 0.004]. No interactions were found [ball speed, F(1, 38) = 0.187, p = 0.668, η_p^2 = 0.005; racket speed, F(1, 38) = 0.537, p = 0.468, η_p^2 = 0.014].

For impact height, neither main effect of group [F(1, 38) = 0.550, p = 0.463, η_p^2 = 0.014] nor test [F(1, 38) = 2.079, p = 0.158, η_p^2 = 0.052] was found. There was no interaction [F(1, 38) = 0.003, p = 0.958, η_p^2 = 0.000].

4 Discussion

We aimed to investigate the effects of grasping materials with the left hand prior to a tennis second serve; a crucial skill players must execute during games. This material can be sewn into sportswear to facilitate easy access during a game. We found beneficial effects of the left-hand contraction (i.e., an increased number of maximum score achievements), extending a preliminary analysis that demonstrated null effects on performance indices (Masaki, 2022).

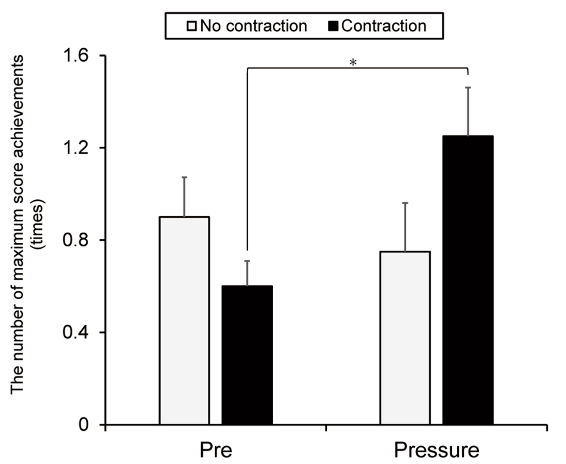

FIGURE 5
The number of maximum score achievements in the no-contraction and contraction groups on the pre- and pressure tests. The error bars indicate standard errors. *p < 0.05.

4.1 Serving scores

We hypothesized that the left-hand contraction could prevent choking under pressure based on previous findings in a series of experiments of Beckmann's group (Beckmann et al., 2013; Gröpel and Beckmann, 2017; Beckmann et al., 2021). However, serve performance did not deteriorate with pressure manipulation, suggesting a failure of choking induction. Therefore, we failed to test the choking intervention, although participants perceived somatic anxiety during the pressure test.

Interestingly, the left-hand contraction group increased the number of maximum score achievements, supporting the assertion that the left-hand contraction may not only prevent choking but also enhance performance under pressure (Beckmann et al., 2013, Study 2; Gröpel and Beckmann, 2017, Study 2; Mesagno et al., 2019, Study 2). Our results reconfirmed the beneficial effects of the left-hand contraction on tennis serve performance, apart from the context of choking intervention. Beckmann et al. (2021) reported the effectiveness of left-hand contraction in preventing choking among skilled tennis players. Therefore, our data further support the evidence of the beneficial effects of left-hand contraction on enhancing tennis serve performance.

Performance enhancement under pressure is referred to as a "clutch" (Otten, 2009) that is conceptually opposite to the choking phenomenon. The occurrence of a clutch can be ascribed to a high level of athletes' perceived control (Otten, 2009), which is an element of implicit knowledge. Based on Seger's (1994) description, Otten (2009) defined perceived control as knowledge derived from the accurate prediction of subsequent stimuli or the ability to control the values of variables. The left-hand contraction may be associated with an improved sense of perceived control.

Given the occurrence of clutches, participants may have perceived increased somatic anxiety as optimal tension rather than a hindrance to their actions. An optimal level of anxiety may increase motivation properly (Eysenck and Calvo, 1992). Cheng et al. (2009) pointed out that success relies on whether individuals can interpret current pressure as a positive event. It is possible that the left-hand contraction also influences the interpretation of anxiety.

TABLE 1 Mean (*SD*) of the VE, BVE, and kinematics measures in the no-contraction and contraction groups on the pre- and pressure tests.

Measures (range)	Pre-test		Pressure test	
	No contraction	Contraction	No contraction	Contraction
VE x (m)	0.92 (0.31)	0.83 (0.25)	0.98 (0.45)	0.78 (0.24)
VE y (m)	0.60 (0.22)	0.62 (0.21)	0.60 (0.21)	0.59 (0.16)
BVE (m)	1.12 (0.31)	1.05 (0.27)	1.17 (0.44)	0.99 (0.24)
Ball speed (km/h)	112.9 (9.5)	111.2 (10.5)	116.3 (10.7)	115.2 (11.7)
Racket speed (km/h)	125.6 (11.6)	127.7 (17.7)	127.1 (11.5)	128.5 (18.1)
Impact height (m)	2.46 (0.14)	2.50 (0.15)	2.47 (0.13)	2.51 (0.15)

SD, standard deviation; VE, variable error; BVE, bivariate variable error; m, meter; km/h, kelometer per hour.

The occurrence of the clutch in our study may be due to the right dominant hemispheric asymmetry induced by the left-hand contraction (Harmon-Jones, 2006; Hirao and Masaki, 2019), which is known to be an appropriate brain state for expert athletes (e.g., Hatfield et al., 1984). Inhibition of the left hemisphere and prefrontal coactivation (i.e., weak T7-Fz connectivity, indicative of unconscious motor control) occurs after left-hand contractions (Hoskens et al., 2020). Furthermore, T7-Fz inhibition occurred more strongly for experts than for novices in golf (Gallicchio et al., 2016), and more for experts than for near experts in shooting (Deeny et al., 2003). Therefore, the inhibition of left hemispheric activity that manifests as the right-dominant hemispheric asymmetry is thought to be an ideal brain state for high performance.

4.2 Kinematic and two-dimensional indices

We posited that the left-hand contraction would conserve the serving kinematics even under pressure, whereas no contraction would disrupt the kinematics. However, this was not the case in this study. We observed no differences in movement kinematics between the two groups. Instead, we found improved performance accompanied by kinematic changes, although the direction of the changes was opposite to our prediction (i.e., the clutch). The kinematic analysis indicated that both groups exhibited faster ball and racket speeds during the pressure tests. In contrast to previous findings that have reported performance deterioration under pressure due to disrupted kinematics (e.g., decreased ball speed) (e.g., Sekiya and Tanaka, 2019), we noted better kinematic changes underlying the clutch phenomenon. Considering that the contraction group exhibited greater accuracy in serving toward the maximum scoring area, left-hand contraction may facilitate optimal serving attributes, such as increased ball speed and accuracy (e.g., Hernández-Davó et al., 2019), particularly under pressure.

The lack of differences in kinematics and serving variability (i.e., VE and BVE) between the groups can be attributed to analytical issues. The achievement of a successful tennis serve requires the coordination of several factors such as speed, impact angle, spin direction, and precision (Colomar et al., 2022). Mirifar et al. (2022) pointed out that the effect of unilateral hand contraction was fairly small and potentially insufficient to affect behavioral levels. Therefore, 3D kinematic analysis might be a good way to detect the beneficial effects of left-hand contraction (e.g., coordination among shoulder rotation, wrist and elbow flexion, or extension). Furthermore, in this study, the participants aimed at the target area instead of a specific target point, which was limited to the evaluation of several measures, including the mean radial error (MRE) and constant error (CE) from the target (Hancock et al., 1995). These indices are commonly used to assess tennis serve performance (Delgado-García et al., 2019; Hernández-Davó et al., 2019; Yamamoto et al., 2019; Beckmann et al., 2021). It would be fruitful to investigate the effects of hand contractions on these indices in future studies.

4.3 Practical implications

Our findings indicate that grasping a polyethylene material with the left hand would be helpful to enhance serving performance during critical, high-pressure matches in tennis. Previous studies have used soft balls (Beckmann et al., 2013; Gröpel and Beckmann, 2017; Mesagno et al., 2019) or tennis balls (Beckmann et al., 2021) for unilateral hand grasping. However, bringing these materials to real sports games is impractical, and grasping the ball *per se* likely interferes with motion. The developed wearable grasping material is likely to make the left-hand contraction more practical in real situations.

According to previous studies, left-hand contraction may be effective for expert or semi-expert players (Beckmann et al., 2013; Gröpel and Beckmann, 2017; Mesagno et al., 2019; Beckmann et al., 2021) but not for novices (Hoskens et al., 2020). Therefore, the effectiveness of our approach might be limited in skilled tennis players.

4.4 Limitations

Our study has several limitations. First, we could not assess the intervention effects during choking. Therefore, pressure manipulation must be reconsidered. Our participants were driven to achieve success through pressure manipulation. We manipulated pressure using a reward of 3,000 yen (approximately 20 USD). While this amount was set to increase the likelihood of participants seeking the reward, it may enhance the clutch phenomenon rather than induce choking. Second, we should point out the technical limitations of EEG recordings in real sporting situations. EEGs are vulnerable to muscular activities. Consequently, in our study, we did not know whether T7-Fz connectivity was reduced by the left-hand contraction. Future studies should employ a certain task (e.g., golf putting) during which EEGs can be recorded.

5 Conclusion

We discovered that grasping a polyethylene material with the left-hand enhanced serve performance, as evidenced by an increase in the number of maximum score achievements under pressure. This finding reinforces the notion that left-hand contraction may not only prevent choking but also contribute to the clutch phenomenon. Our study, utilizing embedded grasping material in sportswear rather than ball grasping, may expedite the practical application of left-hand contraction in real sporting scenarios.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

This study was approved by The Waseda University Ethics Committee. The participants provided their written informed consent to participate in this study.

Author contributions

KM: Writing – original draft. HM: Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Effects of a 6-week on-court training program on the International Tennis Number (ITN) and a range of physical fitness characteristics in young tennis players

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The study aimed to (i) verify the effects of an on-court training program on the International Tennis Number (ITN) of young tennis players, as well as on a set of change of direction, linear sprint, and maximal oxygen uptake (VO_{2max}) variables, and (ii) identify the main predictors of ITN. The sample consisted of 20 young male tennis players (mean age, 13.62 ± 0.23 years). Players underwent a 6-week on-court training program. The ITN and a number of change of direction variables (T-drill and repeated sprint ability), linear sprint (5 m, 10 m, and 20 m distances), and VO_{2max} were measured. All variables improved significantly between the pre- and posttest ($p < 0.001$). The ITN ($7.98 \pm 6.06\%$, $d = 0.82$) and VO_{2max} ($6.77 \pm 1.21\%$, $d = 1.53$) showed the greatest relative improvement with moderate to large effect sizes. The hierarchical linear model retained the time (estimate = 18.90, $p < 0.001$) and the T-drill (estimate = −64.77, $p < 0.001$) as significant predictors of the ITN. This indicates that the ITN improved significantly over the 6-week training program and that the T-drill test was the best and most significant predictor. Coaches and researchers are encouraged to monitor the ITN along with other physical fitness and technical variables. They can also use the T-drill test to understand the ITN of their players.

KEYWORDS

tennis, field tests, International Tennis Number (ITN), physical fitness, prediction

1 Introduction

Tennis is a sport that is practiced worldwide in both recreational and competitive contexts. To improve performance, players must progressively develop and master technical skills essential for effective play during a tennis match (1). By doing so at an early age, tennis coaches or instructors can minimize a hypothetical skill mismatch between players, i.e., some players can meaningfully compete against less-skilled opponents and vice versa (2). Previous literature on tennis has focused on understanding the influence of specific body characteristics, biological maturation, or specific tests on youth tennis development (3–5). It has been noted that growth and maturation processes can have a significant impact on the development of young tennis players (3). This is especially true as each athlete is a unique individual, with a specific rate of development (6). For example, Fernandez-Fernandez et al. (4) conducted a study to examine maturational differences in the neuromuscular performance of young male and female tennis players. The assessment included a series of linear sprints, change of direction tests, and lower limb power. They reported that maturity level (such as peak height velocity) was a better parameter than chronological age when designing training programs specifically for youth tennis (4). Others aimed to understand the effects of specific field tests on player performance (7, 8). Overall, it was pointed out that certain fitness and technical tests should be used in youth tennis, as they provide useful information for the solid and sustainable development of the players.

As mentioned above, tennis players can practice or play against each other with an *a priori* meaningful mismatch between them. To better understand these skill differences, the International Tennis Federation has created the "World Tennis Number (WTN)," which is a scale from 40 to 1 (where 40 is a beginner and 1 is an elite player) that allows you to rank tennis players. According to the WTN website (https://worldtennisnumber.com/eng/faq), a special algorithm uses match results from 2016 onwards to calculate players' ranks. The more matches played, the more accurately the system can understand a player's skill level and rank them accordingly. The WTN aims to increase participation in tennis by allowing players of all skill levels to determine their individual level and thus make more solid progress. A recent study (9) reported that the WTN is a valid rating system for tennis. The authors measured the agreement between the WTN and the Universal Tennis Rating (UTR—considered the gold standard of tennis player rating systems) in 806 matches. There was a strong relationship between the WTN and the UTR, and both showed similar results for accuracy, sensitivity, and specificity in predicting match outcomes (9).

Notwithstanding, the ITF also has another rating protocol called the International Tennis Number (ITN), which consists of a scale of 10 to 1, with 10 being a novice player and 1 being an elite professional (10). The ITN is designed to be easily integrated into a standard coaching program and is also an ideal tool for use in tennis clubs. Unlike the WTN, the ITN consists of an on-court assessment that includes drills based on groundstroke depth, groundstroke accuracy, volley depth, serve, and mobility. Tennis is a physically and technically demanding sport (11). Thus, it can be argued that the ITN is more likely to better represent a player's level, as it is given based on the specific strokes and characteristics of tennis. For several years, the ITN has been used extensively by tennis coaches and researchers to classify player performance levels (12, 13). However, to the best of our knowledge, there is little evidence to understand the effects of on-court tennis training (OTT) on the ITN (14). Furthermore, no attempt was found to predict the ITN based on physical fitness variables that are related to tennis. As far as we know, (i) only two studies reported correlations between the ITN and variables related to physical fitness (15, 16), of which (ii) one study analyzed the effect of a training program on a specific feature of the ITN (13) and the other analyzed the effect of OTT and high-intensity interval training on the ITN (14). Thus, it can be argued that the literature lacks information on the ITN test, especially because it is a test used worldwide to classify or evaluate the level of players based on an on-court assessment. Based on the characteristics of the ITN assessment, one can argue that parameters related to the players' physical fitness (namely related to their quickness) can have a meaningful effect on their ITN level and predict it. This can give coaches and practitioners information about which parameters the players should improve to get better scores in the ITN.

Therefore, this study aimed to (i) verify the effects of an on-court training program on the ITN of young tennis players, as well as on a set of change of direction, linear sprint, and maximal oxygen uptake (VO_{2max}) variables and (ii) identify the main predictors of ITN. It was hypothesized that the on-court training program would significantly improve the players' ITN and all measured variables and the ITN would be predicted by the VO_{2max} simultaneously with another variable related to change of direction or linear sprint.

2 Methods

2.1 Participants

A total of 20 young male tennis players (age, 13.62 ± 0.23 years; height, 161.30 ± 8.27 cm; body mass, 51.95 ± 8.37 kg; maturity offset, −0.25 ± 0.26 years; peak height velocity, 13.86 ± 0.24 years) were recruited. All were right-handed tennis players with at least two years of experience in tennis training and competitions and were classified as Tier 3 athletes, i.e., highly trained athletes competing at the national or state level (17). The inclusion criteria required players to be uninjured and to have practiced regularly for the 6 months prior to data collection. Informed consent was obtained from parents or guardians and the players themselves. The study was carried out in accordance with the tenets of the Declaration of Helsinki and approved by the Local University Research Ethics Committee (47940-01).

2.2 Research design

The training intervention design consisted of 1 week of testing (pretest), 6 weeks of OTT, and 1 week of testing (posttest). The 6 weeks of OTT corresponded to the preparation period of the summer competitive season prior to the junior tennis season. During this period, players participated in three training sessions per week conducted on an indoor hard court. Heart rate (HR) measurements were continuously monitored using HR monitors (Polar V800, Polar Inc., Finland) to assess the intensity of the drills. Between the first week of the OTT and the sixth week, the average HR ranged between 169.6 ± 3.3 bpm and 174.5 ± 3.7 bpm, respectively. The players underwent a 10 min standardized warm-up period, which consisted of light aerobic activity (jogging), dynamic and passive stretching, and functional movements based on tennis-specific actions. Afterwards, they completed a 20 min set of on-court tennis-specific activities that included hitting against an opponent, focusing on consistency, and targeting specific areas of the court (e.g., cross or line shots, serve-return, groundstrokes, volleys). The players then underwent the on-court training program, which lasted 20–40 min. This was designed to improve start speed, acceleration, and speed endurance during tennis strokes, particularly the transition from forehand to backhand. The on-court training program incorporated maximal and submaximal running intensities and placed high demands on stroke quality as reported by others (14). The primary goal was to direct all shots to specific target areas on the baseline. In the on-court training program, various on-court tennis drills were performed using a racquet and ball. These drills followed procedures adapted from previous studies to ensure a structured approach to training (18, 19). The specific drill structure consisted of 2–3 sets of 5–6 repetitions, each lasting 30–60 s of work (10–20 strokes). There was a rest period of 30–60 s between repetitions and a rest period of 60–90 s between sets. The frequency of ball delivery was approximately one ball every 3 s. During the on-court training program, a coach positioned opposite the service boxes fed the balls to the players. The coach made sure that the balls were delivered at a consistent frequency and speed. Experienced coaches with level 3–4 certification from the Turkish Tennis Federation and 10–15 years of experience supervised the training program. At the end of the on-court training, the players performed individual interval training sessions without racquets, which lasted approximately 8–20 min. These sessions focused on explosive bursts to have the players exceed 85% of their maximum heart rate (HR_{max}). At the end of the training session, the players underwent a 10 min cooldown period that included stretching exercises.

2.3 Anthropometric measurements and maturity

Body mass (in kilograms) was measured using a bioelectrical impedance analyzer (BC-418, Tanita, Tokyo). Players' height (in cm) was measured using a stadiometer (Holtain Ltd., UK). Leg length was estimated as stature minus sitting height (which was measured with the stadiometer). A non-invasive technique was then used to assess the players' maturity offset (20). Peak height velocity was calculated by subtracting the maturity offset value from the players' chronological age, as suggested by others (21).

2.4 The ITN test

The International Tennis Test (ITN) is an internationally recognized tennis rating that represents a player's general level of play. This is an objective on-court assessment tool based on tennis-specific tasks such as ball control, accuracy, and power. The ITN is a rating system where players are rated on a scale of 10 levels, from ITN 1 to ITN 10 (with 1 being the best). The ITN (in arbitrary units —a.u.) was performed on an indoor hard court to assess the player's technical skills. A ball machine (Tennis Tutor Plus, Sports Tutor, Inc., USA) was used to feed balls to the players under test. This on-court assessment consists of five technical elements, namely, groundstroke depth (maximum score, 90 points), groundstroke accuracy (maximum score, 84 points), volley depth (maximum score, 72 points), serve (maximum score, 108 points), and mobility (maximum score, 76 points), and was performed according to the International Tennis Federation guidelines for a maximum score of 430 points. The groundstroke depth assessment includes a power aspect and consists of 10 alternate forehands and backhands ground strokes. The groundstroke accuracy assessment also includes a power aspect and consists of six alternate forehands and backhands down the line and six alternate forehands and backhands crosscourt. The volley depth includes a power aspect and consists of eight alternate forehands and backhands volleys. The serve assessment includes a power aspect and 12 serves in total—3 serves in each target area. As for the mobility assessment, this measures the time it takes a player to pick up five tennis balls and return them individually to a specified zone. The scores from each element were added, and then the players' ITN number (i.e., tennis skill level) was reported based on an established normative table (10). Figure 1, which was taken from the official "ITN On-Court Assessment" guide, presents the specificities of the groundstroke depth, groundstroke accuracy, volley depth, and the serve drills (https://sonc.net/wp-content/uploads/2018/08/ITN-Assesment-Guide-levels-4-and-5.pdf). It also shows the mobility scores and the ITN correlation table, which allows the scores to be converted to the ITN.

2.5 Maximal oxygen uptake (VO_{2max})

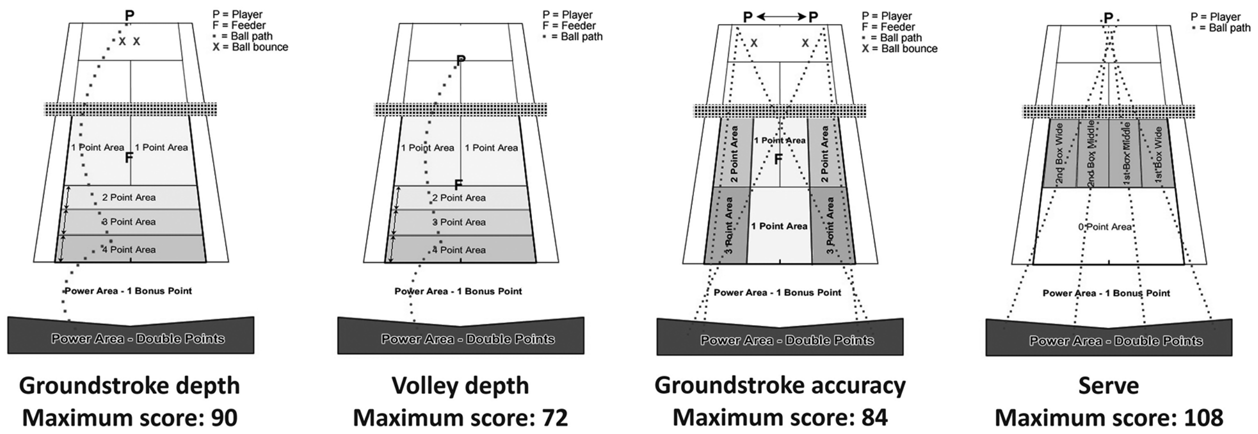
The hit and turn tennis test was used to estimate the maximal oxygen uptake (VO_{2max}, in ml/kg/min). After a typical 5 min warm-up, each player performed the test. This test is an acoustically controlled progressive on-court fitness test for tennis players. It was administrated according to the procedures proposed by (22). The maximal completed value was used to estimate the VO_{2max}. After the test, the estimated VO_{2max} was calculated using the following formula (22):

$$VO_{2\,max} = 33.0 + (1.66 \cdot \mathrm{HTTT}) \quad (1)$$

where VO_{2max} is the maximal oxygen uptake (ml/kg/min) and HTTT is the player's final score on the hit and turn tennis test (a.u.).

2.6 Sprint tests

Each athlete performed a 20 m linear sprint test with 5 m, 10 m, and 20 m intervals (in seconds). The starting point was 70 cm behind the first pair of photocells (Witty, Microgate, Bolzano, Italy) marking the starting line. The participants were instructed to perform a maximal trial up to the 20 m timing gate. Four pairs of photocells were used (start line, 5 m, 10 m, and 20 m). The photocells were placed 0.4 m above the ground to minimize the effect of the hand swing when crossing the gate (23). They were activated upon crossing. The players performed



Mobility assessment - Maximum score: 76

Time	40	39	38	37	36	35	34	33	32	31	30	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15
Score	1	2	3	4	5	6	7	8	9	10	11	12	12	14	15	16	18	19	21	26	32	39	45	52	61	76

ITN Correlation Table

Score (F)	57-79	80-108	109-140	141-171	172-205	206-230	231-258	259-303	304-344	345-430
Score (M)	75-104	105-139	140-175	176-209	210-244	245-268	269-293	294-337	338-362	363-430
ITN	ITN 10	ITN 9	ITN 8	ITN 7	ITN 6	ITN 5	ITN 4	ITN 3	ITN 2	ITN 1

FIGURE 1
Illustration of the groundstroke depth, groundstroke accuracy, volley depth, and serve drills of the International Tennis Number (ITN) on-court assessment guide. Also shown are the mobility scores and the ITN correlation table, which allows the scores to be converted to the ITN.

two trials with a rest period of 120 s between trials. The best performance of the two sprints was used for further analysis.

2.7 T-drill agility test

The T-drill agility test (in seconds) is designed to assess agility performance. The test includes basic movements that are commonly performed in tennis training and matches. To complete the test, the players must sprint from a standing position to a cone placed 9.14 m away and then shuffle sideways to the left without crossing their feet to another cone placed 4.57 m away. After touching this cone, they shuffled to the right to a third cone placed 9.14 m away, shuffled sideways back to the center cone, and ran back to the starting point. Time was measured in seconds using a portable wireless photocell system (Witty, Microgate, Bolzano, Italy). The participants performed two trials with a rest period of 120 s in between. The best performance of the two sprints was used for further analysis.

2.8 Repeated sprint ability test (RSA)

The RSA test (in seconds) consisted of six repetitions of maximal 2 × 15 m shuttle sprints starting every 20 s (24). During the approximately 14 s recovery period between sprints, subjects were required to stand passively. Two seconds before the start of each sprint, the subjects were asked to assume the starting position as described for the 20 m sprints and wait for the start signal from a supervisor. Time was measured in seconds using a portable wireless photocell system (Witty, Microgate, Bolzano, Italy). The mean repeated sprint time (RSA_{mean}) was used as a performance indicator (24). The participants performed two trials with a rest period of 120 s in between. The best performance of the two sprints was used for further analysis.

2.9 Statistical analysis

Descriptive data (mean ± SD) and the relative difference (%) were calculated. The paired samples *t*-test was used to verify the time effect ($p < 0.05$). The mean difference and 95% CI were used. Cohen's d was used to estimate the standardized effect size, which was considered to be (i) trivial, if $0 \le d < 0.20$; (ii) small, if $0.20 \le d < 0.60$; (iii) moderate, if $0.60 \le d < 1.20$; (iv) large, if $1.20 \le d < 2.00$; (v) very large, if $2.00 \le d < 4.00$; and (vi) almost clear, if $d \ge 4.00$ (25).

The hierarchical linear model (HLM) was used as a multilevel statistical procedure to identify the predictors of the ITN test. The ITN was chosen as the dependent variable because it strongly represents the movements and skills of a competitive tennis match. Two models were tested. The first model tested time (the difference between the pre- and posttest, i.e., training effect) as a predictor. This was done to understand if the ITN improved over time. The second model tested the remaining independent variables as predictors. Only significant predictors were included in the final model. Maximum likelihood estimation was calculated using the HLM7 software (26).

3 Results

Table 1 shows the descriptive statistics and the comparison of all measured variables between the pre- and posttest. The ITN and VO_{2max} showed the greatest relative improvement with 7.98 ± 6.06 and 6.77 ± 1.21%, respectively, between the pre- and posttest. All variables improved significantly ($p < 0.001$) between the pre- and posttest. This indicates that the OTT program tended to meaningfully elicit the ITN and all other variables. However, the T-drill test was the variable that improved with the largest effect size ($d = 1.66$).

Table 2 presents the multilevel modeling data. Time (estimate = 18.90, $p < 0.001$, 95% CI = 12.22–25.58) and T-drill (estimate = −64.77, $p < 0.001$, 95% CI = −82.04 to −47.50) remained significant predictors of ITN. For each unit increase in T-drill (in seconds), the ITN decreased by 64.77 points. Thus, lower scores on the T-drill (better performance) would lead to better performance on the ITN.

The following equation can be used to calculate the players' ITN based on the T-drill test:

$$\text{ITN} = 1029.41 - (64.77 \cdot \text{T-drill}) \quad (2)$$

4 Discussion

This study aimed to (i) verify the effects of an on-court training program on the ITN of young tennis players, as well as on a set of change of direction, linear sprint, and VO_{2max} variables, and (ii) identify the main predictors of the ITN. The main findings indicate that the ITN and the remaining variables improved significantly with the on-court training program. On the other hand, the second hypothesis of this study was partially accepted, i.e., only one variable related to change of direction (T-drill) was retained as a main predictor of the ITN.

Regarding the use of variables to measure physical fitness in tennis, a review study on this topic showed that there is a general disagreement in the scientific community regarding the most important physical characteristics and useful tests in tennis (8). The authors summarized the different physical tests recommended and used by practitioners, sport scientists, and institutions (national tennis federations) (8). Therefore, this experimental design included some of the tests indicated as the most appropriate for tennis players (e.g., linear sprints and the hit and turn tennis test—this one to estimate VO_{2max}). In addition, based on more recent evidence, the T-drill test and the RSA were also included, as they also represent tennis movements (27, 28).

Literature can be found on the effects of training programs on variables related to the physical fitness of tennis players (12, 14, 29). However, different results have been found in age groups like those in this study. For example, a study by Fernandez-Fernandez et al. (29) reported that a sport-specific drill training alone failed to promote meaningful improvements in linear sprint, lower limb strength, and agility, with only trivial to small effect sizes. This training design only produced meaningful improvements in oxygen uptake with a moderate effect size. However, when compared to a combined sport-specific drill training and high-intensity training, the latter training design promoted greater improvements (based on the relative difference) in all of these parameters than sport-specific drill training alone (29). On the other hand, others found that both OTT alone and high-intensity interval training programs were able to induce linear sprint, lower limb strength, agility, and oxygen uptake in fourteen-year-old players (14). The differences between groups were only found in the 400 m time and agility tests. It can be argued that the main factor responsible for such an improvement in both training designs was that the OTT had a specific focus on different types of OTT drills. These were based on speed and acceleration at maximal and submaximal intensities, mostly involving the anaerobic system during short- and high-intensity efforts (14). The current data showed similar results, where the OTT program alone was able to promote significant gains in all measured variables, confirming the first hypothesis of this study. OTT typically consists of a variety of activities designed to improve different aspects of a player's game (i.e., technical, tactical, and mental) (30). However, in the present study, the OTT was also designed to improve the players' physical fitness and technical skills simultaneously. Therefore, the 6-week OTT

TABLE 1 Descriptive statistics (mean ± SD) of the measured variables and comparison between the pre- and posttest.

	Mean ± SD			Paired samples comparison		Effect size
	Pretest	Posttest	Rel. diff. (%)	*t*-test (*p*-value)	Mean difference (95% CI)	*d* (descriptor)
ITN (a.u.)	215.90 ± 24.10	234.80 ± 21.93	7.98 ± 6.07	5.40 (<0.001)	18.90 (11.58–26.22)	0.82 (moderate)
VO_{2max} (ml/kg/min)	45.33 ± 2.05	48.63 ± 2.25	6.77 ± 1.21	22.46 (<0.001)	3.30 (2.99–3.61)	1.53 (large)
5 m sprint (m)	1.14 ± 0.05	1.08 ± 0.05	6.32 ± 3.10	9.28 (<0.001)	0.07 (0.05–0.08)	1.20 (large)
10 m sprint (m)	2.16 ± 0.10	2.06 ± 0.08	4.66 ± 1.52	12.90 (<0.001)	0.10 (0.08–0.11)	1.10 (moderate)
20 m sprint (m)	3.61 ± 0.21	3.45 ± 0.21	4.66 ± 1.38	14.90 (<0.001)	0.16 (0.14–0.18)	0.76 (moderate)
RSA_{mean} (s)	6.57 ± 0.11	6.37 ± 0.15	3.24 ± 1.88	7.64 (<0.001)	0.20 (0.15–0.26)	1.52 (large)
T-drill (s)	12.57 ± 0.16	12.26 ± 0.21	2.55 ± 0.97	11.72 (<0.001)	0.31 (0.26–0.37)	1.66 (large)

Rel. diff., relative difference; ITN, international tennis number; VO_{2max}, maximal oxygen uptake; RSA_{mean}, mean repeated sprint ability; 95% CI, 95% confidence intervals; *d*, Cohen's *d* effect size.

TABLE 2 Hierarchical linear model coefficients with 95% CI.

	Estimate	SE	95% CI	*p*-value
Time	18.90	3.41	12.22 to 25.58	<0.001
T-drill (s)	−64.77	8.81	−82.04 to −47.50	<0.001

alone significantly improved the players' physical fitness parameters with moderate to large effect sizes. Notwithstanding, it should be mentioned that these physical fitness variables can be improved even more when high-intensity interval or repetitive sprint training programs are added to the sport-specific training or OTT programs (12).

Only one study was found regarding the objective effects of a specific training program on the ITN (14). Contrary to what was found for the physical fitness variables, the ITN improved significantly in players who underwent an OTT alone rather than a high-intensity interval training (14). As previously reported, OTTs focus on a variety of topics related to player performance rather than just physical fitness, as may be the case with high-intensity interval training. Therefore, if players spend more time performing or training their technical skills, they are more likely to improve their ITN. Another study also showed the effect of rope jumping training on a specific characteristic of the ITN, i.e., accuracy and depth of impact in the stability test (13). The authors found that the experimental group significantly improved both the accuracy and depth in the hit stability test (13). In this case, it appears that this specific physical fitness task allowed the players to improve some parameters of the ITN. Thus, based on the scarce evidence on this topic, it can only be argued that there may be specific physical fitness tasks or drills that can improve the ITN of players. As this test is widely used by coaches and several federations to classify the level of their players based on a number of technical and physical characteristics, it was expected that there would be some evidence on this topic. On the contrary, it was only found that studies with a pre- vs. posttest mainly used the ITN to classify their sample, but not to understand the underlying effects of the ITN (31, 32).

As mentioned above, the ITN test is a worldwide tool for coaches to understand and rank the skill level of their players. In the present approach to the problem, it was decided to use only motion-based variables to predict the ITN. That is, since the ITN is a motion-based test (i.e., it is performed based on the player's displacement) that aims to simulate a tennis point, the variables included are also motion-based. The HLM statistical procedure was used to identify the predictors of the ITN test. Time and the T-drill were retained as significant predictors. Time as a significant predictor confirmed the results of the *t*-test, where the on-court training program allowed a significant improvement in the ITN. As for the T-drill test, lower scores (better performances) on this test led to higher scores (better performances) on the ITN. It should be noted that although the ITN evaluates the technical skills of the players, these can also be related to physical fitness. It has been shown that players with higher physical fitness are more likely to have better skills (8, 33).

Nevertheless, there is a lack of evidence in the literature regarding the relationship between physical fitness variables and the ITN. As mentioned above, most studies on tennis that include physical and technical characteristics do not include the ITN except for sample classification (12, 34). Nevertheless, one study aimed to understand the relationship between strength and power, muscle stiffness, stroke velocity, and the ITN in junior tennis players (15). The authors found that the pectoralis major stiffness and maximal isometric wrist flexion strength were significantly and directly correlated with the ITN (i.e., greater stiffness was correlated with smaller ITN—poorer performance). It has been argued that higher levels of stiffness, especially in the upper body, may have some negative influence on the ITN by interfering with speed production (15). Others noted that the ITN in young children (8–10 years old) was significantly and directly correlated with the standing long jump, that is, greater distances were correlated with better performance on the ITN (16). However, none of these predicted the ITN. The present results suggest that the ITN can be predicted based on a faster field test such as the T-drill, which represents tennis movements. It has been reported that for some athletes, gains in strength and power may not benefit agility skills (35). It can be argued that, depending on player characteristics (in a holistic perspective), excessive lower limb strength and power indices may impair some players' agility. Therefore, dynamic tests, such as the T-drill, may be more representative of the ITN rather than static tests.

The main findings indicate that OTT programs alone can significantly improve the physical fitness characteristics and ITN of tennis players. However, this improvement may be related to the specificity of the OTT content. The ITN is a worldwide test for understanding and ranking the level of the players. Therefore, it can be argued that whenever coaches and researchers want to understand the effects of a given program on physical fitness and technical variables, they should also monitor the ITN. This may provide a deeper insight into the effects of such variables on the ITN. In addition, physical characteristics (specifically the T-drill test) were able to predict the ITN. Thus, coaches and players can use this faster test to meaningfully determine a player's ITN. Furthermore, based on a training or more professional context, ITN monitoring can also help coaches understand the level of their players and cluster them to design more appropriate training programs (36). The main limitations are that (i) these results are only applicable to this age group; (ii) there are other dynamic tests (physical or technical) that may help in the prediction of ITN; and (iii) the VO_{2max} was estimated rather than directly measured. Regarding the estimation of VO_{2max}, it should be mentioned that it is based on a specific field test in tennis (i.e., the hit and turn tennis) (22), which has been validated for both sexes and several age groups. For the specific age group used in the current study, a moderate correlation was found between the measured and the estimated VO_{2max} with an absolute marginal difference (measured $VO_{2max} = 55.0 \pm 4.0$ ml/kg/min; estimated $VO_{2max} = 54.3 \pm 2.0$ ml/kg/min) (22). Thus, this is a valid test that is commonly used by tennis researchers and coaches to measure the aerobic capacity of players. Finally, future studies could focus on understanding these relationships in other age groups and test other physical or technical parameters that can be related to the ITN. Given the paucity of evidence on this topic and the importance of measuring the ITN, researchers might also aim to understand the effects of different training designs (OTT or others) on ITN performance.

5 Conclusions

On-court training programs based on tennis-specific skills can significantly improve physical fitness variables and ITN. Dynamic tests, particularly the T-drill test, can predict the ITN, with better T-drill scores being associated with better ITN performance. Tennis coaches and researchers should be encouraged to monitor the ITN simultaneously with physical and technical variables, as this can provide a deeper insight into the level of the players.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Tokat Gaziosmanpasa University Research Ethics Committee (47940-01). The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

JM: Conceptualization, Data curation, Writing – original draft, Writing – review & editing. BK: Methodology, Writing – review & editing. EA: Methodology, Writing – review & editing. YS: Methodology, Writing – review & editing. HN: Conceptualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Pre and post-competitive anxiety and self-confidence and their relationship with technical-tactical performance in high-level men's padel players

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Introduction: This study aimed to analyze the variations in pre- and post-competitive anxiety and self-confidence considering match outcomes, the performance according to the result and the correlation among performance and psychological variables.

Methods: The sample consisted on 12 matches in which 11 high-level padel players from Finland (top 24) voluntarily participated. CSAI-2R and STAI-S were used to assess psychological variables and technical-tactical performance was evaluated by a certified padel coach.

Results: Losing players presented higher cognitive (p = .004), somatic (p = .020) and state (p = .001) anxiety and lower selfconfidence (p = .014), and winning players showed higher state anxiety (p = .022), after than before the matches. Post-match, winning players exhibited higher self-confidence (p = .015) than losing players. Winning players made more winners (p = .010) than losing players. There are direct correlations between unforced errors and post-state anxiety (p = .015), unforced errors and state anxiety (p = .009) and winners and cognitive anxiety (p = .033), in winning players; between generators of forced error and post-cognitive anxiety (p = .034), forced errors and cognitive anxiety in losing players (p = .001). There are indirect correlations between forced errors and pre-cognitive anxiety (p = .009), winners and somatic anxiety (p = .046), unforced errors and state anxiety (p = .042) in losing players.

Discussion: The outcomes imply the need for intervention programs to equip players, especially those facing defeat, with tools for anxiety management and self-confidence enhancement. Likewise, coaches are advised to incorporate exercises that promote the occurrence of winners.

KEYWORDS
psychology, match analysis, racket sports, CSAI-2R, STAI-S

Introduction

The sport of padel is witnessing exponential growth worldwide, with participation from more than 80 nations affiliated with the International Padel Federation (1). This expansion has prompted a marked rise in scholarly investigations, particularly focused on assessing technical and tactical performance (2–4).

Mental toughness, as evidenced by its capacity to enable athletes to uphold or enhance performance during challenging circumstances (5), holds a particular significance in the context of sports psychology. Within this domain, anxiety is seen as a concept characterized by an emotional reaction to a perceived threat, blending physiological arousal and cognitive apprehensions (6). In a competitive scenario, a distinction can be made between a stable personality disposition termed trait anxiety (7), and the transient symptoms encountered during a specific competition, referred to as state anxiety (8). Cognitive anxiety encompasses adverse anticipations of success or self-evaluation, negative thinking, reduced self-worth, pessimistic inner dialogues, fear of failure, diminished self-belief, performance worries, visions of failure, challenges in concentration, and disrupted attention (9–11). Somatic anxiety is linked to autonomic arousal, presented as increased heart rate or muscle tension, contributing to negative sensations like nervousness, breathing difficulties, heightened blood pressure, dry throat, muscle strain, rapid heartbeat, clammy palms, and a sensation of butterflies in the stomach (9, 11, 12). Self-confidence, defined as a player's conviction in his/her ability to perform effectively in competition (13), is a facet studied within this construct to gauge the athlete's comprehensive sense of accomplishment (14).

In this sense, competitive anxiety and self-confidence, specially prior to competition, has been extensively studied in recent decades (15–17). Research has shown that athletes with elevated anxiety levels often demonstrate poorer performance in competitions in comparison to those with lower anxiety levels (18–20). Additionally, there exists a direct correlation between the player's self-confidence and his/her performance in sports (20, 21). Once the competition is over, athletes from different sports such as football, basketball and volleyball show lower levels of competitive anxiety than moments prior to the event (22–24). The same happened to taekwondo athletes, who also showed higher levels of self-confidence at this stage (25). However, to the best of our knowledge, there is only one study, in tennis, which distinguishes winning vs. losing players regarding post-competitive anxiety and self-confidence, with the former showing notably reduced cognitive anxiety and elevated self-confidence compared to the latter (16).

A key performance indicator shaping match results in professional padel is the effectiveness of the ultimate shot (26–28). From these investigations, it has been established that a point in the game can culminate through a winner, a forced error or an unforced error. A winner occurs when a player secures the point directly (i.e., after the ball bounces correctly on the opposing side after crossing the net, the ball bounces for a second time; or the ball strikes the opponent's body before being out). Conversely, a forced error happens when a player loses the points due to difficulty in executing a shot or being poorly positioned following the opponent's shot. Finally, an unforced error arises when a player loses the point despite facing a relatively straightforward situation with favorable space-time conditions (27). Winning pairs commit more winners and less unforced errors than losing pairs (2, 29, 30). Nevertheless, while previous articles dissect each method of concluding the point separately, our research not only does so but also advocates for the adoption of technical-tactical performance ratios. These ratios are advantageous as they remain unaffected by the number of points, games, or sets. Moreover, regarding the court area, winners are mainly executed from the net area (30) while errors, regardless of the type, are evenly distributed between the net and the back of the court. In absolute terms, overheads and volleys are the primary sources of winners (31), whereas forced errors often result from volleys, and unforced errors mainly arise from volleys and groundstrokes with no wall (26).

Upon reviewing the scientific literature, the combination of mental preparation and performance in padel has received limited attention, with only a few studies exploring precompetitive anxiety and self-confidence (32–34) and none of them studying post-competitive anxiety and self-confidence. Understanding the interplay between a player's anxiety, self-confidence, and performance holds substantial value for players, coaches, and sports psychologists. This insight can enable players to adapt their playing style, while coaches and psychologists can customize feedback and training sessions accordingly. The aims of the present investigation were to analyze: (1) the differences between pre and post-competitive anxiety and self-confidence during matches in high level men's padel players from Finland as a function of the result, (2) the differences between winning and losing players regarding anxiety and self-confidence as a function of the moment (pre or post-match), (3) the technical-tactical performance according to the result and (4) the correlation among technical-tactical performance, anxiety and self-confidence. Therefore, the following hypotheses were put forward: (1) match winning players will show higher levels of self-confidence and lower levels of anxiety in the post-match compared to pre-match; the opposite will happen in the match losing players, (2) before and after the match, respectively, match winning players will display higher levels of self-confidence and lower levels of anxiety than match losing players, (3) match winning players will make more winners and generators of forced errors, and less forced and unforced errors than match losing players, (4) there will be a direct correlation between winners and self-confidence in match winning players, whereas in match losing players, there will be a direct correlation between errors and anxiety, and an indirect correlation between errors and self-confidence.

Material and methods

Study design

The design of this research is framed under an empirical methodology and more specifically it is a study with a descriptive strategy. On one hand, questionnaires are applied (psychological variables) (35) and, on the other hand, matches are observed, the latter being nomothetic, punctual and multidimensional (technical-tactical performance variables) (36).

Sample and participants

We analyzed 12 matches in which 1,514 points were disputed. Following a convenience sampling, these matches were played by a total of 11 men's high-level padel players (27.91 (5.03) years old and 4.64 (1.86) years of competitive experience) from Finland who voluntarily participated in the present study. This represents almost 50% of the total target population. An observational study of elite athletes from volleyball included 14 athletes who were in preparation for competing in important events, representing a similar sample size in a similar context (high-level athletes prior to competition) (37). The STROBE flow chart (Figure 1) was used to ensure that the clear assessment of participants (38). All participants were ranked top 24 in Finland. None of the athletes had any physical injuries nor were they taking any medication at the time of the measurements. In addition, none of the participants had any reason that prevented them from participating in the study.

The study was in accordance with the Helsinki Declaration (39). Participants were treated ethically under the American Psychological Association code of ethics regarding consent, anonymity and responses. Previously, the current investigation had been approved by the Ethics Committee of the European University of Madrid with the code CIPI/22.303. So as to respect the principles of voluntariness and confidentiality, each player was required to sign an informed consent form that clearly explained the objectives of the research and their voluntary participation in it.

Study variables

To carry out this study, the following variables were taken into account:

- Psychological variables: somatic anxiety, cognitive anxiety, self-confidence (9, 11, 13) and state anxiety (40). CSAI-2R questionnaire was used to measure somatic and cognitive anxiety and self-confidence of players (41) and STAI-S questionnaire was used to measure their state anxiety (42). These questionnaires have been used in previous research in padel (34). All questionnaires were completed in a quiet room with controlled temperature of 20°C. Participants completed the questionnaires in English, as it is the only language that both researchers and athletes are fluent in. Participants were not allowed to speak during the assessments. In the analysis of the CSAI-2R instrument, Cronbach's alpha coefficients were obtained, showing reliability scores of .75 (for pre), .72 (for post) for cognitive anxiety, .84 (for pre), .90 (for post) for somatic anxiety, and .72 (for pre), .88 (for post) for self-confidence, all meeting acceptable standards (43–45).
- Technical-tactical performance variables [defined based on their categorical core and degree of openness (46)]:
- Effectiveness of the last shot: a difference was made between winner, forced error and unforced error (27).
- Forced error generator: shot which induces a forced error in the opposing pair (47).

In addition, technical-tactical performance ratios were calculated using the above mentioned technical-tactical performance variables. It is worth noting that the effectiveness of the shots is considered a performance indicator in racket sports (48).

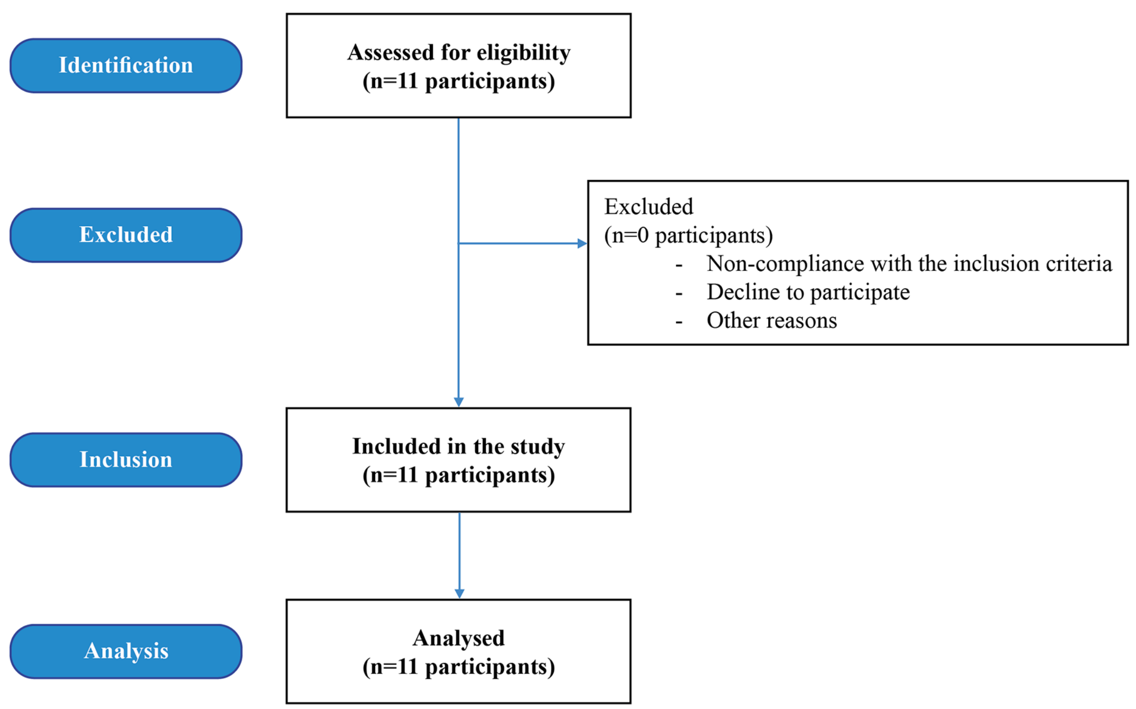

FIGURE 1
STROBE flowchart. Adapted from https://www.strobe-statement.org/.

Procedure

The questionnaires were administered to the players between 30 and 45 min prior to the start of each practice match, following the same criteria to that used by Conde-Ripoll et al. (34). 15–30 min after the practice match is over, the questionnaires were administered for post-competitive anxiety and self-confidence.

During each practice match, which followed the International Padel Federation rules, a certified padel coach with more than 10 years of experience, recorded the technical-tactical performance study variables through an ad-hoc instrument in Excel, following similar criteria than previous research (49, 50). At the end of the collection process, an intra-observer reliability analysis was performed to ensure the veracity of the data collected. The observer reanalyzed a random sample of 3 matches (matches were previously recorded) to ensure enough relevant data to represent 10%–20% of the study sample (51). The mean intra-observer reliability was.90, considered almost perfect (52). In addition, another observer, a doctor in sports sciences, with more than 20 JCR scientific articles published related to the topic of study, also analyzed a random sample of 3 matches to calculate the average inter-observer reliability, which was.84 (52).

Statistical analysis

Shapiro-Wilk (considering $n = 11$ athletes) and a Kolgomorov-Smirnov (considering $n = 1{,}514$ points) tests were used to test the normality of the distribution of the data and it indicated that it is non-parametric. Then, a descriptive analysis was performed to obtain information on the number of times each study variable occurred (median and interquartile range).

Next, inferential analyzes were then conducted, including Wilcoxon signed-rank and Mann-Whitney´s *U*-tests. Additionally, effect sizes [*r*] were calculated for the non-parametric tests, which were classified as follows: .5 is a large effect, .3 is a medium effect and .1 is a small effect (53, 54).

Finally, a bivariate correlation analysis among psychological and technical-tactical performance variables in different contexts using Spearman's correlation.

All data were analyzed using the statistical package SPSS for Macintosh v.25.0 (SPSS Inc, Chicago, IL, United States) and a *p* value of less than .05 was considered to be statistically significant.

Results

As can be seen in Table 1, regarding differences between before and after the matches, losing players showed a significant surge in cognitive, somatic and state anxiety alongside a significant decline in self-confidence; whereas winning players only displayed a significant increase in state anxiety. Besides, match-winning players significantly exhibited more self-confidence post-match compared to losers.

Evidenced in Table 2, winning players significantly produced more winners than losing players per match. The same occurred in every single technical-tactical performance ratio [for example:

TABLE 2 Differences in technical-tactical performance of the padel players according to the match outcome.

Variable	Winning players		Losing players		*p*	ES
	Median	IQR	Median	IQR		
W	13.50	7.00	9.00	6.00	.010*	.373
GFE	8.00	4.00	7.50	5.00	.298	.150
FE	7.00	5.00	9.00	4.00	.110	.231
UE	9.50	5.00	12.00	6.00	.356	.133
W/UE	1.31	0.82	0.91	0.55	.001*	.460
(W + GFE)/UE	2.10	1.22	1.63	0.95	.002*	.442
W/(FE + UE)	0.85	0.51	0.49	0.25	.001*	.502
(W + GFE)/(FE + UE)	1.33	0.75	0.83	0.36	<.001*	.515

W, winner; GFE, generator of forced error; FE, forced error; UE, unforced error; SD, standard deviation; *p*, *p*-value; ES, effect size.
*$p < .05$.

TABLE 1 Anxiety and self-confidence according to the moment (pre and post) and match outcome.

Match outcome	Variable	Pre median (IQR)	Post median (IQR)	Pre vs. post-measure		Winning vs. losing players pre		Winning vs. losing players post		Winning vs. losing players pre-post	
				p	ES	*p*	ES	*p*	ES	*p*	ES
Winning player	CA	1.50 (.60)	1.60 (75)	.407	.169	.361	.132	.457	.107	.064	.267
Losing player		1.30 (.40)	1.70 (.60)	.004*	.592						
Winning player	SA	1.29 (.43)	1.43 (.29)	.731	.070	.328	.141	.323	.143	.124	.222
Losing player		1.43 (.54)	1.50 (1.32)	.020*	.475						
Winning player	SC	3.20 (.60)	3.20 (.60)	.746	.066	.123	.222	.015*	.353	.093	.242
Losing player		3.00 (.40)	3.00 (.80)	.014*	.503						
Winning player	STA	5.50 (3.00)	6.00 (5.00)	.022*	.466	.338	.138	.112	.229	.192	.188
Losing player		6.00 (5.00)	8.50 (7.00)	.001*	.685						

CA, cognitive anxiety; SA, somatic anxiety; SC, self-confidence; STA, state anxiety; *p*, *p*-value; ES, effect size.
*$p < .05$.

winner/unforced error or (winner plus generator of forced error)/unforced error].

As depicted in Table 3, there are indirect correlations between somatic and cognitive anxiety, between state anxiety and self-confidence, in winning players; and between forced errors and cognitive anxiety in losing players.

In addition, there are direct correlations between state anxiety and somatic anxiety in winning players; between state anxiety and cognitive anxiety, and between state anxiety and somatic anxiety, in losing players.

As shown in Table 4, there are indirect correlations between state anxiety and self-confidence in winning players; and between self-confidence and cognitive anxiety, between self-confidence and somatic anxiety, between state anxiety and self-confidence, in losing players.

In addition, there are direct correlations between state anxiety and cognitive anxiety, between unforced errors and state anxiety, in winning players; and between somatic anxiety and cognitive anxiety, between state anxiety and somatic anxiety, between generators of forced error and cognitive anxiety, in losing players.

Highlighted in Table 5, there are indirect correlations between self-confidence and somatic anxiety in winning players; and between winners and somatic anxiety, between unforced errors and state anxiety in losing players.

In addition, there are direct correlations between somatic anxiety and cognitive anxiety, state anxiety and somatic anxiety, winners and cognitive anxiety, unforced errors and state anxiety in winning players; and between somatic anxiety and cognitive anxiety, between state anxiety and cognitive anxiety, between forced errors and cognitive anxiety in losing players.

Illustrated in Table 6, there are direct correlations between unforced errors and generators of forced error, and between unforced errors and forced errors, in winning players; and between unforced errors and winners in losing players.

TABLE 3 Correlations between the pre-competitive values of the psychological and technical-tactical performance variables, in winning and losing players.

	Winning players							
	CA	SA	SC	STA	W	GFE	FE	UE
CA	1	−.558**	−.094	.056	−.211	.029	.104	.295
SA		1	−.281	.456*	.090	.194	−.035	−.217
SC			1	−.662**	.146	.063	−.332	.019
STA				1	−.259	−.018	.299	−.097
	Losing players							
	CA	SA	SC	STA	W	GFE	FE	UE
CA	1	.377	−.305	.458*	.066	.225	−.524**	.247
SA		1	.022	.500*	.111	−.057	.181	.160
SC			1	−.186	.356	−.207	.080	.136
STA				1	−.033	.236	.070	−.049

CA, cognitive anxiety; SA, somatic anxiety; SC, self-confidence; STA, state anxiety; W, winner; GFE, generator of forced error; FE, forced error; UE, unforced error.
*$p < .05$.
**$p < .01$.

TABLE 4 Correlations between the post-competitive values of the psychological variables, and technical-tactical performance variables, in winning and losing players.

	Winning players							
	CA	SA	SC	STA	W	GFE	FE	UE
CA	1	−.221	−.054	.621**	.098	.077	.020	.299
SA		1	−.361	.082	.153	.147	−.085	−.122
SC			1	−.533**	.126	−.025	−.172	−.201
STA				1	.197	.094	.316	.490*
	Losing players							
	CA	SA	SC	STA	W	GFE	FE	UE
CA	1	.602**	−.586**	.285	−.146	.433*	.180	−.131
SA		1	−.412*	.619**	−.233	.089	.189	−.167
SC			1	−.444*	.240	−.247	−.203	.049
STA				1	−.313	.182	.227	−.299

CA, cognitive anxiety; SA, somatic anxiety; SC, self-confidence; STA, state anxiety; W, winner; GFE, generator of forced error; FE, forced error; UE, unforced error.
*$p < .05$.
**$p < .01$.

TABLE 5 Correlations between values of the psychological (post minus pre) and technical-tactical performance variables in match winning and losing players.

	Winning players							
	CA	SA	SC	STA	W	GFE	FE	UE
CA	1	.502*	−.177	.296	.435*	.097	−.077	.155
SA		1	−.592**	.499*	.078	−.129	−.049	.248
SC			1	−.350	.042	−.093	.188	−.154
STA				1	.336	.099	.157	.520**
	Losing players							
	CA	SA	SC	STA	W	GFE	FE	UE
CA	1	.483*	−.377	.492*	−.195	.274	.643**	−.402
SA		1	−.314	.264	−.410*	.106	.162	−.384
SC			1	−.254	−.007	−.155	−.256	−.076
STA				1	−.382	.047	.240	−.418*

CA, cognitive anxiety; SA, somatic anxiety; SC, self-confidence; STA, state anxiety; W, winner; GFE, generator of forced error; FE, forced error; UE, unforced error.
*$p < .05$.
**$p < .01$.

TABLE 6 Correlations between technical-tactical performance variables, in match winning and losing players.

	Winning players			
	Winner shot	Generator of forced error	Forced error	Unforced error
Winner shot	1	.090	.042	.318
Generator of forced error		1	.245	.432*
Forced error			1	.511*
Unforced error				1
	Losing players			
	Winner shot	Generator of forced error	Forced error	Unforced error
Winner shot	1	.329	.246	.512*
Generator of forced error		1	.251	.119
Forced error			1	−.020
Unforced error				1

*$p < .05$

Discussion

Our initial hypothesis suggested that winning pairs would exhibit higher self-confidence and lower anxiety in the post-match, compared to pre-match; while losing players would show the opposite pattern. Our findings partially supported this hypothesis. Winning players displayed higher state anxiety post-match, possibly due to unmet performance expectations or individual variability within winning pairs. Conversely, losing players demonstrated expected increases in anxiety and decreases in self-confidence post-match, potentially due to underperformance and emotional distress. This contrasts with prior research on singles tennis players on official competition (16). Overall, these findings highlight the contrasting impact of victory and defeat, indicating that while winning might not necessarily yield favorable effects, the repercussions of losing could be considerably detrimental to players. Consequently, coaches and players are prompted to participate in psychological training to skillfully manage the outcomes of triumph and loss (55), facilitating their continual evolution and growth as athletes. Additionally, recognizing padel as a partner sport emphasizes the interdependence between players, where individual performance directly affects the overall outcome, underscoring the importance of effective communication, trust, and mutual support within pairs.

The second hypothesis that match-winning players would exhibit higher self-confidence and lower anxiety before and after the practice match, compared to match-losing players, was partially supported. Prior to the match, no significant differences were found, consistent with previous research (34). Post-match, only self-confidence showed significant differences, with match-winning players exhibiting higher levels. This could be due to the fact that the increase of self-confidence is linked, among other factors, to positive performance results (56). In this line, Fuentes-García et al. (16) observed higher post-match self-confidence among winning elite junior tennis players compared to losers.

Additionally, it was third hypothesized that match-winning players would make more winners and forced error generators, and fewer forced and unforced errors compared to match-losing players. This hypothesis was partially supported. Significant differences were found in the number of winners, aligning with prior research (29, 30), highlighting the importance of winners as a key performance indicator in padel. Athletes should collaborate closely with their coaches to enhance strategies for increasing winners during training sessions. This could involve reviewing competitive or practice matches to discern winner shots and their underlying reasons (57). Additionally, coaches could implement exercises that emphasize and incentivize winners (58, 59). Although not statistically significant, winning players produced more generators of forced error, while losing players committed more forced and unforced errors. Regarding the latter, losing players significantly commit more unforced errors than winning players (2, 60) in the professional level. Additionally, winning players demonstrated technical-tactical performance ratios, emphasizing the usefulness of such ratios for evaluating padel players, as they are independent of the number of points, games, or sets. To illustrate, making 10 winners in a 6/0 6/0 match where each game is won at 40/0 (48 points in total) is not equivalent to achieving the same feat in a 7/6(5)—6/7(5)—7/6(5) match where each game is won at a golden point and each tiebreak was won 7/5 (120 points in total).

As a final hypothesis, it was established that there would be a direct correlation between winners and self-confidence in winning players, whereas in losing players, there would be a direct correlation between errors and anxiety, and an indirect correlation between errors and self-confidence. Acceptance of this hypothesis was partial. Winning players showed direct correlations between the number of winners and cognitive anxiety. This suggests that executing winners may evoke a heightened level of mental engagement, reflecting the complexity of the task. Likewise, significant direct correlations were found between generators of forced error and post-cognitive anxiety in losing players. This could be due to the defensive skills of the opponents, the winning players, who actively tried to reach even the most challenging shots. Significant direct correlations were found between unforced errors and state and post-state anxiety in winning players. Committing unforced errors may contribute to heightened state anxiety among winning players, since they may not like the idea of giving "free" points to the opponents through avoidable errors. And heightened anxiety levels indicate a decrease in sports performance (61, 62) and anticipation efficiency (63). Hence, these players could benefit from working closely with a sport psychologist, to develop resilience strategies to effectively cope with the frustration of pressure stemming from errors (64), emphasizing techniques such as reframing perspectives on mistakes. Significant direct correlations were found between forced errors and cognitive anxiety in the losing players. The rationale behind this observation might be losing players' emotional reactions to their failure in executing demanding shots, potentially influencing their perception of the effective technical-tactical maneuvers executed by winning players. Hence, coaches and sport psychologists could implement targeted training sessions focusing on stress management techniques and simulated match scenarios that replicate high-pressure situations (65). Indirect correlations were found between forced errors and pre-cognitive anxiety, and between unforced errors and state anxiety, among the losing players. When losing players make mistakes that they feel they can control and improve upon during practice matches, they may feel more responsible for those mistakes. Tailored approaches may assist in reframing perceptions of errors (66, 67) and pre-competition nervousness, ultimately aiding players in better managing their anxieties during matches. Furthermore, indirect correlations were found between winners and somatic anxiety among losing players. In fact, anxiety has been shown to impair sports performance (68–70).

Practical applications

It is important to consider these results when structuring personalized training programs for each athlete and formulating task-specific training exercises. For example, doing exercises which make the athlete feel a higher level of self-confidence (71) and a lower level of anxiety after losing a practice match, especially if there is a tournament in the upcoming days may be of great importance for the future performance in that competition. Furthermore, coaches are instigated to integrate pressure training into their sessions with athletes to enhance athletes' performance in competition (65). This approach involves exposing athletes to pressure scenarios during practice, fostering their ability to perform proficiently under pressure (59), which can be defined as the athlete's heightened sense of the importance of performing well (72). It is essential to highlight that in padel, players are consistently required to make rapid decisions within brief timeframes (73) and the capability to manage pressure situations directly affects one's performance (74–76). Thus, coaches can implement consequences (such as judgement, forfeits, rewards), establish demands, and planned disruption during pressure training (77, 78). In this line, research indicates that consequences induce higher levels of pressure compared to demands (77), and an example of a consequence could be the head coach monitoring players' padel technical-tactical performance.

Strengths

This study presents several strengths. Firstly, it pioneers research in padel by delving into pre- and post-competitive anxiety alongside self-confidence. Secondly, it stands as the initial study in padel to establish a correlation between technical-tactical performance and anxiety/self-confidence. Thirdly, its findings hold substantial practical implications for coaches and sports psychologists, particularly considering the differences in psychological variables in practice match losing players.

Limitations and future studies

Despite employing a similar methodology to recent research in the domain, it is essential to underscore certain inherent limitations within this study. In future studies, researchers are encouraged to examine whether anxiety and self-confidence responses manifest similarly in both sexes. Although the questionnaires employed are valid and reliable, one specific limitation is that self-confidence and anxiety are assessed through self-perception, and some measurements of internal load (hormones such as cortisol, autonomic modulation or cortical arousal) could enhance the comprehension of the relationship between technical-tactical performance and anxiety/s`elf-confidence. Future research should consider athletes from different levels (beginners, amateur, professional players…).

Conclusion

Losing players demonstrated elevated cognitive, somatic, and state anxiety, along with reduced self-confidence, while winning players experienced an increase in state anxiety post-match compared to their pre-match levels. Post-match, self-confidence was higher among winning players. In terms of technical-tactical performance variables, winning players made more winners than losing players. They also outperformed the losing players in every technical-tactical performance ratio. Besides, direct correlations were observed between unforced errors and state anxiety (both post-, and pre-post), and between winners and cognitive anxiety (pre-post) in winning players; between generator of forced errors and post-cognitive anxiety, and between forced errors and cognitive anxiety (pre-post) in losing players. Indirect correlations were observed between forced errors and pre-cognitive anxiety, between winners and somatic anxiety (pre-post), between unforced errors and state anxiety (pre-post) in losing players. Players are encouraged to develop their mental skills to manage errors and defeat. Likewise, coaches are encouraged to include pressure training and promote the appearance of winners in simulated matches.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Ethics Committee of the Universidad Europea de Madrid with the code CIPI/22.303. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

RC-R: Conceptualization, Data curation, Investigation, Methodology, Resources, Validation, Writing – original draft, Writing – review & editing. AE-T: Conceptualization, Supervision, Validation, Writing – original draft. ÁB-S: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing, Resources.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The handling editor JR declared a past co-authorship with the author AE.

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Anticipation training for expert tennis players when facing a specific player

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Introduction: In fast ball sports, such as tennis, when spatiotemporal constraints are high, players have to anticipate the opponent action. Not much is known about how players acquire and improve this ability. The aim of this study was to use an implicit training protocol (no information was given to participants) based on the knowledge of one particular opponent to analyse how experts could improve their anticipation ability.

Method: Professional tennis players were tested and trained in a protocol consisted of watching videos with temporal occlusions before the opponent stroke and guessing the direction of the stroke. Three groups took part in the experiment: one with a specific training with the same opponent as in pre- and post-tests; one with a various training with players other than the one used in pre- and post-tests (to control that the improvement is link with the knowledge of one specific opponent and not to an adaptation to the task) and one control group without practice.

Results: Only the group trained with the same opponent increased its response accuracy.

Discussion: Our results suggest that anticipation can be improved in professional tennis players with a very specific training providing information about the opponent.

KEYWORDS

anticipation training, contextual information, tennis, implicit protocol, experts

1 Introduction

In ball sports, experts have to produce their actions under a tight time pressure. In some situations, they don't have enough time to wait for a complete information to decide what response to provide (Triolet et al., 2013). In such situations they produce anticipations based on partial information and their knowledge of the game and of their opponent. Therefore, perceptual-cognitive skills are a key attribute of expertise in fast ball sports such as tennis (Williams et al., 2011). One of the questions that arises in this field is how these anticipation skills are learned and can be improved through training. In this article we aim to show that it is possible to improve this ability for expert tennis players against a specific opponent using a short training protocol based on video footages.

It appears that three main factors determine anticipation skills. First, experts are better than novices to recognize sport-specific patterns (North et al., 2011). Secondly, they can better use kinematic information from their opponent when he/she is preparing is action (Farrow et al., 2005). Thirdly, regarding the use of contextual information, the findings from previous studies are more mixed. Indeed, depending on the type of contextual information used [such as knowledge of the opponent (McRobert et al., 2011), the score

(Farrow and Reid, 2012), or the relative positioning of players during the point (Loffing and Hagemann, 2014)], it appears that experts can access to this information, but sometimes intermediate players or even novices can as well. For example, Farrow and Reid (2012) demonstrated that only experts were able of using the score to enhance the relevance of their anticipations, whereas the positioning of opponents and teammates was a source of information accessible to intermediate-level players (Paull and Glencross, 1997). The use of knowledge about the opponent and their playing habits seems to be limited to expert players (McRobert et al., 2011). Finally, the use of the relative positioning of players during the point appears to depend on the quality of the contextual information available (Triolet et al., 2022). If anticipation is admitted as a key determinant of expertise, the training of this skill appears to be an essential question for performance in fast ball sports (see Zentgraf et al., 2017 for a review). Protocols were mostly based on occlusion paradigms (Farrow and Abernethy, 1998) and two different performance factors are generally used to analyze protocol-related improvement, with the decrease of reaction time and/or the improvement of response accuracy.

Concerning response accuracy, Scott et al. (1998) showed an improvement after a training protocol for intermediate tennis players to return a serve. The task was to predict the bounce location of the serve that was occluded at the impact. During training sessions, participants were shown videos of the serve in slow motion (see for more examples, Abernethy et al., 1999; Alsharji and Wade, 2016).

Concerning the decrease of response time, Farrow and Abernethy (1998) conducted a study in which tennis beginners were taught to pay attention to certain elements considered important for anticipation such as the position of the server's feet, the ball's delivery, the position of the racket and its speed. After eight 15-min training sessions in which the players saw videos of various serves from "good players" with temporal occlusions, the trained group significantly improved their response times (see Williams et al., 2003 for more examples).

Finally, Moreno et al. (2002) trained recreational tennis players and analyzed the evolution of accuracy and reaction time. Results mainly showed exchanges between response accuracy and response time. For some participants, a decrease in response time was associated with a decrease in response accuracy while for other participants, the inverse evolution was observed. There are therefore inter-individual differences in learning and the priority between time and accuracy of responses may vary.

Researchers have also investigated the impact of various instructional methods and techniques to direct participants' attention. For instance, Smeeton et al. (2005) conducted an experiment in tennis involving four distinct groups: an explicit group that received prescriptive information, such as the location of relevant advance cues and their impact on performance; a guided discovery group that was informed about the location of key postural cues and encouraged to deduce the relationship between body position and shot outcome; a discovery group that was prompted to explore the relationship between perceptual cues and shot outcomes independently; and a control group that received no instruction. Participants undertook two different tasks: a laboratory task and a field task. All three intervention groups showed performance improvements from pre-test to post-test. However, the explicit group's improvements appeared less robust under pressure. Additionally, the explicit and guided discovery groups demonstrated faster performance improvements during training compared to the discovery group.

The research indicates a predominant focus in training protocols on enhancing the pick-up of kinematic cues (Smeeton et al., 2005; Abernethy et al., 2012), with comparatively fewer studies concentrating on pattern recall (for an exception see Schorer et al., 2018) or the use of contextual information (for an exception see Gray, 2015). Broadbent et al. (2015) recommended integrating contextual information into training protocols to better reflect real-world performance demands. Triolet et al. (2013), in an *in-situ* analysis of expert tennis players, further demonstrated that the use of contextual cues significantly improved anticipation accuracy.

Furthermore, Loffing and Cañal-Bruland (2017) raised an important question concerning the optimal methods for communicating situational probabilities to athletes, pointing toward the need for more effective instructional strategies in training. Given that anticipation often involves implicit processes, it is plausible that implicit learning protocols might provide distinct advantages. Farrow and Abernethy (2002) explored this possibility by comparing explicit and implicit methods. A progressive temporal occlusion paradigm was employed to assess players' abilities to predict the direction of an opponent's serve on the tennis court before and after training. Players were instructed to respond either by attempting a return of serve or verbally predicting the serve's direction. The study included four groups: (a) an explicit learning group, which watched videos of serves accompanied by a tennis instructor explaining the relationships between key biomechanical cues and serve direction; (b) an implicit learning group, which watched the same videos without receiving any explicit information but were instead tasked with estimating the ball's speed during the serve; (c) a placebo group, which received no instructional input beyond watching tennis videos; (d) a control group, which did not watch any videos. The findings showed that only the implicit learning group demonstrated a significant improvement in the accuracy of their serve direction predictions following the training.

Wulf and Weigelt (1997), in a study aimed at developing a complex motor skill on a ski simulator, provided another definition of learning protocols. They distinguished explicit learning, where participants are given explicit information or instructions to aid task performance, and implicit learning, where participants are informed only of the task's goal, without any guidance on how to achieve it.

Finally, it is interesting to underline that only few training research studies have been conducted with experts (for exceptions, see Fadde, 2016 who ran a training protocol during the entire season with a college baseball team or Alsharji and Wade (2016) who ran a training protocol with elite and national youth handball goalkeepers).

In this context, the aim of this study was to use an implicit training protocol according to the definition from Wulf and Weigelt (1997) to determine whether a specific anticipation training protocol facing one specific opponent enable experts to improve their capacity to predict his actions. Three groups took part to the protocol. The first group followed an anticipation training in order to improve their ability to predict the shots of a specific player (same opponent Group). The second had the same training protocol with different players to check if the expected improvement of the first group was not due to an adaptation to the task (various opponents Group). The third one was a control Group without training session.

We hypothesized that the same opponent Group should improve both their percentage of correct responses and their response speed, as the result of taking better account of their opponents' playing preferences (McRobert et al., 2011). Considering that we worked with expert players and that tactical information to enhance anticipation skills can be used even by non-expert players, it is plausible that this information has already been acquired by our expert players and, therefore, will not contribute to further improvements in their anticipation (Triolet et al., 2022). This is why no improvement was expected for the various opponents Group.

2 Methods

2.1 Participants

Thirty-nine male expert players (mean age: 28.1 ± 9.92 years old) took part in this experiment. They were all international or national players and practiced tennis since 17.38 ± 8.5 years on average. They were ranked between 4.5 in the American ranking and the top ten ATP ranking. They have been randomly divided into three groups of 13 players: the same opponent Group, the various opponents Group and the control Group. The three groups were equivalent in terms of tennis experience and age (Table 1). Participants took part voluntarily in the experiment and written and informed consent were obtained. The research received ethical approval from the lead institution.

TABLE 1 Participants' characteristics according to the different groups.

	Mean age (years)	Average number of years of tennis practice (years)
Same opponent group	28.15 (±10.82)	18.62 (±9.36)
Various opponent group	26.62 (±10.44)	15.38 (±7.34)
Control group	29.38 (±9.03)	18.15 (±8.99)

2.2 Materials

2.2.1 Clips and task

One hundred and sixty-eight video clips were obtained from broadcast male ATP tennis games, filmed in the longitudinal axis of the court. Each clip ended with a winning shot (could be any tennis shots, except serves) delivered by the player filmed at the top of the screen from a frontal perspective. The winning shot occurred on the 4th stroke of the rally in a very unfavorable situation for the opponent. This kind of shot was selected to increase the need to anticipate for the participant (Triolet et al., 2013). The occlusion moment was set 340 ms before ball/racket contact in order to avoid providing participants kinematic information related to shot outcome (Farrow and Abernethy, 2003). Participants had to indicate where the occluded shot would be played, either on the right or left side of the pitch, by pressing a corresponding button on a keyboard.

An expert reference player has been chosen to make the pre-test and post-test clips for all groups. He has been ranked ATP No. 4 and was professional until 1999. The pre-test and post-test consisted of 12 trials in which the expert reference player made a winning shot. No feedback was given to the participants after the clip.

After the pre-test, the same opponent Group had a training phase composed of 72 trials in which the expert reference player made a winning shot. Then they finished with the post-test. The various opponent Group was also doing the pre- and post-test facing the expert reference player. However, during the training phase, they were confronted to twelve different players other than the expert reference player. These players have been ranked between ATP Nos. 1 and 12. The clips were selected on the same principle with a winning shot occurring after four shots. This group had the same amount of trials. The control Group only realized the pre-test and post-test without feedback.

2.2.2 Procedure

Video clips were presented on a 17″ laptop (Dell, Round Rock, TX, USA) using a specific software (E-Prime, Psychology Software Tools, Inc., Pittsburgh, USA). Participants sat 40 cm from the laptop's screen. The experiment was run in one session and the total duration of the experiment was ∼1 h for training groups and 15 min for the control group. The response accuracy (right/left) and the response time for each clip were recorded by the E-prime program.

Each trial began with a countdown from 3 to 1 before starting with a freeze frame of the first image. Then the video began 200 ms before the first stroke of the sequence (Figure 1A) and ended 340 ms before the 4th stroke hit by the player at the top of the screen (Figure 1C). To avoid participants being influenced by the behavior of the player at the bottom of the screen (i.e., player to whom the participant had to substitute himself), the player was hidden by a black rectangle 200 ms after his last stroke (Figure 1B).

When occlusion occurred, the screen turned black and the participant had 1 s to indicate if the opponent played a winning shot directed on the right by pressing the key "P" or on the left side of the court by pressing the key "A". For the pre-test and the post-test series, a new trial began immediately after the response. For the training series for training groups, feedbacks were given to the participant.

The experiment began with a familiarization session containing 12 trials with various opponents. After this, the participant had to respond to the pre-test series containing 12 trials with the same player. The same opponent and various opponents groups were then facing six training series of 12 trials each. Finally, the post-test

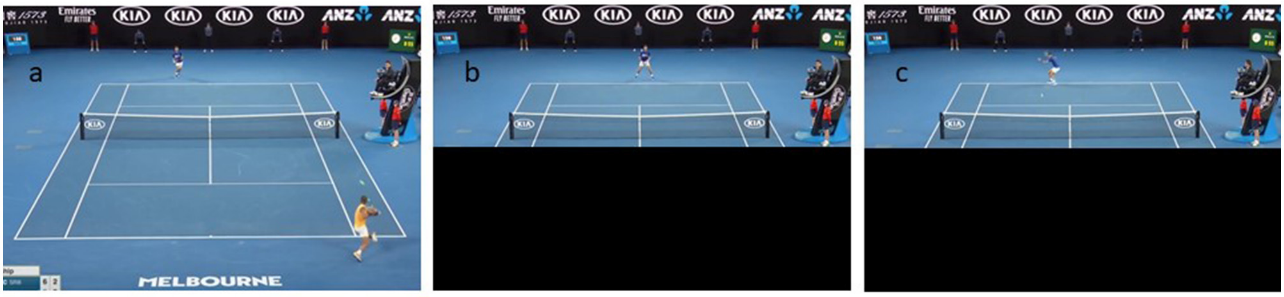

FIGURE 1
Illustration of the procedure of one trial. **(A)** Shows the frozen image at the beginning of the clip. The clip unfolds. **(B)** Shows the rectangle that hides the bottom player after his last shot. **(C)** Shows the last image before total occlusion and the participant's response.

series containing 12 trials was conducted. Training series and clips inside each series were presented in a randomized order.

During the training session, two kinds of feedback were given: first, the participant was told whether his response was right or wrong; second, he watched the sequence again without occlusion to allow him to pick up additional information. No feedback was provided by the experimenter. As soon as the clip with the response was finished, a new trial was started. At the end of each block, feedback relating to the percentage of correct responses for each block was provided to keep the participant's interest and to encourage him to improve it.

2.3 Data analysis

For each participant, the percentage of correct responses and the mean response time were calculated as dependant variables.

No data were excluded by the experimenters. However, there were 52 trials out of 936 in which participants took too long to respond (more than 2 s) and for which no values were recorded.

Data were analyzed using two-way factorial repeated measures ANOVAS with Groups (the same opponent Group, the various opponents Group and the control Group) as a between-participants factor and Tests (Pre and post tests) as within-participants factors. The obtained percentages of correct responses were transformed to Fisher z-scores (Fisher, 1942) in order to run ANOVAS. The significance level set for the statistical analysis was $p < 0.05$.

3 Results

3.1 Percentage of correct responses

ANOVA on mean percentage of correct responses revealed a main effect for Groups, [$F_{(2,36)} = 4.005$, $p < 0.05$, $\eta^2 = 0.182$] and an interaction effect between Groups and Tests [$F_{(2,36)} = 3.528$, $p < 0.05$, $\eta^2 = 0.164$] (Figure 2). Newman-Keuls *post-hoc* tests on the interaction showed that percentages of accuracy were not different for the pre-test between the three groups. The percentage of correct responses of the same opponent Group significantly increased with training, while it was not the case for the others groups. For the post-test, the percentage of correct responses of the same opponent Group is significantly different from the percentages of correct responses obtained by this group in the pre-test and by the control and the various opponents Groups in both the pre-test and the post-test.

3.2 Response time

ANOVA on response time revealed no effect for Groups, [$F_{(2,36)} = 0.976$, $p > 0.05$] and no interaction effect between Groups and Tests [$F_{(2,36)} = 1.730$, $p > 0.05$]. However, *ANOVA* revealed a main effect for Tests [$F_{(1,36)} = 20.087$, $p < 0.05$, $\eta^2 = 0.358$]. The mean response time for all participants decreased from 669 ms (±77) to 495 ms (±84) for the pre- and post-test, respectively (Table 2).

TABLE 2 Mean response time for each group.

	Pre test response time (ms)	Post test response time (ms)
Same opponent group	734.82 (±296)	463.59 (±257)*
Various opponents group	584.42 (±229)	431.24 (±221)*
Control group	687.34 (±327)	589.36 (±282)*

*Shows a significant difference between the mean response time in pre-test and post-test.

4 Discussion

The aim of this study was to evaluate if an implicit perceptual training protocol could enable expert tennis players to better anticipate the action of a specific opponent. Results support this hypothesis with an increase of response accuracy in the same opponent Group. The lack of improvement for the other groups suggests that this improvement is due to this specific training and not to a familiarity effect with the protocol (Williams and Grant, 1999). This result is consistent with previous studies which showed that the knowledge of the opponent can improve expert players anticipation: the opponent preferences (Gredin et al., 2020), the opponent laterality (Loffing et al., 2016) or the knowledge of the opponent level of play (Huesmann and Loffing, 2019).

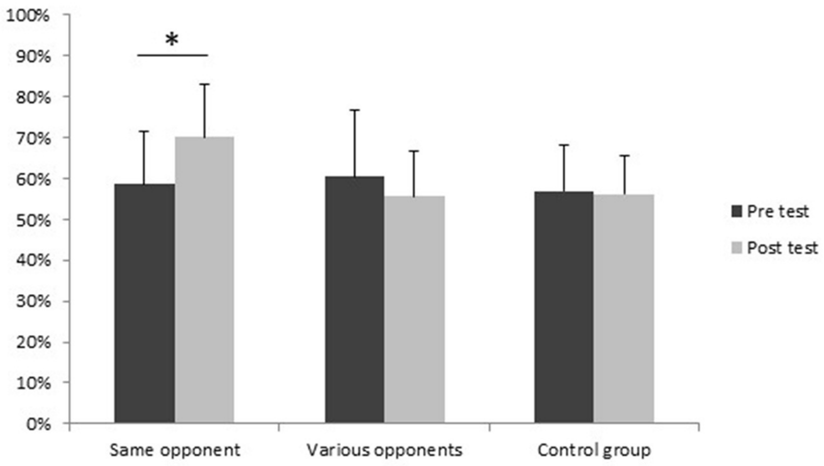

FIGURE 2
Mean percentage of correct responses for pre and post-tests for each group. *Improved response accuracy between pre- and post-tests for the same opponent Group ($p < 0.05$).

Concerning the various opponents Group, it seems they already have the capacity to use the relative position of players to anticipate and this training protocol didn't help them to improve their anticipation judgments.

Regarding the response time, a decrease was recorded for all groups. So we can conclude that there is a familiarity effect to the protocol. The advantage of training with the same opponent did not appear on response time but only on response accuracy (Scott et al., 1998; Abernethy et al., 1999).

The origin of the improvement of response accuracy in the same opponent Group can be questioned. Our protocol used an implicit method leaving open speculations for interpretation. One explanation of this improvement could be the possibility with the feedback to observe regularities in the decision-making of the opponent in some specific situation such as the systematic choice to play cross-court or down the line. Another explanation would be the possibility to memorize information from the opponent in the preparation of the action in which can have a predictive value for the shot direction (Wulf and Weigelt, 1997). This could be the placement of the feet or the orientation of the shoulders which are known to be a source of information for anticipation (Williams et al., 2002).

It could be interesting to replicate this protocol with less skilled players to analyse if this short training time is enough to generate an increase in the ability to anticipate such as Smeeton et al. (2005) in their field experiment. Triolet et al. (2022) demonstrated that tennis-specific tactical information could only be utilized by expert players. However, Murphy et al. (2016) showed that less expert players could also make use of the relative positioning of players on the court. Therefore, it is conceivable that less expert players in the various opponents Group might improve their anticipation skills through the use of this protocol.

It also seems important to ask if the improvement in response accuracy could be transferred to field situations. Indeed, Broadbent et al. (2015) suggested that training protocols should focus on assessing the efficacity of transfer from training to sport field. However, we can reasonably imagine that we could have some transfers as shown by Farrow and Abernethy (2002) or Williams et al. (2003). Another issue would be the question of retention. Indeed, Farrow and Abernethy (2002) showed that the post-test improvement (it was a decision time decrease) disappeared after 32 days, other more recent studies shown retention of learning (Abernethy et al., 2012). Even if the retention remains an important issue, our results suggest that such a protocol could be useful just before playing against a specific opponent. Indeed, we can identify a practical application for our protocol. It is well-known that victory in a high-level tennis match can sometimes hinge on winning just one or two more points than the opponent. Since our protocol appears to improve anticipation of the opponent's gameplay, it would be valuable to create a database of high-level players. A professional player could then engage with the protocol shortly before starting their match, potentially enabling them to perform more efficiently through better reading of their opponent's game from the very first points. The advantage of this protocol is that it does not require the coach to conduct prior analysis of the opponent's game. Furthermore, Masters (1992) demonstrated that implicit learning is more robust under stress conditions.

It is to be noted that our study also presents a number of limitations. Firstly, a tennis match unfolds as a dynamic interplay where players adapt to their opponent's responses and modify their game patterns, as well as their tactical and strategic choices. These evolutions cannot be accounted for in a laboratory study, which is not necessarily representative of what actually happens on the court, as recommended by Avilés et al. (2019) Another limitation relates to the differences in skill levels within our group of experts. Although all our players had extensive experience in tennis, not all of them were at a level to compete against a top 10 ATP player, who displayed significantly superior abilities. It would have been interesting to pair each player with an opponent of similar skill level. However, this approach would not have allowed us to compare the results across players and generalize the findings. Lastly, we hypothesized a practical application for our protocol. However, in order to use this training tool, videos of future opponents are required, which is unfortunately only feasible for high-level players.

To conclude, through our implicit training protocol, we showed that there is a possibility to use knowledge on anticipation to propose specific protocol with an applied perspective of improving the ability of experts to predict the action of a specific opponent. This opens some possibilities for further research to identify what information is used for this specific anticipation and also some future methods to train cognitive abilities in expert players.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by Ethics Committee of Université Paris sud. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

CT: Writing – original draft, Writing – review & editing. NB: Writing – original draft, Writing – review & editing.

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Development and validation of a questionnaire for table tennis teaching in physical education

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This study aimed to validate the "Racquet Sports Attitude Scale (RSAS)" questionnaire intended for the educational field. The RSAS is a Spanish instrument developed using the Delphi method and consists of 42 questions divided into five subsections benefits of table tennis (TT), facilitators for the application of TT, barriers to applying tennis table in physical education (PE), difficulties in applying the tennis table as a PE content and positive attitude toward racket sports), designed to evaluate the use and impact of the practice of the racket sports, in particular TT, among PE teachers. The semantic validation process involved a panel of experts (n = 16), followed by an evaluation carried out by a group of teachers from various secondary schools (n = 20). Three studies were conducted, the first of which was descriptive, comparative and correlational, to establish the data's sociodemographic characteristics. The second was an exploratory factor analysis to confirm the number of dimensions of the questionnaire and its reliability and validity. The last study was a confirmatory factor analysis (to establish the final number of items and their structure. The ordinal alpha values ranged from 0.65 to 0.72, obtaining an average value of 0.70, indicating coherence between the measurement of the items. Chi-square values (X^2 = 197.383; p < 0.001; CFI = 0.934; TLI = 0.923 and RMSEA = 0.030), showed that the original 5-factor model and 21 final items prevailed over the one-factor model, obtaining values >0.90. On the other hand, the validation results indicated that the factor structure of the RSAS scale was able to explain 46.72% of the variance (F1 = 13.93%; F2 = 10.97%; F3 = 8.57%; F4 = 6.85%; F5 = 6.38). It can be concluded that the structure of the RSAS is fully confirmed by the statistical analyses derived from the different models of structured equations and confirmatory factor analysis, suggesting that the validated model optimally addresses the data provided and contributes to the validation of the questionnaire under study.

KEYWORDS

racket sports, questionnaire, physical education, teacher skills, educational content

1 Introduction

Racket sports (RS) are regulated and institutionalized disciplines that appeared throughout the twentieth century to respond to a growing social demand for alternative sports that differ from traditionally practiced sports. This family of sports, among which some as popular and consolidated as badminton, tennis, table tennis (TT) or squash stand out, and others of more recent creation and in the process of expansion and development such as paddle tennis, pickleball or beach tennis, have an excellent acceptance in today's society. The characteristics of RS are of great social interest since they allow any type of population to practice them regardless of their culture, age, physical condition, gender, socio-economic level and physical or intellectual disability (Pradas and Herrero, 2015).

TT is one of the different disciplines that comes from real tennis, a sport that came from the *Jeu de Paume*, a twelfth century's game played in England and the common ancestor of most of the RS which are currently practiced worldwide (Herrero et al., 2015). TT has evolved into a highly popular sport, recognized as one of the most well-known and widely played RS in the world. Currently, more than 300 million people practice TT, with at least 40 million licensed players (Pradas et al., 2021). Since its consolidation as a competitive sport in the first half of the twentieth century and its inclusion in the 1988's Olympic Games, TT has been valued not only for its recreational nature and accessibility but also for its important physical and mental development benefits (International Table Tennis Federation (ITTF), 2022; Fuchs et al., 2018).

In recent years, TT has shown a positive impact in multiple areas. At health level, it has been demonstrated that its practice can improve coordination, agility and cardiovascular function, as well as promote mental sharpness, focus and concentration (Pradas et al., 2021; Liu et al., 2021). These characteristics have made TT a valuable tool for implementation in rehabilitation and disease prevention programs across a wide range of ages (Zhang et al., 2023; Smith and Lee, 2021).

In the educational context, TT has become an accepted and integral part of physical education (PE) programs due to its versatility and adaptability. It offers numerous benefits for students' psychomotor and cognitive development. Various studies, including those by Han and Wang (2023), indicate that playing TT enhances both physical and mental health in adolescents. Its incorporation into education not only fosters the development of physical skills and social interaction but also promotes important values such as discipline, respect and teamwork. (Hernández and Robles, 2023). For these reasons, the need to implement TT has been highlighted in various locations (Herrero et al., 2016).

The use of TT in school curricula, both in primary and secondary education, has been minimally researched. It remains largely unclear whether this sport is effectively integrated into PE program. However, incorporating TT could provide significant benefits to the teaching and learning process in PE across various educational stages, broadening the opportunities for motor skills development, education, health and recreation. To support its educational settings' integration, it is essential to have assessment tools to measure not only sports skills but also the cognitive and emotional benefits for students. Unfortunately, there is currently a lack of specific questionnaires designed to systematically and reliably evaluate these aspects (González-Devesa et al., 2024).

In this sense, this article aims to validate a questionnaire designed to measure the impact of TT in the educational context. The goal is to provide a reliable tool for teachers and professionals to analyze its implementation and evaluation in school programs related to PE.

2 Materials and methods

2.1 Methods

For sample selection, the main researcher of the study contacted a significant number of Spanish public high schools and then prepared a definitive list of participating educative centres. In the same way, the researcher explained to each secondary school's potential participants the objectives of the study, its needs, the confidentiality and treatment of the data, and the procedures and implications of their participation. Subsequently, an informed consent for participation was provided which the interested parties had to read, fill in and sign if they agreeded to participate in the days following the explanatory session. Ethical standards, confidentiality, and data protection protocols were upheld at all times. The study responded to a quasi-experimental, ex post facto approach with incidence sampling using qualitative and quantitative analyses (Alto and Vallejo, 2015).

2.2 Participants

A total of 104 educational centres of Compulsory Secondary Education and Baccalaureate in the Region of Murcia agreed to participate. The target population was made up of a total of 384 PE teachers, achieving a total participation of 196, representing 50.5% of the total population belonging to this subject. According to gender, sample's distribution was 142 males (72.4%) and 54 females (27.6%) with an average age between 31–35 years and 5–10 years of teaching experience. The whole study's protocols and ethical considerations followed the Declaration of Helsinki, complying with all the criteria formulated (voluntary participation; informed consent and right to information; protection of personal data and full confidentiality; non-discrimination; free of charge; and the possibility of leaving the study at any time). The Ethics Committee of the Government of Aragon (ID: 12/2021) reviewed and approved the study.

2.3 Instruments

Within the framework of the survey research, a simple self-administered questionnaire was designed, in which the respondents themselves answered in writing without direct intervention from any person. The questionnaire is prepared to include questions on subject's identification (age, sex, etc.) and content questions (Bisquerra, 1996). Moreover, different steps and actions are also considered in its construction to guarantee its reliability and validity. In this sense, Lozano and Fuentes, 2009 raised the importance of developing a questionnaire that accurately measures the study variable in a research process.

In this case, the questionnaire was developed using the Delphi method, a process that involves consulting experts to gather their opinions on a topic of interest during questionnaire design. The reasons to consider this method over the traditional one were: (a) It includes several rounds of questionnaires, interactions and queries related to and influenced by the previous round. (b) The answers are anonymous, which prevents the most prestigious participants from influencing the opinions of others. (c) In the Delphi method, no expert knows the identity of the others who are part of the group. (d) Each member of the group is equally considered. (e) It is based on the participant's continuous feedback. Results are derived from a compendium of assessments and decisions on previous reviews. (f) The individual character of the participants is guaranteed.

The procedure followed to apply the Delphi method consisted of firstly designating a coordinating group, in this case, a single person.

The coordinator, together with the principal investigator, stablished participants' selection criteria, scheduled a calendar of actions, chose the e-mail as the technical mean to share the questionnaire, prepared the questionnaire, encouraged the participation of the experts, analyzed the responses, modified the questionnaire and prepared the following ones, provided appropriate feedback, interpreted the results, and finally, supervised the correct progress of the investigation.

A group of experts was then selected to participate in developing and validating the questionnaire. The group was made up of 16 people; active teachers belonging to different Spanish universities ($n = 4$), teachers from secondary schools ($n = 8$) and TT coaches with extensive experience at national and international level ($n = 4$). The experts' selection was based on: (a) their professional profile, (b) research carried out, (c) publications on the subject, (d) proven experience, and finally, (e) their direct link with RSs, either in the educational field, the competitive field or in both situations, since they are considered to have relevant knowledge about the research topic.

From this moment on, a first questionnaire called the Racquet Sports Attitude Scale (RSAS) was prepared, where a total of 62 potential questions were formulated, including demographic data, distributed in five categories: (a) difficulties in applying PE content, (b) positive attitude toward RSs, (c) benefits of TT, (d) facilitators for the application of TT; In the phase of preparing the initial questionnaire, the way of asking is specified, deciding on the number of questions, the order and their arrangement. After this preliminary design, a quantitative pilot study of reliability and validity with a sample of 20 professionals from different autonomous communities of Spain (Andalusia, Aragon, Castilla y León, Castilla la Mancha, Catalonia, Valencian Community and Madrid) was carried out. This initial sample enabled the first checks on the reliability indices of the items, dimensions, and consistency of the questionnaire, resulting in Alpha indices ranging from 0.66 to 0.88. All this allowed 3 studies to be carried out (the first two converging into one) on a final sample of 196 PE professionals.

2.4 Statistical analysis

The first study (1a) was descriptive, comparative, and correlational in nature, aiming to establish the sociodemographic characteristics of the data. Reliability and validity were calculated to determine the psychometric properties of the preliminary questionnaire using Cronbach's alpha as a measure of consistency. However, in subsequent analyses, this consistency was corroborated through ordinal Alpha data and parallel analyses.

The second study (1b) was based on an Exploratory Factor Analysis (EFA) that confirmed the number of dimensions of the questionnaire, as well as its reliability and validity. To achieve this, the Kaiser-Meyer-Olkin (KMO) index was calculated, and Bartlett's test of sphericity was performed using the principal components method and oblimin rotation. Oblimin was selected considering the oblique relationship between the dimensions, rather than a closer relationship where a Varimax rotation would have been used.

Finally, the third study consisted of a Confirmatory Factor Analysis (CFA), which established the final number of items and their structure. Indicators of goodness-of-fit were examined, including Chi-square, the Comparative Fit Index (CFI), the Tucker-Lewis Index (TLI), and the Root Mean Square Error of Approximation (RMSEA) with a 90% confidence interval. Typical criteria for validity were values of CFI and TLI > 0.90, indicating good fit. RMSEA values of less than 0.08 and 0.06 were considered acceptable and excellent fits, respectively.

3 Results

The results are divided into two general studies. However, as previously indicated, the first study integrates descriptive and correlational studies with the first exploratory factor analysis (EFA). In this way, Study 1 reports on construct validity, internal consistency analysis, convergent validity, and exploratory factor analysis (EFA). As for the results of Study 2, they correspond to confirmatory factor analysis (CFA).

3.1 Study 1

3.1.1 Construct validity

The primary objective of this study was the validation of the RSAS questionnaire. After the general design of the questionnaire based on the Delphi method with expert consultation, it was critically reviewed by a pilot sample of 20 PE teachers, followed by evaluation once again by the expert panel. This iterative quantitative and qualitative feedback process reduced the initial 62 questions to 42, including demographic data, and finally to 28 items without demographic data, distributed across five scales.

A principal components analysis with Oblimin rotation was chosen as the appropriate method after assuming oblique relationships between the dimensions of the questionnaire. The Kaiser-Meyer-Olkin (KMO) test yielded a value of 0.701, suggesting a moderate relationship between variables and indicating that the correlations among pairs of variables could be explained by the remaining variables. This necessitated a factor analysis, resulting in the distribution of five factors explaining 46.72% of the variance (F1 = 13.93%; F2 = 10.97%; F3 = 8.57%; F4 = 6.85%; F5 = 6.38%). Finally, the component matrix showed minimum values of 0.377 for item 19 in factor 4 and maximum values of 0.679 for item 18 in factor 3.

3.1.2 Convergent validity

In turn, the different components of the dimensions were analyzed to check if there were significant correlations between them: (a) Benefits of table tennis; (b) Facilitators for the application of table tennis; (c) Barriers to the application of table tennis; (d) Difficulties in applying PE content and (e) Positive attitude toward racket sports. Table 1 shows the correlational analysis.

The different components of the dimensions were analyzed to determine whether significant correlations existed among them: (a) Benefits of TT, (b) Facilitators for the application of TT, (c) Barriers to the application of TT, (d) Difficulties in applying PE content, and (e) Positive attitudes toward racquet sports. Table 1 presents the correlation analysis.

3.1.3 Reliability

To corroborate the findings from the EFA and test the reliability of the instrument, ordinal alpha values were calculated for the set of items. Additionally, parallel analysis and polychoric matrices were

TABLE 1 Correlations among dimensions of the RSAS questionnaire.

	1	2	3	4
1. Benefits of TT				
2. Facilitators for the application of TT	0.48**			
3. Barriers to the application of TT	−0.16*	-		
4. Difficulties in applying PE content	0.10	−0.27	0.11	
5. Positive attitudes toward racquet sports	0.49**	0.32**	−0.28**	−0.04

TT, table tennis; PE, physical education.

TABLE 2 Equation models and validity comparison.

	CFI	TLI	AIC	Chi-square	RMSEA
5 F Model	0.934	0.923	343.383	197.383	0.030
1 F Model	0.462	0.342	568.658	442.658	0.083

5 F, five-factor; 1 F, one-factor.

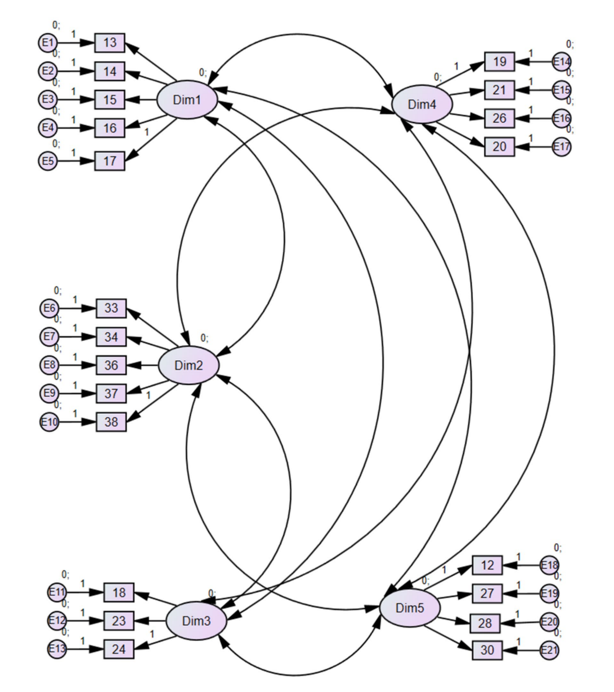

FIGURE 1
Five-factor model diagram.

conducted to confirm the five-factor structure. Global ordinal alpha values ranged from 0.65 to 0.72, with an average value of 0.70. Regarding the parallel analysis, the five-dimensional factor structure reported by the EFA model was confirmed. Ordinal alpha values between 0.70 and 0.90 indicate consistency in item measurement and, therefore, are suitable for measuring the same construct.

3.2 Study 2

The second study consisted of a confirmatory analysis to examine the internal structure of the scale. According to Batista and Coenders (2000), this was deemed the appropriate procedure to establish both general and item-specific validity and reliability. Two models were tested: the first, the original five-factor model (Figure 1), and a second, unidimensional model.

The purpose of this procedure was to compare the original model with alternative variants. To achieve this, a structural equation model was conducted using the maximum likelihood method. This yielded values for Chi-square, CFI, TLI, and AIC, which demonstrated that the original five-factor model with 21 final items outperformed the unidimensional model. The results showed values >0.90 for CFI and TLI, as well as RMSEA parameters below 0.06.

Therefore, considering the goodness-of-fit indices, the various parameters reported values indicating the sustainability of the initial five-factor model. Values obtained were $X^2 = 197.383$; $p < 0.001$; CFI = 0.934; TLI = 0.923; and RMSEA = 0.030, which are significantly better than those yielded by the single-factor model (Table 2). Hence, it can be concluded that this structure was fully confirmed through statistical analyses derived from the different structural equation models and confirmatory factor analysis (CFA). All this suggests that the validated model optimally addresses the data provided and contributes to the validation of the questionnaire under study.

4 Discussion

The aim of this research is to validate a questionnaire designed to measure the impact of TT in the educational context in order to provide a reliable tool for teachers and professionals to analyze its implementation and evaluation in school programs related to PE.

In this regard, this article explores and validates the RSAS questionnaire, contributing to the growing body of research dedicated to developing and adapting specific instruments to measure various variables in educational and sports contexts. Considering the target population of study and analysis, studies such as the one conducted by Gudiel-Hermoza et al. (2021), in which the ASQ-3 questionnaire was adapted for the early detection of developmental problems in children, concluded the need to design tools that address the cultural and linguistic particularities of target populations.

On the other hand, works such as those developed by Rodríguez-Rivadulla et al. (2019), focused on emerging sports, or those by Pi et al. (2022), centered on sports well-being, clearly highlight the usefulness of adapted questionnaires to address gaps in data systematization or to promote safer and healthier practices—areas of great interest in the educational field today. Similarly, other questionnaires such as the NSKQ-BR, which evaluates knowledge of nutrition in sports (Sousa et al., 2024), or the APSQ-Cro, which measures various psychological aspects in athletes (Sore et al., 2024), expand the scope of analysis expectations in sports by developing evaluation tools for even more specific areas. In line with this, studies by Trpkovici et al. (2023) developed and validated a questionnaire to measure athlete anxiety in a multidimensional way, addressing other aspects of interest such as concentration and self-confidence, or the work by Delrue et al. (2019), which refined a questionnaire designed to assess different training styles through a dynamic and situational approach.

However, as can be seen, and to the best of our knowledge of the scientific literature published, there are few questionnaires that assess specific sports applied to the school environment and their impact. In this research line, a pioneering questionnaire can be highlighted, attempting to analyze the situation of racquet sports in PE at the secondary education level in the Murcia region, particularly focusing on TT as a school subject (Herrero, 2015). Considering the importance of further exploring the educational field and the sports content used, this study differs from other publications where questionnaires have been developed and validated, as it addresses the integration of racquet sports in a very specific context—educational settings—focusing on TT and analyzing its significance in the teaching and learning process as educational content. This is an area that has been scarcely explored and is largely unknown but holds great potential and motivation to enrich the PE curriculum.

Given the background outlined, the need of creating a new tool through the development and validation of the RSAS questionnaire arises. To meet this demand in the educational and sports contexts, a systemic and methodological validation system was carried out, which included expert design, qualitative assessment, pilot testing, and both quantitative and qualitative analysis, as well as exploratory analysis of the proposed model and confirmatory analysis of the proposed five-factor model and an alternative unidimensional model. The results obtained in this process confirmed the five-factor structure in both the exploratory analysis and the parallel analysis, indicating good factor loadings and statistically valid alpha values for each item and its grouping into dimensions (Michel et al., 2013).

Furthermore, the validation results indicated that the factor structure of the RSAS scale was able to explain 46.72% of the variance, which, along with the previously described values, supports the consistency of the scale, indicating its validity and reliability. This finding reinforces what was reported by Sousa et al. (2024) and Sore et al. (2024) about the importance of establishing robust models to evaluate complex constructs in various fields, such as nutritional knowledge and athletes' mental health.

Additionally, the relationship between factors was examined through correlation data, and although no correlation was found between dimensions for all pairings, this was supplemented with other control elements for oblique relationships, such as the Oblimin rotation method, parallel analysis, polychoric matrices, and evaluation of ordinal alpha parameters above Cronbach's Alpha. This led to the conclusion of the effectiveness of each item and dimension in measuring the same global construct.

Supporting the validation results obtained in this questionnaire are several works, such as those by Trpkovici et al. (2023) and Delrue et al. (2019), which emphasize the importance of using exploratory and confirmatory factor analyses to ensure the psychometric quality of questionnaires, as was done in this study. Taken together, these studies illustrate the positive impact of validated tools in educational and sports practice, promoting evidence-based strategies that optimize the physical, emotional, and cognitive development of participants.

5 Limitations

Although the validation analyses have reached optimal conclusions regarding the tool's robustness and validation, certain limitations should not be overlooked, such as the need to expand the participant sample, as well as its educational and geographical diversity. This would allow for conclusions not only about the validity of the instrument, which has already been confirmed by this study, but also regarding the actual use of the tool and its results. All of this would lead to a greater understanding of the current status of racquet sports in PE across different educational stages: Primary Education, Secondary Education, High School, and University.

6 Conclusion

The RSAS questionnaire is designed to assess teachers' opinions on the practice and impact of racquet sports, particularly TT, as an educational content in PE classes.

The results obtained from the design process of the RSAS questionnaire confirm that the five-factor structure, both in exploratory analysis and parallel analysis, presents adequate saturation values and statistically valid alpha values for each item and its grouping into dimensions. On the other hand, the validation results indicate that the factorial structure of the RSAS scale was able to explain 46.72% of the variance, which, combined with the previously described values, supports the consistency of the scale, indicating its validity and reliability.

Moreover, the relationship between factors was also examined through correlation data. Although no correlation was found between dimensions for all pairings, this was supplemented with the use of other control elements for oblique relationships, such as the Oblimin rotation method, parallel analysis, polychoric matrices, and evaluation of ordinal alpha parameters above Cronbach's alpha. This led to the conclusion of the effectiveness of each item and dimension in measuring the same global construct.

This study improves the evaluation of racquet sports in the educational field through the RSAS questionnaire, especially the use and impact of TT, allowing for an understanding of teachers' opinions about this sport in terms of its implementation or lack thereof in PE classes, addressing attitudes, benefits, barriers, and difficulties in using this sports content. Future research is expected to use the RSAS to assess the opinions of teachers from different educational contexts to understand the level of use of these sports and take appropriate measures for their correct and proper use at any level in PE classes.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding aurhor.

Ethics statement

The study was approved by the Institutional Ethics Committee of the Government of Aragon (ID: 12/2021).

Author contributions

MO-Z: Writing – original draft, Writing – review & editing, Data curation, Formal analysis, Software, Validation. AC-L: Conceptualization, Data curation, Software, Supervision, Writing – original draft, Writing – review & editing. AQ: Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. AG-G: Conceptualization, Formal analysis, Methodology, Project administration, Software, Writing – original draft, Writing – review & editing. ML: Visualization, Writing – original draft, Writing – review & editing, Formal analysis, Funding acquisition, Investigation, Methodology. FP: Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Single-session upper limb plyometric training is as effective as two sessions for improving muscle strength, power, and serve velocity in male youth tennis players: a randomized parallel controlled study

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Introduction: Providing a balanced training stimulus that promotes positive adaptations without excessively increasing training volume—and thereby avoiding disruptions to the training process—is a challenging task for strength and conditioning coaches. This study aimed to compare the effects of one vs. two weekly sessions of upper limb plyometric training (ULPT) on muscle strength, power, and serve velocity in male youth tennis players.

Methods: We conducted a randomized controlled study with two ULPT groups: one receiving one session weekly (ULPT1w) and the other two sessions (ULPT2w), alongside a control group maintaining regular tennis training. The intervention lasted 8 weeks. A total of 47 male youth tennis players (15.6 ± 0.9 years), competing at the trained/developmental level, participated in the study. Evaluations were conducted twice—once before the intervention and once after—assessing isometric shoulder rotation strength (internal [ISRT] and external [ESRT]) with a dynamometer, the medicine ball chest throw (MBCT), seated shot-put test (SST), and serve velocity using a radar gun.

Results: In the post-intervention, significant differences were observed between groups for the variables of ISRT (p = 0.010; η_p^2 = 0.189), ESRT (p = 0.004; η_p^2 = 0.226), MBCT (p = 0.012; η_p^2 = 0.181), SST (p = 0.019; η_p^2 = 0.164), and tennis serve velocity (p = 0.004; η_p^2 = 0.226).

Conclusion: The study found that ULPT significantly improves upper limb muscle strength, power, and serve velocity in young male tennis players, with both once and twice weekly training yielding similar benefits. As practical implications coaches can effectively incorporate ULPT once a week to enhance physical performance in young male tennis players.

KEYWORDS

resistance training, reactive strength, athletic performance, strength, power

1 Introduction

The tennis serve is crucial for overall match performance, as it not only initiates play with the potential to gain an immediate advantage through speed and placement but also sets the tone for the subsequent rally, influencing both offensive and defensive strategies (Gillet et al., 2009). Muscle strength and power are important factors in optimizing tennis serve and overall performance due to their direct influence on kinetic chain efficiency and stroke mechanics (Colomar et al., 2022b). Research indicates that greater muscle strength enhances the ability to generate force quickly, which is essential for the explosive movements required in a powerful serve (Colomar et al., 2023). Specifically, studies have shown that upper body strength, particularly in the shoulder and core muscles, correlates with serve velocity and accuracy (Palmer et al., 2018). Among these, the rate of force development (RFD) in shoulder internal rotation emerges as one of the most critical parameters (Baiget et al., 2022; Colomar et al., 2022a). Additionally, power output, defined as the rate at which work is performed, plays a crucial role in facilitating rapid racket acceleration and increasing ball speed, which in turn enhances overall performance (Kovacs and Ellenbecker, 2011). Consequently, developing targeted strength and power training regimens can significantly improve a player's serve and competitive performance in tennis (Reid and Schneiker, 2008).

Among the various strength and power training methods available, plyometric training is particularly interesting because it can be performed in diverse settings without the need for substantial equipment (Deng et al., 2022). Research has established that plyometric training significantly contributes to positive adaptations in muscle strength and power across different sports, making it a valuable tool for athletes looking to enhance their performance (Booth and Orr, 2016). In particular, upper limb plyometric training (ULPT) can be particularly beneficial in supporting the development of tennis serve performance by potentially enhancing muscle strength and power through improved neuromuscular capabilities for generating explosive movements (Fernandez-Fernandez et al., 2016; Garcia-Carrillo et al., 2023).

Plyometric exercises, such as medicine ball throws and explosive push-ups, emphasize rapid stretching and shortening of muscles (Davies et al., 2015), which increases muscle potentiation and recruits fast-twitch fibers (Macaluso et al., 2012). Studies have shown that such training leads to greater improvements in upper body strength and power output—important components for an effective serve (Garcia-Carrillo et al., 2023). Additionally, plyometric training enhances the kinetic chain involved in the serve by promoting coordination and timing (Davies et al., 2015), which may translates into increased racket speed and ball velocity. Consequently, integrating upper limb plyometric exercises into a training regimen can establish a solid foundation for improvements in serve mechanics and overall tennis performance by maximizing the athlete's explosive capabilities and functional strength (Deng et al., 2022).

However, the integration of ULPT must be carefully considered in relation to the player's overall availability and the tennis training schedule, which often constrains adjustments and planning for coaches (Afonso et al., 2022). These challenges can be particularly pronounced for youth athletes, who must balance their training with numerous other responsibilities (e.g., academics, family). Therefore, minimizing the impact of strength training while ensuring its effectiveness becomes a key consideration. Previous studies on lower limb plyometric training have consistently showed that a single session can effectively enhance muscle strength and power in youth athletes across various sports, such as soccer (de Villarreal et al., 2008; Ramirez-Campillo et al., 2018; Bouguezzi et al., 2020). However, research on ULPT is particularly scarce (Deng et al., 2022). A recent systematic review (Deng et al., 2022) of plyometric training in tennis revealed a lack of studies on this topic and highlighted that none of the available research examined the impact of training volume, specifically the number of weekly sessions, on tennis players' adaptations. Given this gap, it is essential to research the effects of different weekly training volumes of ULPT on key variables such as muscle strength, power, and serve velocity in tennis players.

Therefore, this study aims to compare the effects of one (ULPT1w) versus two (ULPT2w) weekly sessions of upper limb plyometric training (ULPT) on muscle strength, power, and serve velocity in male youth tennis players. We hypothesize that both ULPT1w and ULPT2w will significantly enhance muscle strength, power, and serve velocity compared to a control group. Furthermore, based on previous research on lower limb plyometric training (de Villarreal et al., 2008; Ramirez-Campillo et al., 2018; Bouguezzi et al., 2020), we anticipate that ULPT1w may be similarly effective as ULPT2w.

2 Methods

This study report follows to the CONSORT guidelines for reporting randomized study designs (Merkow et al., 2021).

2.1 Participants

The study included 47 male youth tennis players at the trained/developmental competitive level (McKay et al., 2022), with an average age of 15.6 years (±0.9) and a training history averaging 3.6 years (±0.8). Participants had a mean height of 170.0 cm (±6.1) and an average body mass of 58.7 kg (±7.2), resulting in a body mass index (BMI) of 20.3 kg/m^2 (±1.9). Detailed characteristics of each group are listed in Table 1. Baseline comparisons of the demographic and anthropometric data for each group were conducted. No significant differences were observed between the groups in terms of age ($p = 0.628$), experience ($p = 0.819$), height ($p = 0.104$), or body mass index ($p = 0.101$). However, significant differences were found in body mass ($p = 0.030$), with players in the control group being significantly heavier than those in the ULPT1w group (mean difference: 6.3 kg; $p = 0.030$).

These players regularly participated in regional tournaments, trained approximately three times a week, totaling around 330 min of tennis practice weekly. It is important to note that all training sessions were conducted exclusively by their respective coaches, without any involvement from the research team.

G*Power software (version 3.1.9, Universität Düsseldorf, Germany) recommended a total sample size of 9 participants to achieve a statistical power of 0.95 and a significance level of 0.05 for the *F* tests, specifically focusing on the repeated measures ANOVA for within-between interactions. This calculation was based on an effect size of 0.79, which was determined from the effect size observed in young tennis players who underwent ULPT related to serving velocity (Fernandez-Fernandez et al., 2016). With the required sample size determined, recruitment began by directly approaching the local tennis clubs, involving coaches and directors in the process. The research team outlined the study's framework and extended a voluntary invitation to coaches, parents, and tennis players. Tennis players who expressed interest were then screened based on specific inclusion criteria.

Tennis players were qualified for inclusion if they met the following: (i) commitment to attend both evaluation sessions (pre and post-intervention), (ii) at least 4 years of tennis experience, (iii) participation in 85% or more of the intervention sessions, (iv) no injury or illness during the study or in the preceding month, (v) no participation in additional strength or conditioning programs, and (vi) no being previously exposed to a structured ULPT. Conversely, exclusion criteria were defined as (i) missing any evaluation session or test and (ii) using drugs or illegal substances that could influence training adaptations. In total, 52 tennis players were initially enrolled in the study. However, throughout the course of the research, five players were removed from the analysis: two due to injuries from activities not related to the intervention, and three for not attending the first evaluation session (Figure 1).

Ethical approval for the study was granted by the Ethics Committee of Chengdu Institute of Physical Education, with the protocol registered as code number 124 (September 5, 2023). Participants were given comprehensive information about the study's goals and procedures prior to joining. Informed consent was voluntarily provided by the tennis players parents through signed consent forms as well as the participants. The study followed the ethical guidelines of the Declaration of Helsinki, ensuring voluntary participation throughout.

2.2 Interventions

Each group engaged in consistent on-court tennis training, exclusively designed by the coaches, independent of any researcher influence. These sessions typically included warm-up activities that focused on dynamic stretching and footwork drills, followed by strength and conditioning exercises aimed at improving agility and

TABLE 1 Demographic and anthropometric data for the tennis players involved in this study.

	ULPT1w (n = 16)	ULPT2w (n = 16)	Control (n = 15)	Between-group ANOVA
Age (years)	15.4 ± 0.6	15.6 ± 1.0	15.7 ± 0.9	p = 0.628
Experience (years)	3.7 ± 0.9	3.7 ± 0.8	3.5 ± 0.6	p = 0.819
Height (cm)	169.3 ± 6.9	168.1 ± 6.0	172.6 ± 4.5	p = 0.104
Body mass (kg)	56.4 ± 6.2¶	57.4 ± 8.1	62.7 ± 5.8	p = 0.030
Body mass index (kg/m^2)	19.6 ± 1.2	20.2 ± 1.9	21.1 ± 2.3	p = 0.101

ULPTw1: group participating in one session per week of upper limb plyometric training; ULPTw2: group participating in two sessions per week of upper limb plyometric training.
¶Significantly different (p < 0.05) from control group.

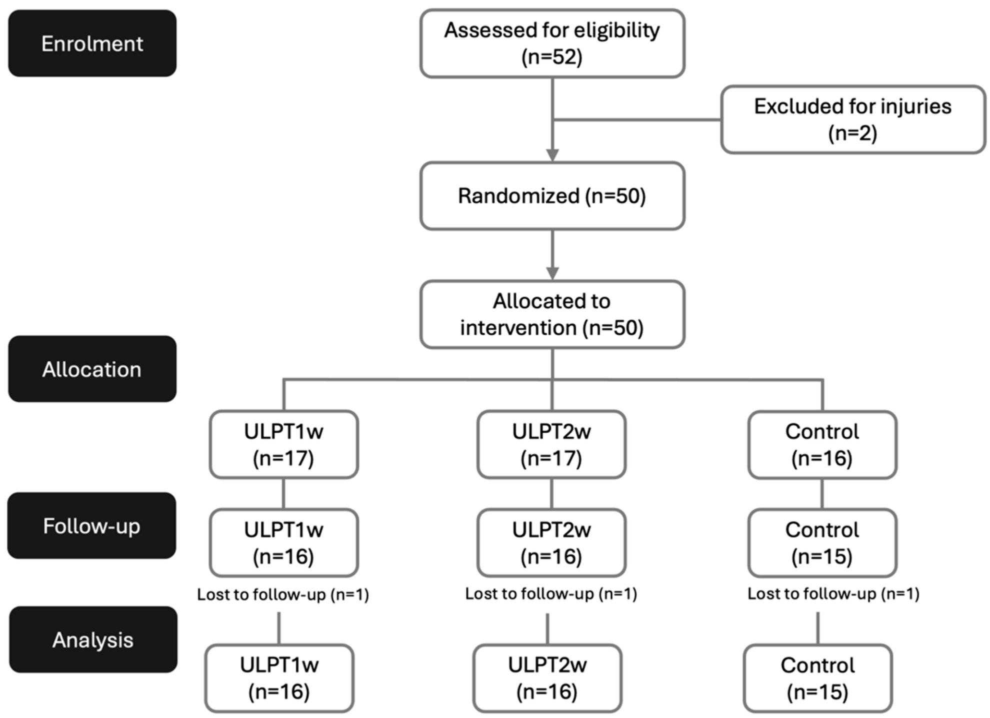

FIGURE 1
Flowchart of participant progression through the study phases. ULPTw1: group participating in one session per week of upper limb plyometric training; ULPTw2: group participating in two sessions per week of upper limb plyometric training.

reactivity, combined with technical movements. After that, players would work on individual skill development through drills for forehands, backhands, volleys, and overheads. The session would then transition to set matches or situational drills before concluding with game strategy discussions and formal match play.

In addition to the regular training sessions, the experimental groups—ULPT1w and ULPT2w—also included ULPT. This supplementary training occurred during the first session of the week for both groups. Additionally, the ULPT2w group received ULPT during the third training session of the week (72-h after the first ULPT), which was integrated before their regular training session. All ULPT sessions were supervised by two researchers, both experts in strength and conditioning training, each with over 5 years of experience working with athletes and in sports training. The ULPT was preceded by a standardized warm-up that included 5 min of jogging around the court, followed by dynamic stretching exercises. These exercises comprised arm circles, shoulder dislocations with a resistance band, external and internal rotations using resistance bands, elbow flexion and extension, wrist flexor and extensor stretches, and torso twists, totaling 7 min. After finishing the warm-up, the players were directed to begin the ULPT plan (Table 2).

From the first to the third week, the ULPT1w (one training session a week) group performed 60 medicine ball throws per week, while the ULPT2w (two training sessions a week) group completed 120 throws. From the fourth to the sixth week, the ULPT1w group increased their throws to 90 per week, while the ULPT2w group performed 180 throws. During the seventh and eighth weeks, when the intensity was increased by using heavier medicine balls, the ULPT1w group performed 72 throws per week, while the ULPT2w group completed 144 throws. The intervention sessions lasted between 14 and 18 min, including the warm-up.

To ensure that tennis players utilized proper techniques and exerted adequate effort, the two strength and conditioning coaches provided feedback and ensured that every exercise was performed with full intensity to enhance the training effect. Clear instructions were given to players to maximize their effort on each repetition (i.e., maximal intent), with verbal motivation provided during workouts to foster dedication and involvement.

2.3 Outcomes

2.3.1 Study design

To prevent specific tennis training from influencing the outcomes, each tennis player was randomly assigned to one of three groups: two experimental intervention groups (ULPTw1 and ULPTw2) and a control group (CON) that continued to their usual tennis training. Twice, evaluations were conducted—before and after the intervention—on the same days of the week to maintain uniform conditions. These assessments occurred indoors in the afternoon. Participants had a 72-h rest period following their last training prior to the evaluations.

Participants for the study were sourced through convenience sampling from a two tennis clubs. To ensure proper randomization and minimize bias from each club's training approach, the randomization within each club was conducted in a balanced manner, with players being allocated into three groups. Random assignment followed a 1:1 allocation ratio and was implemented by a simple randomization method, involving opaque envelopes given to tennis players prior to their initial assessments, ensuring unbiased allocation. The randomization process was supervised by a researcher uninvolved in later assessments, preserving the blinding procedure.

Independent researchers, with no knowledge of group assignments or intervention details, carried out evaluations 1 week before the intervention, and after 8 weeks of training. Tennis players and coaches, however, were aware of the training protocols being delivered.

2.3.2 Assessments context

The structured sequence of the evaluations began with collecting demographic information and anthropometric measurements. This was succeeded by a warm-up consisting of 5 min of jogging around the court, followed by dynamic stretching exercises. These exercises comprised arm circles, shoulder dislocations with a resistance band, external and internal rotations using resistance bands, elbow flexion and extension, wrist flexor and extensor stretches, and torso twists, totaling 7 min. After the warm-up, participants completed the tests in a predetermined sequence. They began by assessing isometric shoulder rotation strength, measuring both internal (ISRT) and external (ESRT) rotation using a dynamometer. Next, they performed a medicine ball chest throw. Following that, participants engaged in the seated shot-put test (SST) for both their dominant and nondominant arms. Finally, they evaluated serve velocity using a radar gun. To ensure variety, half of the players were randomly chosen to start the unilateral tests (i.e., ISRT, ESRT, and SST right and left) with their left leg, while the other half began with their right leg. This sequence was kept consistent throughout both evaluation sessions. Between each assessment test, a 3-min rest was provided, with a 2-min rest between repetitions within each test. Each player alternated starting with one upper limb, resting, then performing with the other upper limb, and repeating this for the second trial. Each unilateral test included two trials per upper limb during each evaluation, with averages per leg calculated for further analysis. Throughout both evaluation periods, all participants followed the same order and sequence for the assessments.

2.3.3 Isometric shoulder rotation strength

Using a hand-held dynamometer with a 0–500 N range and 0.2 N sensitivity (Nicholas Manual Muscle Test, Co, Lafayette, IN, USA), ESRT and ISRT strength were evaluated. The procedures follow a previous study in tennis players (Moreno-Pérez et al., 2019). Each testing session began with the hand-held dynamometer calibrated according to the manufacturer's specifications. Participants were placed in a supine position on a bench, ensuring their arms were abducted to 90 degrees and rotated to 0 degrees within the scapular plane. With their elbows flexed at 90 degrees, participants pressed their humerus down against the bench while the testing angle was visually checked.

For measuring ESRT, the hand-held dynamometer calibrated was positioned just proximal to the ulnar styloid process, allowing participants to externally rotate their shoulders against it. In contrast, for assessing ISRT, the hand-held dynamometer was placed just proximal to the radial styloid process, where participants internally rotated their shoulders. To eliminate variability in the process, the

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TABLE 2 Description of the training protocols for the upper limb plyometric training (ULPT).

	ULPT 1st session of the week	ULPT 2nd session of the week
Week 1	2 × 10 Chest throw with 2-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 2 × 10 overhead throw with 2-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 2 × 10 Forehand 2-kg BM Closed Stance (rest between sets: 2 min)	2 × 10 Chest throw with 2-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 2 × 10 overhead throw with 2-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 2 × 10 Forehand 2-kg BM Closed Stance (rest between sets: 2 min)
Week 2	2 × 10 open-stance throw with 2-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 2 × 10 overhead throw with 2-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 2 × 10 2-hand overhead throw with rotation (rest between sets: 2 min)	2 × 10 open-stance throw with 2-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 2 × 10 overhead throw with 2-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 2 × 10 2-hand overhead throw with rotation (rest between sets: 2 min)
Week 3	2 × 10 Chest throw with 2-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 2 × 10 overhead throw with 2-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 2 × 10 Stepping overhead 2-kg MB throw (rest between sets: 2 min)	2 × 10 Chest throw with 2-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 2 × 10 overhead throw with 2-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 2 × 10 Stepping overhead 2-kg MB throw (rest between sets: 2 min)
Week 4	3 × 10 Chest throw with 2-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 3 × 10 overhead throw with 2-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 3 × 10 Forehand 2-kg BM Closed Stance (rest between sets: 2 min)	3 × 10 Chest throw with 2-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 3 × 10 overhead throw with 2-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 3 × 10 Forehand 2-kg BM Closed Stance (rest between sets: 2 min)
Week 5	3 × 10 open-stance throw with 2-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 3 × 10 overhead throw with 2-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 3 × 10 2-hand overhead throw with rotation (rest between sets: 2 min)	3 × 10 open-stance throw with 2-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 3 × 10 overhead throw with 2-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 3 × 10 2-hand overhead throw with rotation (rest between sets: 2 min)
Week 6	3 × 10 Chest throw with 2-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 3 × 10 overhead throw with 2-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 3 × 10 Stepping overhead 2-kg MB throw (rest between sets: 2 min)	3 × 10 Chest throw with 2-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 3 × 10 overhead throw with 2-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 3 × 10 Stepping overhead 2-kg MB throw (rest between sets: 2 min)
Week 7	3 × 8 Chest throw with 4-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 3 × 8 overhead throw with 4-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 3 × 8 Forehand 4-kg BM Closed Stance (rest between sets: 2 min)	3 × 8 Chest throw with 4-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 3 × 8 overhead throw with 4-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 3 × 8 Forehand 4-kg BM Closed Stance (rest between sets: 2 min)
Week 8	3 × 8 Chest throw with 4-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 3 × 8 overhead throw with 4-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 3 × 8 Stepping overhead 4-kg MB throw (rest between sets: 2 min)	3 × 8 Chest throw with 4-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 3 × 8 overhead throw with 4-kg MB (rest between sets: 2 min) Rest between exercise: 3 min 3 × 8 Stepping overhead 4-kg MB throw (rest between sets: 2 min)

MB, medicine ball.

dynamometer was secured against a stable, flat surface to prevent any interference from the evaluator.

The assessments for both ESRT and ISRT involved two maximal voluntary contractions lasting 5 s each, with a 30-s rest between sets. Peak strength values were recorded for each repetition, and averages were calculated—both for each limb and across both trials. The results were then normalized according to the participants' body mass (N/kg).

2.3.4 Medicine ball chest throw

The medicine ball chest throw (MBCT) was conducted following a previous study protocol (Hackett et al., 2018) that showed strong predictive ability for muscular strength and power in adolescents. Participants were seated on an upright bench, approximately at a 90-degree angle. The seat height was adjusted so that their knees were bent at roughly 90 degrees, keeping their feet flat on the floor. They were instructed to push a 3 kg medicine ball away from their chest as forcefully as possible, ensuring that their head, shoulders, and lower back stayed in contact with the bench. A 10-meter tape measure was laid out alongside the bench, and a researcher visually marked where the medicine ball first touched the ground during each throw. The distance achieved was recorded to the nearest 5 cm. Participants were allowed one practice attempts to get accustomed to the movement before starting the actual trials. They then completed two attempts, with 60 s of rest in between, and the longest throw (measured in cm) was registered. Verbal encouragement was provided to motivate them during each trial.

2.3.5 Seated shot-put test

Using a standard 18-inch chair without armrests, the one-arm seated shot put (SST) was conducted, with the front legs aligned on a line marked by the tester (Negrete et al., 2010). An additional 18-inch chair positioned directly in front supported the participant's feet and lower legs, aligning the hips, knees, and ankles in a straight line parallel to the ground. Across the upper body, a strap was secured diagonally while the non-throwing arm was crossed over the chest (Negrete et al., 2010). A 3-kg medicine ball was utilized, with participants instructed to avoid throwing it in an overhead baseball-style manner. Participants were allowed one practice attempts to get accustomed to the movement before starting the actual trials. Each arm was allowed two attempts, with a 30-s rest period in between. The distance (cm) was measured from the tapeline at the front of the chair to the point where the ball first made contact with the ground. The longest throw (measured in cm) was registered for analysis. Throughout the test, verbal encouragement was provided to support high-intensity effort.

2.3.6 Tennis serve velocity

Measured by a valid and reliable radar gun (model Pocket Radar Ball Coach PR1000BC, Republic of South Korea; Hernández-Belmonte and Sánchez-Pay, 2021), serve speed was set to 'continuous mode' to detect maximum ball speed in the range of 40 to 210 km/h. Calibration was completed according to the manufacturer's specifications prior to each test. Conducted as previous studies (López-Samanes et al., 2017; Moreno-Pérez et al., 2019), the serve test procedure involved positioning the radar in the center of the baseline on the tennis court, 4 meters behind the server, aligned with the approximate height of ball contact (around 2.2 meters) and aimed down the center of the court. Following three practice serves, and three submaximal serves (not registered), the serve velocity test at maximal intent was performed. Required to serve into a designated 1 × 1-meter area in the far diagonal corner of the service area, participants attempted to deliver five maximal speed serves in as few attempts as possible (Moreno-Pérez et al., 2019). Calculated for further analysis was the peak velocity (km/h) of these five serves (Moreno-Pérez et al., 2019).

2.3.7 Reliability of the tests

The coefficient of variation (CV), expressed as a percentage, was calculated within participants for each test, taking into account the repetitions performed within each session. The results indicated a CV of 4.1% for the ISRT and 3.6% for the ESRT, based on the participant averages. The analysis showed a CV of 3.8% for the MBCT, and 4.4% across both arms for the SST. Additionally, the participants' overall average yielded a CV of 5.2% for tennis serve. The intra-class correlation (ICC) values were used to measure how consistent the test results were. The ISRT had a ICC of 0.85. The ESRT had an even higher ICC of 0.88. The MBCT showed an ICC of 0.86. The SST had a slightly lower ICC of 0.8. Finally, the Tennis Serve test had an ICC of 0.75.

2.4 Statistical methods

To assess the normality of the sample, we employed the Kolmogorov–Smirnov test, which yielded p-values greater than 0.05. Additionally, Levene's test was performed to evaluate the homogeneity of variances, also resulting in p-values exceeding 0.05. Comparisons of demographic and anthropometric data between groups at baseline were conducted using one-way ANOVA, followed by the Bonferroni post-hoc test. The CV was used to calculate the variability within each participant across repetitions within the tests. The overall CV was computed as the pooled mean of the individual participant CVs, where the CV for each participant was determined by dividing the standard deviation of their repetitions by the mean value, and then multiplying by 100 to express the result as a percentage. Additionally, the ICC for absolute agreement was calculated. For analyzing the interaction between time and group, a mixed ANOVA was conducted. Effect sizes were calculated using partial eta squared (η_p^2) and Cohen's d for comparisons of pre- and post-intervention measurements. The classification of effect sizes followed the thresholds proposed by Hopkins et al. (2009): small (≥ 0.10), moderate (≥ 0.30), large (≥ 1.2), and very large (≥ 2.0). Post-hoc analyses utilized the Bonferroni test. The JASP software (version 0.18.3, University of Amsterdam, The Netherlands) was used to perform the statistical analysis, with a significance level set at $p < 0.05$.

3 Results

Table 3 shows the baseline and post-Intervention performance values for three groups. Significant interactions (time*group) were found in ISRT ($F = 39.761$; $p < 0.001$; $\eta_p^2 = 0.644$), ESRT ($F = 32.327$; $p < 0.001$; $\eta_p^2 = 0.629$), MBCT ($F = 85.933$; $p < 0.001$; $\eta_p^2 = 0.796$), SST ($F = 95.675$; $p < 0.001$; $\eta_p^2 = 0.813$), and tennis serve velocity ($F = 43.695$; $p < 0.001$; $\eta_p^2 = 0.665$). No significant differences were found between groups in the baseline for the variables of ISRT ($F = 0.836$; $p = 0.440$; $\eta_p^2 = 0.037$), ESRT ($F = 1.652$; $p = 0.203$; $\eta_p^2 = 0.070$), MBCT ($F = 0.134$; $p = 0.875$; $\eta_p^2 = 0.006$), SST ($F = 0.010$; $p = 0.990$; $\eta_p^2 = 0.000$), and tennis serve velocity ($F = 0.999$; $p = 0.376$; $\eta_p^2 = 0.043$).

In the post-intervention, significant differences were observed between groups for the variables of ISRT ($F = 5.113$; $p = 0.010$; $\eta_p^2 = 0.189$), ESRT ($F = 6.435$; $p = 0.004$; $\eta_p^2 = 0.226$), MBCT ($F = 4.871$; $p = 0.012$; $\eta_p^2 = 0.181$), SST ($F = 4.315$; $p = 0.019$; $\eta_p^2 = 0.164$), and tennis serve velocity ($F = 6.427$; $p = 0.004$; $\eta_p^2 = 0.226$). Specifically, the control group exhibited significantly lower ISRT values compared to ULPT1w ($p = 0.014$; ES = 1.053, moderate) and ULPT2w ($p = 0.014$; ES = 1.130, moderate). Similarly, the control group exhibited significantly lower ESRT values compared to ULPT1w ($p = 0.012$; ES = 1.143, moderate) and ULPT2w ($p = 0.008$; ES = 1.333, large). In the case of MBCT, the control group had significantly lower values compared to ULPT1w ($p = 0.026$; ES = 1.115, moderate) and ULPT2w ($p = 0.030$; ES = 1.004, moderate), while similarly in SST the control group also presented significantly smaller values compared to ULPT1w ($p = 0.047$; ES = 0.911) and ULPT2w ($p = 0.038$; ES = 0.943). Finally, the control group exhibited significantly lower tennis serve velocity values compared to ULPT1w ($p = 0.037$; ES = 0.888, moderate) and ULPT2w ($p = 0.004$; ES = 1.258, large). No significant differences were observed between ULPT1w and

TABLE 3 Mean and standard deviation (SD) of baseline and post-intervention performance values for three groups.

	ULPT1w (*n* = 16)	ULPT2w (*n* = 16)	Control (*n* = 15)
ISRT (N/kg)			
Baseline	1.80 ± 0.10	1.82 ± 0.13	1.77 ± 0.09
Post-intervention	1.86 ± 0.10[¶]	1.89 ± 0.14[¶]	1.76 ± 0.09
p-value and ES (post-pre)	$p < 0.001$; ES = 0.600	$p < 0.001$; ES = 0.519	$p = 0.211$; ES = -0.111
ESRT (N/kg)			
Baseline	1.56 ± 0.03	1.55 ± 0.03	1.57 ± 0.03
Post-intervention	1.61 ± 0.04[¶]	1.61 ± 0.03[¶]	1.57 ± 0.03
p-value and ES (post-pre)	$p < 0.001$; ES = 1.429	$p < 0.001$; ES = 2.000	$p = 0.705$; ES = 0.000
MBCT (cm)			
Baseline	621.4 ± 60.5	619.5 ± 61.0	611.5 ± 45.4
Post-intervention	668.1 ± 59.4[¶]	667.1 ± 68.9[¶]	610.2 ± 44.5
p-value and ES (post-pre)	$p < 0.001$; ES = 0.779	$p < 0.001$; ES = 0.733	$p = 0.705$; ES = -0.029
SST (cm)			
Baseline	529.3 ± 56.5	531.4 ± 53.1	529.1 ± 42.0
Post-intervention	575.1 ± 57.9[¶]	576.7 ± 50.6[¶]	528.9 ± 43.5
p-value and ES (post-pre)	$p < 0.001$; ES = 0.801	$p < 0.001$; ES = 0.874	$p = 0.923$; ES = -0.005
Tennis serve velocity (km/h)			
Baseline	150.8 ± 8.1	152.7 ± 7.2	148.7 ± 8.0
Post-intervention	155.4 ± 8.2[¶]	157.9 ± 7.2[¶]	147.9 ± 8.7
p-value and ES (post-pre)	$p < 0.001$; ES = 0.564	$p < 0.001$; ES = 0.722	$p = 0.122$; ES = -0.096

ISRT: internal isometric shoulder rotation strength; ESRT: external isometric shoulder rotation strength; ES: effect size using cohen's d; SST: one-arm seated shot put test; ULPTw1: group participating in one session per week of upper limb plyometric training; ULPTw2: group participating in two sessions per week of upper limb plyometric training.
[¶]Significantly different ($p < 0.05$) from control group.

ULPT2w in ISRT ($p > 0.999$; ES = 0.250, small), ESRT ($p > 0.999$; ES = 0.000, trivial), MBCT ($p > 0.999$; ES = 0.016, trivial), SST ($p > 0.999$; ES = 0.029, trivial), and the tennis serve velocity ($p > 0.999$; ES = 0.325, small).

Within-group analysis revealed that ULPT1w showed significant improvements from baseline to post-intervention in the ISRT ($p < 0.001$; ES =0.600, moderate), ESRT ($p < 0.001$; ES = 1.429, large), MBCT ($p < 0.001$; ES =0.779, moderate), SST ($p < 0.001$; ES =0.801, moderate), and tennis serve velocity ($p < 0.001$; ES =0.564, small). Similarly, ULPT2w exhibited significant improvements from baseline to post-intervention in the ISRT ($p < 0.001$; ES =0.519, small), ESRT ($p < 0.001$; ES =2.000, large), MBCT ($p < 0.001$; ES =0.733, moderate), SST ($p < 0.001$; ES =0.874, moderate), and tennis serve velocity ($p < 0.001$; ES =0.722, moderate). In contrast, the control group did not show significant improvements from baseline to post-intervention, as evidenced by the ISRT ($p = 0.211$; ES = −0.111, trivial), ESRT ($p = 0.705$; ES =0.000, trivial), MBCT ($p = 0.705$; ES = −0.029, trivial), SST ($p = 0.923$; ES = −0.005, trivial), and tennis serve velocity ($p = 0.122$; ES = −0.096, trivial).

4 Discussion

The current research revealed that both ULPT1w and ULPT2w were effective in enhancing upper limb muscle strength, power, and serve velocity. While both interventions improved muscle strength, power, and tennis serve performance, there were no significant differences between them. Therefore, for young male tennis players who are newly introduced to ULPT, one weekly session may be sufficient to achieve effective adaptations.

The 8-week ULPT training intervention significantly enhanced isometric shoulder rotation strength. It was observed that, regardless of the weekly training frequencies tested, the benefits were equally effective compared to the control group. However, this study does not align with a previous report involving baseball athletes (Carter et al., 2007) who participated in ULPT, which found no statistically significant differences in any of the isokinetic strength measurements between the plyometric and control groups from pre- to post-training. On the other hand, a previous study comparing strength training and ULPT found that the latest one was significantly more effective in enhancing internal rotation (Swanik et al., 2016). Although no studies have specifically examined ULPT in tennis players or analyzed its impact on these tests, a previous study (Behringer et al., 2013) comparing traditional resistance training with plyometric training for the lower and upper limbs found that both programs significantly improved maximal strength, as measured by dynamic exercises like the chest press and pull-down.

ULPT likely fosters neuromuscular adaptations that enhance motor unit recruitment and synchronization, leading to improved force production (McKinlay et al., 2018). The explosive nature of plyometric exercises may have stimulated muscle power development through the stretch-shortening cycle, which can translate into increased isometric strength (Walshe et al., 1998). Additionally, adaptations in tendon stiffness and strength may contribute by enhancing force transmission (Ramírez-delaCruz et al., 2022). Even with varying training frequencies, the intensity of the exercises provided a sufficient stimulus for muscle adaptations. This effect can be further justified by the youth of the players, as younger athletes tend to exhibit higher trainability and a greater capacity for adaptation, making them particularly responsive to this type of training (Michailidis et al., 2013).

Both the MBCT and the Seated Shot-Put Test showed significant and positive improvements after the ULPT compared to the control group, with no significant differences observed among the training frequencies in which the players participated. The results align with a study by Fernandez-Fernandez et al. (2016) which reported significant benefits of introducing ULPT for enhancing the MBCT. Additionally, they are consistent with findings from another study that demonstrated positive adaptations in MBCT following plyometric training (Fernandez-Fernandez et al., 2018). A possible explanation for observing these positive adaptations is that ULPT may significantly enhanced the neural and physiological mechanisms by optimizing the stretch-shortening cycles and potentiation, which may have activated the stretch reflex and increased neural drive to the muscles involved in throwing (Turner and Jeffreys, 2010). This process possibly facilitated greater recruitment of fast-twitch muscle fibers, known for their ability to produce high force and power output quickly (Macaluso et al., 2012). Additionally, plyometrics possibly improved neuromuscular efficiency by enhancing motor unit synchronization and firing rates, leading to more coordinated and forceful muscle contractions (Wallace and Janz, 2009). These adaptations may result in heightened muscle stiffness and elasticity, which contributed to a more effective transfer of force during explosive movements (Fouré et al., 2011).

The serve speed improved in both ULPT groups, regardless of training frequency, and was significantly more effective compared to the control group. This finding aligns with a previous study (Fernandez-Fernandez et al., 2016) in adolescent tennis players, which found that after combining ULPT with lower limb plyometric training, serve velocity increased by 6.2%, a significant improvement over the control group. Our results also align with another study (Terraza-Rebollo et al., 2017) that showed an 8-week program using resistance, medicine balls, and elastic bands significantly enhanced both serve speed and medicine ball throwing ability in adolescent tennis players. Additionally, our findings are in agreement with a study in adolescent tennis players (Behringer et al., 2013) that compared upper and lower limb plyometric training with strength training and a control group, revealing that plyometrics alone led to a unique increase in serve velocity, by approximately 3.8%. The possibly improved mechanism of the stretch-shortening cycle may have enabled muscles to store elastic energy during a quick pre-stretch phase, releasing it explosively during the subsequent contraction phase (Turner and Jeffreys, 2010). This rapid cycle possibly enhanced the speed and power of upper limb movements by increasing both neural activation and muscle-tendon elasticity (Swanik et al., 2016), which are essential for producing forceful and fast serves. Furthermore, the tennis serve relies heavily on powerful actions (Colomar et al., 2023), which showed significant improvement through MBCT and the Seated Shot-Put Test. These enhancements support the observed increase in serve velocity, aligning with previous studies that showed the interdependence of these muscle power measures and serve performance (Palmer et al., 2018).

The lack of observed differences between ULPT1w and ULPT2w may be attributed to the heightened responsiveness of adolescent muscle fibers to neuromuscular adaptations, driven by growth-related increases in muscle size and hormonal changes (Gillen et al., 2019). Plyometric training can optimally support these physiological developments, enhancing neuromuscular efficiency and coordination (De Almeida et al., 2021). Research suggests that neural and muscular adaptations are particularly pronounced in younger athletes (Legerlotz et al., 2016), making plyometric training especially beneficial for adolescent tennis players. This age group's greater trainability, combined with their first exposure to this type of training, may have enabled significant improvements even with just one session per week.

Despite the positive findings, this study has some limitations that should be addressed in future research. The sample consisted solely of young male tennis players, limiting the generalizability of the findings to other ages, trainability levels, and genders. Future studies should increase diversity by including older athletes and female participants to better assess ULPT's broader applicability. Additionally, the 8-week duration does not account for potential long-term effects, making it essential to examine ULPT's sustainability and optimal training frequencies and duration. This could help identify any performance plateaus or phases of increased sensitivity to training volume adjustments. Another limitation is the absence of a strain gauge capable of recording the force-time curve, due to resource constraints. However, this approach would provide valuable insights into a critical aspect of the analysis, and future studies should incorporate it. Furthermore, incorporating biomechanical analyses, such as motion capture or electromyography, could provide a deeper understanding of the neuromuscular adaptations associated with ULPT, which were not explored in this study. Finally, our study may also have a limitation in that we replicated the same exercises in the second session of the week as those implemented in the first. Including different exercises in the second session could potentially yield different results, and this should be acknowledged and explored in future studies.

Despite the limitations, the findings of this study offer practical implications for coaches working with young male tennis players. Given that both one and two weekly ULPT sessions effectively enhanced upper limb strength, power, and serve velocity, it appears that a single weekly session may be sufficient to produce meaningful adaptations in beginners. This is particularly valuable for time-constrained training schedules, allowing players to allocate more time to other skill-based without compromising upper limb development. Additionally, the study highlights the utility of ULPT in fostering muscular power adaptations crucial for explosive and determinant movements like serving. By incorporating ULPT into training, coaches can help players optimize upper limb performance, which is critical for effective serve velocity and overall competitive performance.

5 Conclusion

The study concluded that ULPT is an effective training intervention for improving upper limb muscle strength, power, and serve velocity in young male tennis players. Both ULPT training frequencies (once and twice weekly) showed significant performance enhancements over the control group, with no meaningful differences between the two frequencies, indicating that a single weekly session may suit for positive adaptations in youth players. Despite promising results, the study is limited by its focus on young males, making further research necessary to explore effects across different ages, genders, and long-term outcomes. Coaches can utilize these findings to implement ULPT one a week in training, even on restricted schedules, to promote upper limb power and serve speed, essential for competitive tennis performance.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving humans were approved by the study received ethical clearance from the Institutional Ethical Review Board at the ChengDu Sports Univ, under the reference number 124/2023. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin.

Author contributions

JW: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. QX: Conceptualization, Formal Analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Publisher's note

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Exploring the impact of equipment modifications on novice tennis players: a scoping review

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Tennis equipment modifications, such as smaller rackets and low-compression balls, are increasingly being used because they can better align with beginners' physical capabilities, enhancing learning and engagement. This scoping review aimed to map current research on equipment modifications for beginner tennis players, identifying how these modifications impact skill acquisition, game performance, biomechanical variables, psychological aspects, and coaches' perspectives. Searches across the Web of Science, Scopus, PubMed, and SPORTDiscus, along with expert input following the PRISMA procedures, yielded 35 studies. These studies involved empirical interventions related to scaled tennis equipment for beginners and were published in English or Spanish. Narrative reviews and studies lacking empirical data were excluded. The results indicate that equipment modifications enhance control, technique, and engagement in skill acquisition, improve tactical play with more aggressive strokes, and reduce joint stress, thereby minimizing injury risk. Psychological benefits include greater enjoyment and self-efficacy, and coaches strongly support these adaptations. These findings suggest practical implications for junior tennis development. However, future research should focus on expanding real-game applications, increasing participant diversity, and conducting detailed psychological and biomechanical assessments to further optimize player progression.

KEYWORDS

racquet sports, scaled equipment, skill acquisition, performance, psychological benefits, coaches' perceptions, biomechanics

1 Introduction

The initiation phase in any sport is crucial for the comprehensive development of players as it establishes the foundation for their future athletic careers. In this context, sports equipment plays a pivotal role in shaping tactical understanding, technical learning, physical adaptation, and mental readiness during the initial performance of beginners. Contemporary motor learning theories, such as the Constraints-Led Approach (CLA), emphasize the importance of adjusting constraints related to the player, environment, and task to facilitate skill development (Davids et al., 2008). From this perspective, adapting sports equipment to suit the characteristics of beginner players has garnered growing interest in scientific research and sports practice.

The CLA approach supports the notion that the design of sports equipment and the dimensions of the playing area should be tailored to athletes' physical needs, technical skills, and experience. Numerous studies have shown the benefits of such adaptations, particularly in enhancing skill acquisition, competitive performance, and enjoyment of the activity (Farrow and Reid, 2010; Buszard et al., 2014b; Kachel et al., 2015; Limpens et al., 2018). In tennis, initiatives such as Play and Stay and Tennis 10s, promoted by the International Tennis Federation (ITF), have implemented strategies involving the use of smaller rackets, low-compression balls, and scaled-down courts to adapt the sport to the needs of developing players. These strategies are organized into three progressive phases: red, orange, and green balls (International Tennis Federation, 2023).

Existing evidence highlights the positive impact of adapted equipment on tennis player development, particularly among children and young beginners. For example, (Buszard et al., 2020a) reported improvements in stroke accuracy, swing stability, and movement variability. Similarly, Larson and Guggenheimer (2013) noted enhancements in control, speed, and overall success, allowing beginner gameplay to more closely resemble adult gameplay using standard equipment. Beyond technical benefits, these adaptations also have psychological advantages, offering higher success rates and greater enjoyment, which promote skill learning in beginners (Farrow and Reid, 2010).

Despite the extensive literature in this field, existing reviews have focused on specific areas, such as adaptations in competitive contexts or skill acquisition processes, often addressing these topics in isolation (Buszard et al., 2016a; Chapelle et al., 2023). However, recent studies have identified complementary research lines and studies not included in previous reviews, underscoring the need for a more holistic perspective.

In this context, the present article aimed to review the existing literature on equipment modifications in tennis, differentiating key research lines and identifying knowledge gaps that could inform future studies. The central question guiding this review was as follows: What does the scientific literature reveal about scaled equipment in tennis and game adaptations concerning skill acquisition, match performance, biomechanical and psychological variables, and coaches' perspectives? This comprehensive approach sought to provide an updated overview of the various dimensions of adapted equipment in tennis, fostering a broader and more multidimensional understanding of its impact on player development.

2 Methods

This scoping review was conducted following the protocol established by the Preferred Reporting Items for Systematic Reviews and Meta-Analysis Protocols (PRISMA-P), specifically adhering to the recommendations of the PRISMA Extension for Scoping Reviews 2020 (PRISMA-ScR) (Tricco et al., 2018).

2.1 Information sources

The literature search was conducted across different databases: the multidisciplinary Web of Science and Scopus; the biomedical and life sciences database PubMed; and the sport-dedicated database SPORTDiscus. Additional articles not indexed in these databases were provided by experts in the field. Grey literature sources were identified by searching titles through Google Scholar and the ITF Coaching & Sport Science Review journal, the official journal of the ITF. References from relevant articles were also reviewed to identify additional studies using the snowballing method (Naderifar et al., 2017).

2.2 Search strategy

The systematic search included all publications up to August 2024 to ensure a comprehensive identification of sources related to the topic. The following search terms and operators were applied across all databases in title-abstract-keywords parameters: (*tennis NOT table NOT elbow*) *AND* (*scal** OR adapt* OR modif* OR mini*). These terms were selected after expert consultation. All database searches were performed by a single researcher to maintain consistency in the process.

2.3 Eligibility criteria

The criteria for article selection were established by the researchers following the PECOS framework (Higgins et al., 2019), as detailed in Tables 1, 2.

The focus of the review was on novice tennis players, so it was a priority to include young tennis players between the ages of 6 and 14 as participants. However, it was also considered important to include other participants without prior experience, such as beginner adult players or players with disabilities.

Regarding the exposure criteria, studies with a cross-sectional design (data collection lasting between 1 and 5 days) were included. These studies involved participants with no prior training under adapted conditions and only observed differences between different conditions. Studies involving an intervention (either short-term or long-term) were also considered, corresponding to a training period with adaptations. Long-term exposure was defined as a training duration of 5 weeks or more since the longest intervention observed lasted 8 months.

To be included in the review, the research had to relate to scaled or adapted equipment in the sport of tennis, specifically focusing on intervention-based or empirical studies. Eligible studies were required to include a data collection or measurement process, accompanied by data analysis—whether qualitative, quantitative, or mixed methods—concerning the use of adapted equipment in tennis training, match performance, coaches' perspectives, or other relevant variables. In addition, this review was restricted to manuscripts written in Spanish or English due to the linguistic capabilities of the researchers and because these

TABLE 1 Selection criteria for the scoping review.

Category	Inclusion criteria	Exclusion criteria
Type of study	Article, review article	Book, book chapter, systematic reviews
Language	English or Spanish	Other languages
Methodological design	Interventional or empirical	Reviews, without intervention

were the predominant languages in the literature. Consequently, narrative documents, reviews synthesizing articles already included in the study, and publications in languages other than Spanish or English were excluded.

2.4 Selection of the sources of evidence

Titles and abstracts were sequentially evaluated, and those unrelated to the main topic were discarded. After removing duplicates, the full text of the remaining publications was reviewed to ensure compliance with the inclusion criteria. If the exclusion criteria, listed in Table 2, were identified during the full-text reading, the article was excluded. All titles and abstracts were independently reviewed by two researchers. To ensure a rigorous process, only articles deemed eligible by both reviewers were included based on the inclusion criteria. In cases of discrepancies, discussions were held until consensus was reached. This procedure aimed to minimize bias in the study selection process. For the systematic reviews identified in the process, the number of studies potentially meeting the inclusion criteria was noted, particularly if those studies had been overlooked during the initial search.

2.5 Critical appraisal of the individual sources of evidence

The quality of the articles included in the study was assessed using an adapted version of the Downs and Black (1998) checklist. Each article was evaluated on the following aspects: study purpose, background literature, study design, sample characteristics, statistical significance, data analysis methods, results, conclusions, and implications for future research (see footnote in Table 3). Each criterion was scored as follows: "+" if fulfilled, "−" if not fulfilled, and "NR" if the information was not reported. The scores were summed to obtain a total score, categorized as follows: less than 5 indicated low quality, between 5 and 7 indicated good quality, and 8 or more indicated high quality (van der Fels et al., 2015). The aim of this assessment was to identify and exclude any low-quality studies from the review.

2.6 Data charting process

After the initial classification of the sources, a matrix was developed to extract the most relevant data from the included articles. The matrix captured the following:

1 Authors.
2 Year of publication.
3 Study objectives.
4 Sample and methodology.
5 Main results.

Using this information, the studies were categorized into the following emerging research lines:

- Skill acquisition and learning processes.
- Match performance.
- Influence on psychological variables.
- Analysis of biomechanical variables.
- Perceptions and opinions of coaches and professionals.

3 Results

3.1 Selection of the sources of evidence

Of a total of 6,900 articles identified, after the refinement procedure and application of the exclusion criteria, the final sample consisted of 35 studies. The selection and screening processes of the studies finally included in the review, according to the PRISMA procedure, are graphically presented in Figure 1.

TABLE 2 Inclusion and exclusion criteria for each PECOS domain in relation to adaptations in the players' environment.

PECOS	Inclusion criteria	Exclusion criteria
Population	Tennis players under 10, 12, and 14 years old with or without experience. Players of all ages with disabilities. Adult novice tennis players. Tennis coaches and professional experts with experience.	Tennis players over 14 years old with experience. Adult players with experience. Tennis coaches without experience in adapted conditions.
Exposure	Transversal studies (less than a week of exposure). Short-term studies (1–4 weeks of training). Long-term studies (more than 5 weeks of training).	Without exposure to adapted conditions.
Comparison	Playing tennis with adapted conditions/materials compared to non-adapted conditions or standard materials.	
Outcome	Results regarding the influence of adaptations on physical, biomechanical, technical-tactical, or psychological variables. Opinions of coaches and experts on adapted equipment.	
Study design	Interventional or experimental quantitative studies. Selective studies (quantitative or qualitative). Observational studies.	Reviews and summaries without intervention. Articles where no original data were analyzed.

TABLE 3 Quality assessment of the articles included (Downs and Black, 1998).

	Question number										
Author (year)	1	2	3	4	5	6	7	8	9	10	Total
Coldwells and Hare (1994)	+	–	+	NR	+	+	+	+	+	–	7
Hammond and Smith (2006)	+	+	+	+	+	+	+	+	+	+	10
Farrow and Reid (2010)	+	+	+	–	+	+	+	+	–	–	7
Hardoy et al. (2011)	+	–	+	+	+	+	+	+	–	+	8
Larson and Guggenheimer (2013)	+	+	+	+	+	+	+	+	+	+	10
Sánchez-Alcaraz (2013)	+	+	+	NR	+	+	+	+	–	–	7
Buszard et al. (2014a)	+	+	+	–	+	+	+	+	–	–	7
Buszard et al. (2014b)	+	+	+	+	+	+	+	+	+	–	9
Kachel et al. (2015)	+	+	+	NR	+	+	+	+	+	–	8
Timmerman et al. (2015)	+	+	+	NR	+	+	+	+	–	+	8
Buszard et al. (2016a)	+	+	+	+	+	+	+	+	+	+	10
Bayer et al. (2017)	+	+	+	+	+	+	+	+	–	–	8
Fitzpatrick et al. (2017)	+	+	+	+	+	+	+	+	+	+	10
Prodan and Grosu (2017)	+	+	+	+	+	+	NR	+	–	–	7
Sanz (2017)	+	+	–	–	+	–	+	+	–	–	5
Schmidhofer et al. (2014)	+	+	+	+	+	+	+	+	–	–	8
Ciuntea (2018)	+	+	+	NR	+	+	NR	+	–	–	6
Fitzpatrick et al. (2018)	+	+	+	+	+	+	+	+	+	–	9
Limpens et al. (2018)	+	+	+	+	+	+	+	+	+	+	10
Cortela et al. (2019)	+	+	+	NR	NR	–	NR	+	+	–	5
Davies (2019)	+	+	+	+	NR	–	NR	+	–	–	5
Giménez-Egido et al. (2020c)	+	+	+	+	+	+	+	+	–	–	8
Buszard et al. (2020c)	+	+	+	+	+	+	+	+	–	–	8
Buszard et al. (2020a)	+	+	+	+	+	+	+	+	+	+	10
Buszard et al. (2020b)	+	+	+	+	+	+	+	+	+	+	10
Gimenez-Egido et al. (2020a)	+	+	+	NR	+	+	+	+	+	+	9
Gimenez-Egido et al. (2020b)	+	+	+	+	+	+	+	+	+	–	9
Broadbent et al. (2021)	+	+	+	+	+	+	+	+	+	+	10
Fauzi et al. (2021)	+	+	+	+	+	+	+	+	+	+	10
Fadier et al. (2023)	+	+	+	+	+	+	+	+	+	+	10
Martínez-Gallego et al. (2022)	+	+	+	+	+	NR	+	+	+	+	9
Kilit et al. (2023)	+	+	+	NR	+	+	+	+	+	+	9
Touzard et al. (2023)	+	+	+	+	+	+	+	+	+	+	10
Gimenez-Egido et al. (2023)	+	+	+	NR	+	+	+	+	+	+	9
Kilit et al. (2024)	+	+	+	+	+	+	+	+	+	+	10

NR = not recorded; + = meets criteria; – = does not meet criteria. Questions: (1) Was the objective of the study clearly stated? (2) Was the relevant precedent literature reviewed? (3) Was the sample described in detail? (4) Was the sample size justified? (5) Was the design appropriate to the research question? (6) Were the results reported in terms of statistical significance? (7) Were the methods of analysis appropriate to the research design? (8) Were the conclusions appropriate given the findings of the study? (9) Are there implications for future research given the results of the study? (10) Did the authors acknowledge and describe the limitations of the study?

3.2 Critical appraisal within the sources of evidence

Table 3 shows the quality scores for each article included in the scoping review, following the Downs and Black (1998) checklist. A total of 74% of the studies received high-quality ratings, and all exceeded the score of 5, at which the articles were considered to have good quality.

3.3 Characteristics of the sources of evidence

The main characteristics of each study included in this scoping review are summarized in Table 4. The full matrix detailing the characteristics of each study can be found in the Supplementary materials.

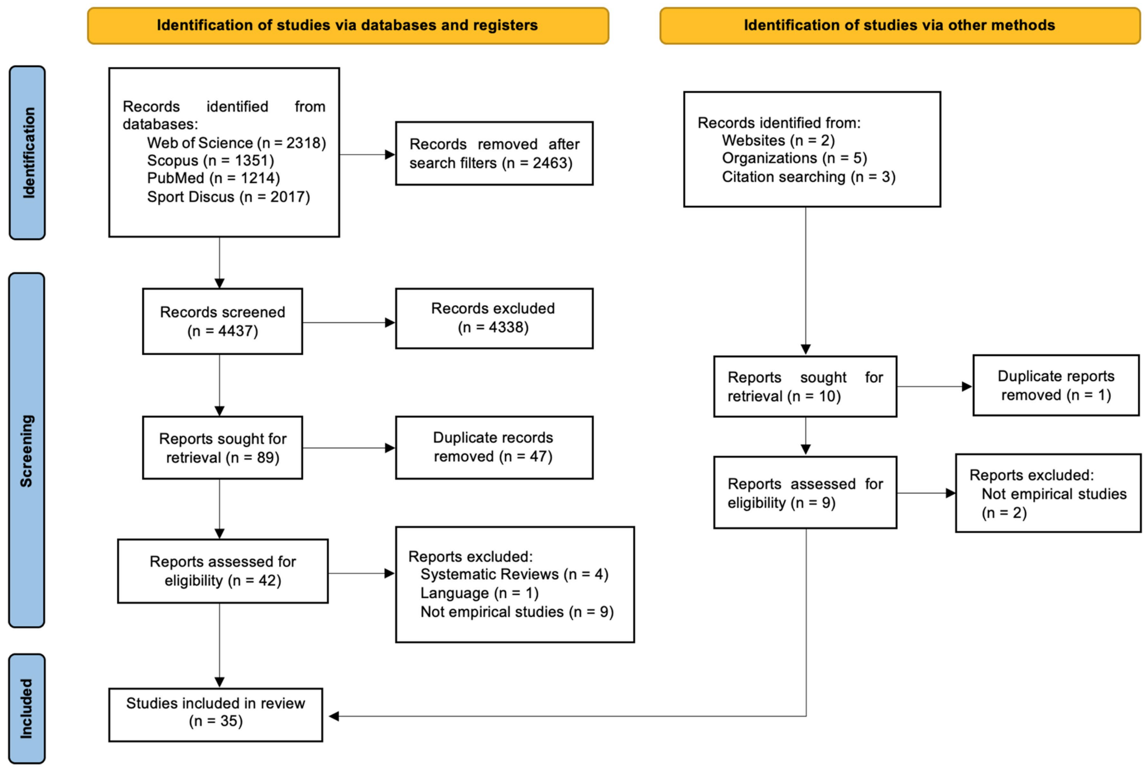

FIGURE 1
Flowchart based on the PRISMA guidelines.

3.4 Synthesis of the results

The analysis of all the articles identified different strands of research, into which they were classified, as reflected in Table 5. Although some articles addressed more than one topic and were included in multiple categories, this table provides a global overview of the research on adapted material in tennis, according to the themes identified.

4 Discussion

The scoping review identified 35 articles that examined equipment and game modifications in tennis, focusing on their influence on relevant factors for beginner players. Several key research lines within this topic were identified and are elaborated below.

4.1 Effects on the skill acquisition process

A prominent and frequently addressed topic in the literature on modifying tennis equipment is its impact on the learning process of tennis skills, particularly in the development of technical abilities.

Most of the studies have focused on training methodologies and their role in skill acquisition. The key variables analyzed included stroke technique and performance (Farrow and Reid, 2010; Buszard et al., 2014b; Hammond and Smith, 2006; Buszard et al., 2014a; La, 2017; Fitzpatrick et al., 2018; Kilit et al., 2023). These studies typically examined the phases of the stroke—such as positioning, backswing, impact, and follow-through—comparing performance with scaled and standard equipment. Stroke performance is assessed through variables such as stroke volume, opportunities, and success rates. Buszard et al. (2014b) reported greater technical losses and disruptions with standard equipment compared to scaled equipment. Other studies employed specific skill tests, such as the TSST, as seen in studies by Fitzpatrick et al. (2018) and Kilit et al. (2023).

Notably, research on groundstrokes has shown significant improvements in speed, accuracy, and the relationships between speed, accuracy, and success when using scaled equipment. These adaptations have led to better forehand and backhand performances, with greater precision and power (Larson and Guggenheimer, 2013; Prodan and Grosu, 2017; Buszard et al., 2020b). A significant finding was the reduction in ball speed when using low-compression balls (Larson and Guggenheimer, 2013; Prodan and Grosu, 2017). The slower balls provide players with more time for preparation and positioning, resulting in greater technical efficiency and stroke success.

Studies have also explored broader adaptations, such as comparing mini-tennis to adult tennis, in terms of their effects on basic motor skills. Improvements were observed in hand-eye coordination (Hardoy et al., 2011), agility, and speed (Ciuntea, 2018), as well as in tennis-specific skills such as positioning, stroke technique, and court movement (Coldwells and Hare, 1994; Buszard et al., 2016b). These studies have consistently reported significant improvements and demonstrated that mini-tennis provides a positive transfer to adult gameplay.

TABLE 4 Summary of the articles' main characteristics.

Reference	Topic	Sample and methods	Results
Coldwells and Hare (1994)	MT skill transfer to real game.	*N* = 16 (7–10 years) in the EG / CG	MT showed better transfer of skill acquisition to real tennis than the CG.
Hammond and Smith (2006)	LCB in learning tennis skills.	*N* = 14 (5–11 years) in the EG/CG. 8 sessions.	LCB improved technique, length of points, and hitting opportunities.
Farrow and Reid (2010)	Adaptations on skill acquisition.	*N* = 23 (8 years without experience). 5 weeks.	Adapted conditions improved rally volume, technique, chances, success, enjoyment, and commitment.
Hardoy et al. (2011)	MT intellectual disabilities.	*N* = 24 (18–40 years) in the EG / CG. 6 months, 3h twice a week.	MT decreased the anxiety scale and improved coordination.
Larson and Guggenheimer (2013)	Modified court and ball on the forehand.	*N* = 8 (7–9 years with experience)	LCB and reduced courts resulted in higher speed, accuracy, and success scores.
Sánchez-Alcaraz (2013)	Adaptations over time structure and actions of play.	*N* = 8 (8 years with experience) 16 matches (8 orange, 8 yellow)	Orange court and ball: longer points, fewer unforced errors, and a greater number of strokes and winners.
Buszard et al. (2014a)	Examine racket sizes and ball compressions.	*N* = 80 (6–8 years without experience). Task with 3 conditions.	Small racket + red ball: the best hitting performance. Red ball: better with a small/medium racquet.
Buszard et al. (2014b)	Observe learning a motor task with scaled material.	*N* = 40 (9–11 years). Task with 2 conditions.	Adapted equipment: stepped forward, swung from bottom to top, correct impact with the ball more often.
Schmidhofer et al. (2014)	Differences in play structure between ATP and Tennis 10s.	*N* = 87 (67 elite players, 20 children).	U9: scores were better when playing on a smaller court.
Kachel et al. (2015)	Adaptations in junior competition.	*N* = 20 (10 years). 40 matches: standard/ green.	Modified ball: faster rally speed, more comfortable height shots, and at the net. Yellow ball: more "high" shots.
Timmerman et al. (2015)	Court sizes and net height in child tennis players.	*N* = 16 (9 years). 4 conditions combining a scaled court and net with the standard.	Scaled net: more winners, more forced errors, more shots at a comfortable height, and a more aggressive style of play.
Buszard et al. (2016b)	Scaled rackets on skill acquisition primary school.	*N* = 46 (Grade 1–2 PE). SR group, LR group. 30min x 5 weeks.	SR: Improved both the forehand and backhand and transferred the skills to the larger racket
Bayer et al. (2017)	Lime court in the transition from orange to green.	*N* = 24 (9–10 years) 12 matches on a green court and 12 on a lime court.	Lima: the structure of play more similar to adult game than the green court, more forced errors and winners, more points won with the 2nd serve, and ICT closer to an adult.
Fitzpatrick et al. (2017)	Court and ball dimensions over playing behavior.	*N* = 48 divided into 4 age groups (7, 8, 9, and 13 years). 35 matches.	Duration of points and number of forehand strokes declined; variability of play increased as age groups progressed.
Prodan and Grosu (2017)	Investigate racket sizes and ball compression on the backhand.	*N* = 20 (8–9 years) in the EG and CG. Red, orange, and green balls.	The accuracy-speed variable was much higher with scaled equipment. Low-pressure balls resulted in more successful shots.
Sanz (2017)	Compare traditional and adapted methodology.	*N* = 100 (7–10 years) in 2 EGs (orange & green ball) and 2 CGs.	The EG showed greater improvements than the CG, both at the technical and execution levels, as well as at the tactical level.

(Continued)

TABLE 4 (Continued)

Reference	Topic	Sample and methods	Results
Ciuntea (2018)	Analyze Tennis 10s on the development of motor skills.	*N* = 56 (7–9 years) in the EG and CG. 8 months of 2 x sessions/week.	The EG improved more than the CG. Children up to 10 benefit from the Tennis 10s because of the gradual resizing of the materials.
Fitzpatrick et al. (2018)	Investigate adaptations in match behavior and skill tests.	*N* = 16 (7 years) in the EG and CG. 8-week intervention 1h/week.	EG: better stroke symmetry, more backhand strokes, and fewer forehand strokes. Higher backhand success rates, ability, and technical proficiency.
Limpens et al. (2018)	Examine reductions of net height on match performance.	*N* = 16 (9 years) 4 matches per pair with 4 net heights.	Lower net height: improved serving performance, more aggressive play, faster rallies, more winners, and decreased rally length.
Cortela et al. (2019)	Describe the transition from green to yellow ball.	*N* = 14 Brazilian club coordinators with experience in programs.	Not possible to identify criteria; the clinical eye of the coach is the main parameter for determining the transition.
Davies (2019)	Perspective of coaches on adapted equipment.	*N* = 20 coaches with experience in scaled equipment.	Emphasized that transitions should be based on skill levels rather than age to ensure adequate skill acquisition before moving to the next level...
Giménez-Egido et al. (2020c)	Impact of a modified competition on groundstrokes.	*N* = 20 (U10) 4 matches each, in different net heights and court lengths.	Modified competition: increased the number of flat shots and a more offensive style of play, but less variability in shots.
Buszard et al. (2020c)	Study different arm segments as determining variables.	*N* = 21 (6–9 years) in the EG and CG. 40 attempts at forehand.	Shoulder-racquet distance is a determining variable. Adapted equipment: more distal control in hand-racquet distance.
Buszard et al. (2020a)	Coaches' perceptions of a modified tennis campaign.	*N* = 114 (35 key figures from national tennis associations and 79 coaches)	Perceived Play and Stay campaign increased and sustained participation, facilitated skill development, and had a positive effect on attitude.
Buszard et al. (2020b)	Adaptations over coordination and variability.	*N* = 25 Forehand hitting task using 2 pieces of equipment: scaled and normal.	Adapted materials: greater accuracy, temporal stability of the swing, and better coupling between the upper arm and forearm.
Gimenez-Egido et al. (2020a)	Compare 2 adapted competitions on serving in U10 players.	*N* = 20 (U10) 80 matches services, 40 in U10 and 40 in adapted conditions.	Modified competition: more effective serves, direct serves, unreturned serves, and improved serving performance.
Gimenez-Egido et al. (2020b)	Modifying net height and court length on technical-tactical.	*N* = 20 (U10) 40 matches, 20 U10 conditions, 20 adapted conditions.	Modified condition: more variability, shots close to the net, offensive play, and greater serve effectiveness (fewer 2nd serves).
Broadbent et al. (2021)	Calculating pi ratios for adaptations in junior sports.	Federation guidelines compared to children's dimensions to calculate ratios.	Most children compete at larger sizes than would be appropriate, particularly younger ones. Girls' competitions are better suited than boys'.
Fauzi et al. (2021)	Mini-tennis training on forehand groundstrokes.	*N* = 44 (6–8 years) 22 in the EG and 22 in the CG.	The EG performed better on the post-test than the CG. Significant differences were found between the pre-test and post-test.

(Continued)

TABLE 4 (Continued)

Reference	Topic	Sample and methods	Results
Martínez-Gallego et al. (2022)	Find out experts' opinions on Play and Stay	*N* = 35 experts from federations answered a questionnaire.	Most of them were aware of the rule change, applied it, had access to materials, and agreed it had a positive impact on U10 players.
Fadier et al. (2023)	Influence of serve distance and net height on biomechanics.	*N* = 10 (9–12 years) 3 serves from 3 distances (red, orange, and green courts).	Red conditions: more powerful, faster serves, improved maximum angular velocities of trunk and knee flexion.
Kilit et al. (2023)	Ball and court adaptations on skill learning in adults.	*N* = 24 university students. 6-week training.	LCB group: higher accuracy, rally performance, technique control, speed, direction, greater stability, and pace of play.
Touzard et al. (2023)	Racket size on serve biomechanics and performance.	*N* = 9 (10 years) 3 serves, 3 racquet sizes.	Racket size: not influenced ball speed or racket head speed. LR: increased shoulder and elbow loads, raising the risk of upper limb injury.
Gimenez-Egido et al. (2023)	Net height and court size on self-efficacy and efficiency.	*N* = 20. Assessed Perceived Physical Ability + Self-Efficacy.	Reduced net height and court size: higher self-efficacy and service efficiency.
Kilit et al. (2024)	LCB versus standard balls in adults.	*N* = 24 (18–34 years). 24 matches. Psychophysiological state and match play.	Green ball: higher HR, % HR, and enjoyment, longer rallies, more controlled pace, and lower perceived and mental efforts.

EG = experimental group; CG = control group; MT = mini tennis; ATP = Association of Tennis Professionals; LCB = low compression balls; U10 = under 10 years old players; SR = scaled racquet; LR = large racquet; HR = heart rate.

In terms of age groups, research in this area has predominantly focused on children aged 6 to 9 years, as scaled adaptations are typically recommended for these age groups. However, more recent studies, such as Kilit et al. (2023), have included beginner adults, demonstrating that the benefits of scaled adaptations are not limited to children. These findings highlight the need for further exploration of the effects of scaled equipment on other populations, including adolescents, older adults, and individuals with functional diversity.

4.2 Effects on match performance

Another extensively studied area concerns the impact of equipment modifications in competitive contexts, with a focus on match performance. Research in this domain has often analyzed real or simulated matches, investigating technical-tactical variables and playing styles.

Several studies have examined the effects of equipment modifications on game structure, including point duration and effective playing time. Low-compression balls and reduced court dimensions were found to significantly increase point duration compared to traditional equipment (Sánchez-Alcaraz, 2013; Bayer et al., 2017; Fitzpatrick et al., 2017, 2018; Kilit et al., 2024). These modifications give players more time to react, position themselves, and execute strokes, resulting in longer rallies and more dynamic gameplay. Longer point durations also increase effective playing time, offering more opportunities to practice skills and engage in realistic match scenarios.

Other studies have focused on technical-tactical variables, particularly serve and groundstroke performance. Modifications such as reduced net height and smaller court dimensions have been associated with greater first-serve effectiveness and improved serve placement (Limpens et al., 2018; Bayer et al., 2017; Schmidhofer et al., 2014; Gimenez-Egido et al., 2020a; Gimenez-Egido et al., 2020b; Gimenez-Egido et al., 2023). For groundstrokes, scaled adaptations promote greater symmetry in the use of the forehand and backhand (Fitzpatrick et al., 2018; Fitzpatrick et al., 2017), addressing the common tendency of young players to favor the forehand over the backhand (Farrow and Reid, 2010) and aligning their play more closely with adult tennis.

Reducing net height has been shown to facilitate a more offensive playing style, increasing the frequency of flat, winning shots and net approaches (Giménez-Egido et al., 2020c). In addition, Kachel et al. (2015) reported that green balls resulted in more frequent net play and higher ball speeds. These findings suggest that scaled adaptations facilitate a playing style that mirrors adult tennis, providing players with more opportunities for tactical development.

Despite the consistent focus on technical-tactical variables in competitive scenarios, the studies reviewed varied in methodology, participant age and skill levels, and the specific adaptations implemented. Most studies explored modifications to court size and net height, while others examined balls with varying compression. Further research is needed to investigate the long-term effects of scaled equipment, the transition to

TABLE 5 Classification of the studies according to the research areas identified.

Research area	Studies
Skill acquisition and learning processes	Farrow and Reid (2010), Buszard et al. (2014b), Buszard et al. (2020a), Larson and Guggenheimer (2013), Hammond and Smith (2006), Buszard et al. (2014a), La (2017), Fitzpatrick et al. (2018), Kilit et al. (2023), Prodan and Grosu (2017), Buszard et al. (2020b), Hardoy et al. (2011), Ciuntea (2018), Coldwells and Hare (1994), Buszard et al. (2016b), Fauzi et al. (2021)
Match performance	Kachel et al. (2015), Limpens et al. (2018), Fitzpatrick et al. (2018), Sánchez-Alcaraz (2013), Bayer et al. (2017), Fitzpatrick et al., 2017, Kilit et al. (2024), Schmidhofer et al. (2014), Gimenez-Egido et al., 2020a, Gimenez-Egido et al. (2020b), Gimenez-Egido et al. (2023), Giménez-Egido et al. (2020c), Timmerman et al. (2015)
Analysis of biomechanical variables	Buszard et al. (2020b), Buszard et al. (2020c), Broadbent et al. (2021), Fadier et al. (2023), Touzard et al. (2023)
Influence on psychological variables	Farrow and Reid (2010), Hardoy et al., 2011, Kilit et al. (2024), Gimenez-Egido et al. (2023), Timmerman et al. (2015)
Perceptions and opinions of coaches and professionals	Buszard et al. (2020a), Davies (2019), Cortela et al. (2019), Martínez-Gallego et al. (2022)

standard equipment, and the customization of materials to player characteristics.

4.3 Biomechanical variables

Studies examining biomechanical variables associated with scaled tennis equipment have focused on aspects of motor control and performance. Research by Buszard et al. (2020c) and Buszard et al. (2020b) highlighted improvements in stroke precision and distal arm segment control with scaled equipment. These studies observed increased temporal stability and reduced movement variability, along with better coordination between the upper arm and forearm. Methodological differences between the studies included analyses of racket-shoulder distance in relation to task success, control, and impact point in one study and variability in arm segment coordination and flexibility in the other.

Broadbent et al. (2021) expanded the biomechanical focus to include other sports, such as rugby, netball, basketball, and hockey, evaluating the relationship between athletes' body measurements and sport-specific adaptations. The study noted that adaptations were more acceptable in female competitions than in male ones and that younger athletes (under 9 years old) faced greater challenges with oversized courts and equipment.

In serving, significant improvements in kinematic and kinetic variables were reported (Fadier et al., 2023; Touzard et al., 2023). Fadier et al. (2023) found that reduced court and net dimensions led to higher racket and ball speeds, increased knee extension velocity, and improved trunk flexion in young players. Touzard et al. (2023), while not observing significant differences in racket and ball speeds, reported increased angular velocities in distal arm segments and reduced loads on the shoulder and elbow with scaled rackets compared to standard rackets.

These findings are particularly important for injury prevention in young players aged 8 to 12 years. Scaled equipment reduces joint stress while maintaining, or even enhancing, performance and stroke control. Proper implementation of these adaptations in under-8, under-10, and under-12 competitions is essential for optimizing player development. Future research should investigate injury prevention in other strokes and evaluate scaled equipment's precision and effectiveness in real-match contexts, as many studies currently focus on controlled conditions.

4.4 Psychological variables

Studies examining the psychological effects of equipment modifications have highlighted variables such as practice commitment, enjoyment, and self-efficacy. Scaled equipment has been shown to enhance enjoyment by fostering a more aggressive playing style, which creates a more positive experience for players. Specifically, reduced net height has been associated with increased self-efficacy in beginner players, improving their success rate in serves. This improvement in performance boosts their comfort and enjoyment during practice, ultimately increasing their commitment (Gimenez-Egido et al., 2023; Timmerman et al., 2015). However, these effects were significant only for serves and did not extend to other strokes.

Kilit et al. (2024) observed that playing with green balls resulted in a more positive mood among adult beginner players, whereas using standard balls led to higher tension, fatigue, and frustration, as well as a greater perceived mental effort. Similarly, Farrow and Reid (2010) found that adapted courts and balls increased player engagement compared to standard conditions due to a higher number of opportunities and successful strokes. In contrast, Timmerman et al. (2015) reported that players exhibited more confidence with standard courts and nets, potentially due to unfamiliarity with modified conditions.

The psychological benefits of equipment modifications are especially evident in players with functional diversity. Hardoy et al. (2011) reported reduced anxiety and frustration, as well as improved self-confidence and hand-eye coordination, under adapted conditions in players with intellectual disabilities. These findings underscore the importance of further research focused on individuals with physical and mental disabilities to better understand and expand these benefits.

Insights gained from examining psychological and attitudinal variables are critical for understanding player behavior on the court and enhancing their overall experience. However, psychological variables were often treated as complementary in the studies reviewed, typically included as secondary outcomes alongside technical-tactical or physiological variables. Challenges in this area of research arise from the variability in psychological metrics studied across different articles, which complicates comparisons and interpretations. Moreover, underrepresented groups, such as adults and individuals with functional diversity, require more attention. Future studies should explore psychological and emotional variables more thoroughly across diverse player populations and investigate their interplay with related physiological variables.

4.5 Coaches' and professionals' perceptions

Four studies in this review examined coaches' perceptions of the International Tennis Federation's (ITF) campaigns and the use of modified equipment, consistently highlighting a positive impact on children's learning. Hammond and Smith (2006) conducted interviews with coaches, who unanimously praised low-compression balls for improving beginner players' control and technique.

Using a qualitative approach, Davies (2019) found that coaches preferred the Constraints-Led Approach methodology and valued scaled equipment programs. They emphasized the importance of aligning equipment with players' skills rather than biological age and advocated for cooperative, varied teaching methods. Cortela et al. (2019) examined the transition from green to yellow balls, revealing that individual coaches relied on specific criteria, such as impact height and grip, with the commencement of competitive play being a decisive factor.

From a quantitative perspective, Buszard et al. (2020a) evaluated professionals' opinions on the Tennis 10s, Tennis Xpress, and ITF Play and Stay campaigns and regulatory changes. They concluded that these initiatives effectively increased tennis participation and improved key skills, particularly the forehand and backhand. Similarly, Martínez-Gallego et al. (2022) focused on the ITF Play and Stay campaign and regulatory changes in under-10 competitions. They confirmed that coaches were familiar with and applied these standards during training and competitions and had access to the necessary equipment for implementation. The study concluded that the campaign positively influenced participation and learning among beginner players.

These findings provide essential insights for federations and organizations managing grassroots and school tennis programs, highlighting the effectiveness of these campaigns and coaches' satisfaction with their implementation. Nonetheless, future research could expand this area of inquiry by employing quantitative, qualitative, and mixed methods to deepen the understanding of coaches' perspectives. In addition, extending the analysis to include federations and organizing bodies could offer a broader perspective on the adoption and impact of these initiatives.

5 Limitations

As a scoping review, this study prioritized identifying general themes and trends over in-depth analyses of causal relationships or specific effects. One limitation is the representativeness of the results, as the inclusion criteria depended on the availability of studies in certain languages or databases. Furthermore, scoping reviews are not designed to answer specific research questions or synthesize evidence quantitatively, necessitating systematic reviews or meta-analyses to validate robust conclusions.

6 Future research directions

Based on the results from this review, future research should focus on real-game contexts, delve deeper into biomechanical aspects for injury prevention and development optimization in children, and prioritize the study of psychological variables. Including underrepresented groups, such as adults and individuals with functional diversity, would provide valuable insights. Furthermore, examining gender- and age-related differences in greater detail is recommended.

6.1 Practical applications

These findings hold relevance for federations, clubs, and coaches, who can standardize the use of scaled equipment in training programs and competitions to facilitate beginner players' technical progression, foster greater adherence to the sport, and improve retention rates. In under-10 competitions, events organized by federations should universalize these adaptations in their regulations to prevent injuries and promote safe tennis practice from an early age. Insights into the game structure can help clubs organize coaching programs for players of all ages. Coaches can facilitate skill acquisition by planning training sessions for beginner players that offer opportunities to focus on strategic learning and decision-making. Finally, integrating this approach into coach education programs worldwide, accompanied by certifications issued by federations, would help standardize these methodologies among professionals.

7 Conclusion

This scoping review aimed to identify and categorize existing research on scaled equipment in tennis and summarize the most relevant findings within each area, providing a preliminary map of the evidence without assessing the quality or validity of individual studies. The main findings suggested that scaled adaptations improve stroke control and precision, facilitate the learning of basic techniques, and promote a more efficient and tactical playing style. In addition, they reduce joint stress, minimize injury risk, and enhance satisfaction, self-efficacy, and commitment during practice in young players. Coaches positively regard scaled equipment for its effectiveness in teaching processes.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

AP-P: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. MC: Conceptualization, Investigation, Project administration, Supervision, Visualization, Writing – original draft, Writing – review & editing. JR-L: Conceptualization, Funding acquisition, Investigation, Project administration, Supervision, Visualization, Writing – original draft, Writing – review & editing. JG: Conceptualization, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. RM-G: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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Match-play data according to playing categories in badminton: a systematic review

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Introduction: This systematic review aimed to investigate differences in match-play data according to the five playing categories in badminton.
Materials and methods: The systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Searches were conducted on ScienceDirect, PubMed, Google Scholar, Scopus, Web of Science, and Cochrane Library databases. Studies assessing technical-tactical actions, activity profiles, or external and internal loads as match-play outcome measures according to the five playing categories in badminton were deemed eligible. Quality assessment was performed using a modified version of the AMSTAR-2 checklist to compare the outcome measures, effect sizes (ES) and associated 95% confidence intervals were calculated.
Results: Of the 12,967 studies that were identified, 34 met the eligibility criteria. Among these, 29 and five were rated as excellent and good quality, respectively. Some individual ESs of activity profiles showed up to large differences (ES ≤ 4.52) favouring the men's compared with the women's singles category. Some individual ESs of activity profiles showed up to large differences (ES ≤ -2.72) favouring the women's doubles category compared with other doubles categories. The overall ESs for the activity profiles were large (ES = −0.76 to −0.90), favouring the doubles over the singles categories in both sexes.
Discussion: There are up to large differences in match-play data according to the five playing categories in badminton, each category placing specific demands on the players. Thus, each category requires specific training and testing procedures, what should be considered by scientists and coaches.

KEYWORDS
game characteristics, metabolism, notational analysis, physical demands, physiology, racquet sports

1 Introduction

Since 1992, badminton has been part of the Olympic Games and has developed into a racquet sport with a professional structure and high level of competition (1). It has been estimated that over 200 million people play this sport recreationally and more than 7,000 athletes compete in hundreds of international and national competitions each year (1). To compete, the intermittent characteristics of badminton require optimised physical, technical-tactical, and psychological factors (2–4). An important aspect of badminton is the five different playing categories: men's and women's singles and men's, women's, and mixed doubles (5). Without strong evidence, the different playing categories are assumed to place specific demands on the players (1). Thereon, specific training and testing procedures are required to prepare the players (6, 7). Generally, such procedures should mimic particular playing demands (8), thereby requiring knowledge of match-play data (9, 10).

Badminton match-play data can be categorised into four groups: (1) technical-tactical actions, (2) activity profiles, (3) external (mechanical), and (4) internal (physiological) loads (9, 11). The four groups are interrelated (12). For example, technical-tactical actions such as smash, drive, drop, lob, and clear shots affect the activity profiles regarding the match duration, rally time, and work density (13–15). Furthermore, the resulting activity profiles affect the external and internal loads that players must meet (1, 9, 10). Finally, internal loads can induce long-term adaptations that can influence all the aforementioned aspects (10). Thus, a comprehensive understanding of these variable groups and their interactions is valuable to consider for scientists and coaches in badminton, when aiming to design specific training and testing procedures for the playing categories and other important influencing attributes of the players such as sex, playing level, and age (1, 9, 16–18). As evidence, analyzing match-play data helps identify the specific demands placed on players, enabling them to enhance performance through physiological adaptations and reduce the risk of injuries (17). Unfortunately, evidence on match-play data in badminton is limited; especially, regarding the specific demands of the five playing categories (1). Thus, more evidence-based research is needed.

To our knowledge, there are three reviews on badminton match-play. One systematic review investigated the effects of badminton on health outcomes and discovered that this sport improves cardiopulmonary function and physical abilities such as endurance and strength (19). A further review on general playing characterises of badminton was narrative in its nature (1) and the other solely focused on internal loads across several racquet sports (20). While previous reviews have provided evidence of the health benefits (19), general characteristics (1), and internal loads of badminton (20), there is no systematic overview regarding match-play data in badminton yet. Consequently, how the existing literature on badminton match-play data differs especially based on the five playing categories is still unclear. This problem creates ambiguity and debates among scientists and coaches (1). Therefore, a systematic literature review of match-play data concerning the five playing categories in badminton is warranted.

Thus, this systematic review aimed to investigate differences in match-play data according to the five playing categories in badminton.

2 Materials and methods

2.1 Research design and search strategy

The systematic review was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (21). The initial literature search was conducted in databases, including ScienceDirect, PubMed, Google Scholar, Scopus, Web of Science, and Cochrane Library on 1 June 2023. Additionally, to ensure that all actual available literature was included, an update was conducted immediately before submission on July 2024. The P = Population, I = Intervention, C = Comparisons, and O = Outcomes (PICO) scheme (21) was used to develop the search lines. Search terms were created by linking category sections with the Boolean operator "AND" to ensure that at least one term from each section appeared in searches, while the "OR" operator was used to link terms within a section (Table 1). The received entries were downloaded to a citation manager (Clarivate Analytics, Endnote X9, London, UK), and duplicates were removed. Furthermore, the "related citations" feature of PubMed was used to identify further relevant studies. A spreadsheet (Microsoft Office,

TABLE 1 Search line according to the PICO scheme.

PICO scheme		Category	Keyword search
P	Badminton players	Sex	"Males" OR "men" OR "females" OR "women"
		Playing level	"Recreational" OR "hobby" OR "amateur" OR "professional" OR "elite"
		Age	"Junior" OR "adolescent" OR "adult" OR "senior"
I	Match-play	Playing context	"Official" OR "competitive" OR "simulated" OR "training"
C	Participants groups	Badminton playing categories	"Singles" OR "doubles" OR "mixed"
O	Match-play outcome measures	Technical-tactical actions	"Smash" OR "drive" OR "drop" OR "lob" OR "clear" OR "net" OR "forced error" OR "unforced error" OR "shuttlecock placement"
		Activity profiles	"Match duration" OR "number of rallies" OR "rally time" OR "shot" OR "stroke" OR "shot per rally" OR "stroke per rally" OR "shot frequency" OR "rest time" OR "work to rest ratio" OR "effective playing" OR "work density"
		External loads	"Jump" OR "lunges" OR "speed" OR "velocity" OR "acceleration" OR "deceleration" OR "distance covered"
		Internal loads	"Oxygen uptake" OR "VO_2″ OR "tidal volume" OR "V_T" OR "respiratory frequency" OR "f_B" OR "minute ventilation" OR "$\dot{V}_E$" OR "carbon dioxide production" OR "$\dot{V}CO_2$" OR "respiratory exchange ratio" OR "RER" OR "respiratory ratio" OR "RQ" OR "ventilatory equivalents for oxygen" OR "$\dot{V}E/\dot{V}O_2$" OR "ventilatory equivalents for carbon dioxide" OR "$\dot{V}E/\dot{V}CO_2$" OR "oxygen end-tidal pressure" OR "$PetO_2$" OR "carbon dioxide end-tidal pressure" OR "$PetCO_2$" OR "heart rate" OR "blood pressure" OR "blood lactate concentration" OR "ratings of perceived exertion" OR "RPE" OR "energy expenditure" OR "energy supply" OR "aerobic" OR "oxidative" OR "anaerobic" OR "lactic" OR "alactic" OR "creatine phosphate" OR "phosphocreatine system" OR "PCr" Or "anaerobic glycolysis" OR "blood hormone" OR "testosterone" OR "estrogen" OR "cortisol" OR "thyroid levels" OR "fluid electrolyte balance" OR "sodium" OR "calcium" OR "potassium" OR "chloride" OR "phosphate" OR "magnesium" OR "body composition" OR "body height" OR "body weight" OR "body mass index" OR "BMI" OR "body mass" OR "lean mass" OR "fat-mass" OR "fat-free Mass"

Excel 2016, Redmond, WA, USA) was created to manage the detected studies following the developed PICO scheme. The titles, abstracts, and full texts of the selected studies were screened based on the defined eligibility criteria and studies considered unsuitable were excluded. Additionally, the reference lists of eligible studies were reviewed to identify relevant studies that were not detected by the search line. Any studies using the pre-2006 scoring system were excluded due to significant differences in playing time, which could affect the match-play outcome measures (22). All data were independently extracted by two authors (BW and TA). In terms of disagreements, a third author (MWH) was added and it was discussed until a consensus was reached. This proceed was also applied to the study quality assessment described below.

2.2 Eligibility criteria

This review included cross-sectional and longitudinal studies involving both sexes, playing level, all ages of badminton players investigated during match-play. The specific eligibility criteria included studies: (1) written in English; (2) with ethical approval (except for retrospective studies); (3) involving non-injured or non-paralympic players; (4) including the five badminton playing categories; (5) investigating official or simulated matches without experimental approaches; and (6) involving technical-tactical actions, activity profiles, or external and internal loads as match-play outcome measures.

2.3 Study quality assessment

A modified version of the AMSTAR-2 checklist (23) was used to assess the study quality based on 16 specific questions related to: (1) clarity of purpose; (2) relevance of background literature; (3) appropriate study design; (4) study sample; (5) sample size justification; (6) informed consent procedure (if any); (7) reliability and (8) validity of outcome measures; (9) detailed method description; (10) results reporting; (11) analysis methods; (12) description of practical importance; (13) description of drop-outs (if any); (14) appropriately drawn conclusions; (15) implications for practice; and (16) acknowledgement of study limitations. Previous study was modified critical review components into a single score, which proved effective for assessing the risk of bias in observational studies (10). Each question was scored using binary values (0 = no, 1 = yes), except for questions 6 and 13, for which “not applicable” was also an option. Finally, the results were converted into a percentage score by summing all individual scores and dividing by the maximum possible score; thus, a higher percentage indicated a higher study quality (10). As previously conducted, the scores were divided into three methodological quality categories: low (≤50%), good (51% to 75%), and excellent (>75%) (10, 24).

2.4 Data extraction

The data were extracted using the PICO scheme. The following data were collected: P = sample size, sex, playing level, and age; I = playing context (official or simulated match-play); C = single, double, or mixed playing categories; and O = main outcome measure regarding technical-tactical actions, activity profiles, and external and internal loads. If published data were unclear or missing, the corresponding authors were contacted via e-mail.

2.5 Data synthesis

The outcome measures were categorised into the five playing categories in badminton. Additionally, sex (men and women) and playing level were considered, whereby the latter was clustered into world-class, elite/international level, highly trained/national level, trained/developmental, and recreationally active players, as previously recommended (25).

2.6 Statistical analysis

Since a meta-analysis could not be conducted due to the large heterogeneity of the included studies and their data, effect sizes (ES) and associated 95% confidence intervals (CI) were alternatively calculated to compare differences in means (26), as conducted in previous systematic reviews with similar applied sport science purposes before (27, 28). The main advantage of that alternative statistical approach is that ESs can easily be computed from the means and standard deviations of the included original studies, which enhances the transparency and reliability of the outcome statistics of reviews. With respect to the computation, both individual and overall ESs were computed. Therefore, the mean differences were divided by the average standard deviations (29), with pooled baseline standard deviations (30). Based on established criteria (30), ESs were interpreted as small (<0.40), moderate (0.40–0.70), and large (>0.70). For validity, ESs were calculated only for means based on, at least in part, two studies or comparisons. Microsoft Excel 2016 (Microsoft, Redmond, WA, USA) was used for all the calculations.

3 Results

3.1 Literature search

Figure 1 illustrates the results of the literature search. Initially, 12,967 studies were identified, with 3,946 removed because of duplication, leaving 9,021 studies. These studies were screened by title and abstract against the defined eligibility criteria, resulting in the exclusion of 8,904 studies. The remaining 117 studies underwent full-text screening, with 77 excluded based on the exclusion criteria. From the 40 studies considered, seven additional studies were obtained from the reference lists. Of these, three were excluded for not meeting the eligibility criteria, resulting in 44 studies. However, 10 of these 44 studies were removed because they used an outdated badminton scoring system that existed until 2006 (13–15, 22, 31–36). Finally, the remaining 34 studies were considered for the quality assessment (2–5, 37–66).

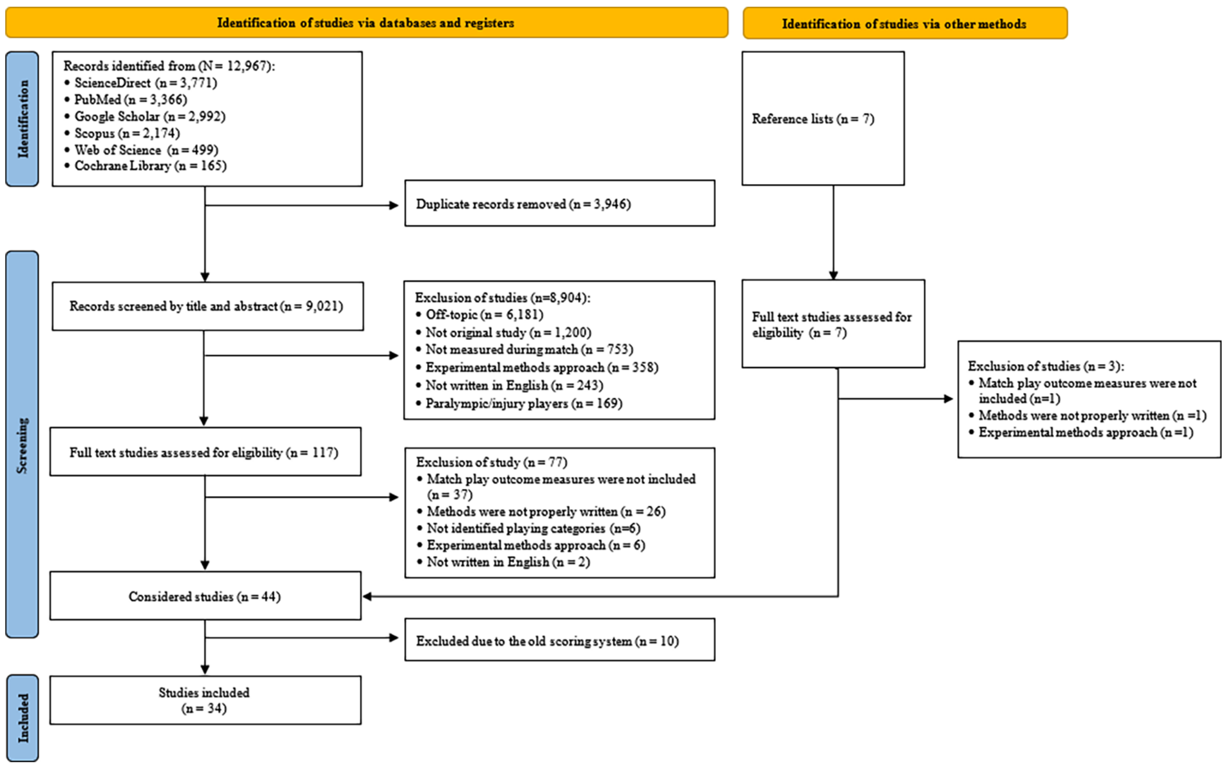

FIGURE 1
Flow chart of the literature search strategy adopted from the PRISMA-guidelines.

3.2 Study quality of the studies

Table 2 presents the results of the quality assessment of the 34 included studies. The mean quality score was 83.1%. No study had a score of 100%, but 29 studies (2–5, 37–45, 47, 50–62, 65, 66) were rated as excellent quality. Five studies (46, 48, 49, 63, 64) were of good quality; no study was of low quality. Studies with higher scores had practical implications (Question 15) and limitations (Question 16). No study provided drop-out rates, making question 13 always "not applicable". Fifteen studies (2, 4, 42, 43, 46, 48, 49, 51, 52, 54, 58, 62, 64–66) showed "not applicable" for question 6 owing to their retrospective designs. All studies lost quality points on sample size justification (Question 5), and 12 studies (2, 4, 43, 46, 48, 49, 52, 54, 58, 62, 64, 65) lost points owing to sample description (Question 4).

3.3 Study characteristics

Tables 3–5 summarise the characteristics of the 34 studies using the PICO scheme. Fourteen studies (4, 42, 43, 46, 48, 49, 51, 52, 54, 58, 62, 64–66) did not provide data regarding sample size. The remaining 20 studies reported data on 362 players, including 244 men and 118 women. The mean age of all players was 20.6 ± 4.9 years, with 21.5 ± 5.4 and 18.9 ± 3.5 years for men and women, respectively. Sixteen studies (2, 4, 37–41, 43, 48, 51, 52, 56, 57, 59, 62, 63) investigated men and women; 14 studies (3, 5, 42, 44–47, 49, 50, 53, 58, 60, 61, 65) investigated only men; and four studies (54, 55, 64, 66) reported data on only women. Regarding playing level, world-class players were most frequently observed in 14 studies (2, 4, 40, 42–45, 49–52, 54, 58, 64); twelve studies (3, 5, 37–39, 46, 48, 53, 61, 62, 65, 66) focused on elite/international players; seven (41, 55–57, 59, 60, 63) on highly trained/national players; and one study (47) investigated recreationally active players. No study investigated players at the training or developmental levels.

In terms of playing context, official matches were most commonly investigated in 24 studies (2–5, 38–40, 42–46, 48, 49, 51, 52, 54, 56–58, 62, 64–66), followed by simulated matches in nine studies (37, 41, 47, 50, 53, 55, 60, 61, 63). One study (59) analysed official and simulated matches. Regarding playing categories, men's singles were most often investigated in 28 studies (2, 3, 5, 37–52, 56–63, 65), followed by women's singles in 19 studies (2, 37–41, 43, 48, 51, 52, 54–57, 59, 62–64, 66). Fewer studies have been conducted in the doubles categories: men's doubles in five studies (4, 43, 51, 53, 62), women's doubles in four studies (4, 43, 51, 62), and mixed doubles in three studies (43, 51, 62). Concerning outcome measures, most studies focused on activity profiles with eight studies (4, 43, 46, 51, 52, 58, 64, 65), followed by the internal loads with seven studies (37–40, 44, 45, 59). Seven studies (2, 3, 42, 48, 49, 54, 62) combined technical-tactical actions and activity profiles, five studies (5, 47, 56, 57, 61) combined internal and external loads,

TABLE 2 Study quality assessment using the AMSTAR-2 checklist for the 34 included studies.

Study	Question																Score (%)	Quality
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16		
Abdullahi et al. (3)	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N/A	Y	Y	Y	93.3	Excellent
Abdullahi et al. (5)	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N/A	Y	Y	Y	93.3	Excellent
Abián et al. (42)	Y	Y	Y	Y	N	N/A	Y	Y	Y	Y	Y	Y	N/A	Y	Y	N	85.7	Excellent
Abian-Vicen et al. (2)	Y	Y	Y	N	N	N/A	Y	Y	Y	Y	Y	Y	N/A	Y	Y	N	78.6	Excellent
Abian-Vicen et al. (40)	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N/A	Y	Y	N	86.7	Excellent
Abián-Vicén et al. (38)	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N/A	Y	N	N	80.0	Excellent
Abián-Vicén et al. (4)	Y	Y	Y	N	N	N/A	Y	Y	Y	Y	Y	Y	N/A	Y	Y	N	78.6	Excellent
Apriantono et al. (53)	Y	Y	Y	Y	N	N	Y	Y	Y	N	Y	Y	N/A	Y	Y	Y	80.0	Excellent
Bisschoff et al. (45)	Y	Y	Y	Y	N	N	Y	Y	Y	Y	Y	Y	N/A	Y	Y	Y	86.7	Excellent
Bisschoff et al. (44)	Y	Y	Y	Y	N	N	Y	Y	Y	Y	Y	Y	N/A	Y	Y	Y	86.7	Excellent
Chiminazzo et al. (49)	Y	Y	Y	N	N	N/A	Y	Y	Y	Y	Y	Y	N/A	Y	N	N	71.4	Good
Deka et al. (47)	Y	Y	Y	Y	N	N	Y	Y	Y	Y	Y	Y	N/A	Y	N	Y	80.0	Excellent
Faude et al. (37)	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N/A	Y	N	N	80.0	Excellent
Fernandez-Fernandez et al. (41)	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N/A	Y	Y	N	86.7	Excellent
Fu et al. (57)	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N/A	Y	Y	Y	93.3	Excellent
Gawin et al. (43)	Y	Y	Y	N	N	N/A	Y	Y	Y	Y	Y	Y	N/A	Y	Y	N	78.6	Excellent
Gomez et al. (58)	Y	Y	Y	N	N	N/A	Y	Y	Y	Y	Y	Y	N/A	Y	Y	Y	85.7	Excellent
Gómez-Ruano et al. (54)	Y	Y	Y	N	N	N/A	Y	Y	Y	Y	Y	Y	N/A	Y	Y	Y	85.7	Excellent
Green et al. (60)	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N/A	Y	Y	Y	93.3	Excellent
Hoffmann et al. (65)	Y	Y	Y	N	N	N/A	Y	Y	Y	Y	Y	Y	N/A	Y	Y	Y	85.7	Excellent
Jiménez et al. (39)	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N/A	Y	N	N	80.0	Excellent
Kui et al. (63)	Y	Y	Y	Y	N	Y	Y	N	Y	N	N	Y	N/A	Y	Y	Y	73.3	Good
Le Mansec et al. (62)	Y	Y	Y	N	N	N/A	Y	Y	Y	Y	Y	Y	N/A	Y	Y	Y	85.7	Excellent
Leong et al. (46)	Y	Y	Y	N	N	N/A	Y	Y	N	Y	Y	Y	N/A	Y	Y	N	71.4	Good
Lin et al. (61)	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N/A	Y	N	Y	86.7	Excellent
Nagano et al. (55)	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N/A	Y	Y	Y	93.3	Excellent
Phomsoupha et al. (50)	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N/A	Y	N	N	80.0	Excellent
Rojas-Valverde et al. (56)	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N/A	Y	Y	Y	93.3	Excellent
Sales et al. (59)	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	N/A	Y	Y	Y	93.3	Excellent
Torres-Luque et al. (51)	Y	Y	Y	Y	N	N/A	Y	Y	Y	Y	Y	Y	N/A	Y	Y	N	85.7	Excellent
Torres-Luque et al. (52)	Y	Y	Y	N	N	N/A	Y	Y	Y	Y	Y	Y	N/A	Y	Y	N	78.6	Excellent
Valldecabres et al. (48)	Y	N	Y	N	N	N/A	Y	Y	N	N	N	Y	N/A	Y	Y	Y	57.1	Good
Xiang-Qian Xu et al. (64)	Y	Y	Y	N	N	N/A	Y	Y	N	Y	Y	Y	N/A	Y	Y	N	71.4	Good
Zhang et al. (66)	Y	Y	Y	Y	N	N/A	Y	Y	Y	Y	Y	Y	N/A	Y	Y	N	85.7	Excellent

Y, yes; N, no; N/A, not applicable.

two studies (41, 60) combined activity profiles and internal loads, two studies (50, 63) combined technical-tactical actions, activity profiles, and internal loads, one study (53) combined technical-tactical actions and internal loads, one study (66) focused on technical-tactical actions only, and one study (55) focused on external loads only.

3.4 Differences in match-play outcome measures

Table 6 summarises the descriptive differences in match-play outcome measures. The outcomes are further specified concerning sexes and playing categories.

3.4.1 Differences between singles category in both sexes

Figure 2 shows the individual and overall ESs regarding differences in match-play outcome measures between men's and women's singles categories. Concerning technical-tactical actions, men performed largely more drive (9.9 ± 11.9 vs. 4.6 ± 3.7%; ES = 1.18 ± 0.96) and smash shots (20.3 ± 9.4 vs. 14.6 ± 6.3%; ES = 1.29 ± 0.79) than women. All further individual differences were small (ES = 0.37). The overall ES for technical-tactical actions was small (ES = 0.04 ± 0.43), favouring men's singles. Regarding activity profiles, men had a largely higher effective playing time (34.1 ± 5.3 vs. 29.0 ± 6.6%; ES = 1.13 ± 0.78), longest rally (41.7 ± 1.7 vs. 32.2 ± 4.1 n; ES = 0.86 ± 0.75), shots per rally (8.9 ± 2.1 vs. 6.9 ± 1.1 n; ES = 0.82 ± 0.43), shots per second (1.0 ± 0.2 vs. 0.8 ± 0.2 shots/s; ES = 4.52 ± 1.30), total points played (77.0 ± 7.5 vs. 42.3 ± 20.6 points; ES = 2.71 ± 1.15), and rest time between rallies (22.9 ± 10.6 vs. 17.2 ± 4.4 s; ES = 0.81 ± 0.56) than women. All further differences were small (ES = 0.00). The overall ES for the activity profiles was small (ES = −0.34 ± 0.37), favouring women's singles. No large differences were observed for external loads between men's and women's single categories. However, men executed moderately more acceleration (25.9 ± 0.6 vs. 24.7 ± 0.2 n/min;

TABLE 3 Study characteristics of the 34 included studies concerning the population, intervention, and comparison.

Authors	Population (sample size, sex, playing level, age)	Intervention (official or simulated match-play)	Comparison (singles, doubles, or mixed playing category)
Abdullahi et al. (3)	12 men elite/international level African badminton players (24.4 ± 4.6 years)	Five official badminton matches of the All-Africa Senior Badminton Championships 2014	Comparison among single playing categories regarding descriptive tactical actions and activity profiles data.
Abdullahi et al. (5)	21 men elite/international level African badminton players (23.2 ± 3.6 years)	46 official badminton matches	Comparison among single playing categories regarding descriptive of internal and external loads.
Abián et al. (42)	Men world class badminton players of unknown age and sample size	40 official badminton matches (20 matches in the 2008 Beijing Olympic Games, 20 matches in the 2012 London Olympic Games)	Comparison among single playing categories regarding activity profiles and technical-tactical actions in the two Olympic games.
Abian-Vicen et al. (2)	10 men and 10 women world class badminton players of unknown age	20 official badminton matches of the 2008 Beijing Olympic Games	Comparison among single playing categories regarding the differences between the activity profiles and technical-tactical actions in the games of each match and both playing categories.
Abian-Vicen et al. (40)	13 world class Spanish badminton players (6 men, 7 women; 23.0 ± 4.8 years)	Official Spanish Badminton Championship of the second round and quarterfinal match	Comparison among single playing categories regarding the relationship of internal loads between the first factor (pre-match vs. post-match) and the second factor (second round vs. quarterfinals).
Abián-Vicén et al. (38)	46 men highly trained/national level Spanish badminton players (22.7 ± 4.2 years), 24 women highly trained/national level Spanish badminton players (23.0 ± 5.7 years)	Official Spanish Badminton Championships	Comparison among single playing categories regarding the relationship of internal loads between the first (pre-match vs. post-match) and second factors (men's singles vs. women's singles).
Abián-Vicén et al. (4)	Men and women world class badminton players of unknown age and sample size	48 official badminton matches from the quarterfinals to the finals of the 2008 Beijing, 2012 London, and 2016 Rio Olympic Games	Comparison among double playing categories regarding the differences between the activity profiles variables in the two playing categories and among the three Olympics Games.
Apriantono et al. (53)	12 men elite/international level Indonesian badminton players (16.5 ± 0.6 years)	Simulated badminton match	Comparison among double playing categories regarding the differences of technical-tactical actions and internal loads.
Bisschoff et al. (45)	22 men world class African badminton players (23.3 ± 3.9 years)	46 official badminton matches	Comparison among single playing categories regarding the differences in internal loads between successful players and less successful players.
Bisschoff et al. (44)	22 men world class African badminton players (23.3 ± 3.9 years)	46 official badminton matches	Comparison among single playing categories regarding differences of internal loads in pre-match, in-match, resting, and post-match.
Chiminazzo et al. (49)	Men world class badminton players of unknown age and sample size	56 official video badminton matches in the 2016 Rio Olympic Games (43 video matches in the group stage, 13 video matches in the play-off phase)	Comparison among single playing categories regarding differences of technical-tactical actions and activity profiles in groups and play-offs.
Deka et al. (47)	14 men recreationally active badminton players (35.9 ± 6.6 years)	30 min simulated badminton match	Comparison among single playing categories regarding differences in internal and external loads data in the first, middle, and last 10 min, 15 min, and 30 min of the match.
Faude et al. (37)	4 men elite/international level badminton players (21.3 ± 1.7 years), 8 women elite/international level badminton players (21.8 ± 2.1 years)	Simulated badminton match	Comparison among single playing categories regarding differences in internal loads between men and women players, as well as between players who won and lost matches.
Fernandez-Fernandez et al. (41)	8 men highly trained/national level badminton players (16.0 ± 1.4 years), 8 women highly trained/national level badminton players (16.0 ± 2.3 years)	Simulated badminton match	Comparison among single playing categories regarding differences in activity profiles and internal loads between men and women players.
Fu et al. (57)	8 men highly trained/national level badminton players (18.2 ± 3.4 years), 6 women highly trained/national level badminton players (16.5 ± 2.5 years)	Simulated badminton match	Comparison among single playing categories regarding differences in external and internal loads between men and women players, as well as between players who won and lost matches.
Gawin et al. (43)	Men and women world class badminton players of unknown age and sample size	50 official videos badminton matches from 2010 to 2012 in the world-series tournaments (10 videos for each badminton playing category)	Comparison among five badminton playing categories regarding differences of activity profiles variable among each playing category.
Gómez et al. (58)	Men world class badminton players of unknown age and sample size	14 official video badminton matches in the 2016 Rio Olympics Games	Comparison among single playing categories regarding differences of tournament stage, game number, and game half on technical-tactical actions, and activity profile variables.
Gómez-Ruano et al. (54)	Women world class badminton players of unknown age and sample size	14 official video badminton matches of the 2016 Rio Olympic Games matches from the group stage, quarterfinal, semi-finals, and final matches phases who played by the three medallists (gold, silver, and bronze)	Comparison among single playing categories regarding the relationship between the technical-tactical actions (serving player) and activity profiles.

(*Continued*)

TABLE 3 Continued

Authors	Population (sample size, sex, playing level, age)	Intervention (official or simulated match-play)	Comparison (singles, doubles, or mixed playing category)
Green et al. (60)	10 men highly trained/national level British badminton players (14.0 ± 1.2 years)	Simulated badminton match	Comparison among single playing categories regarding differences of internal loads and activity profile variables in the first and second games of the simulated match-play and for the total game.
Hoffmann et al. (65)	Men elite/international level badminton players of unknown age and sample size	56 official videos badminton matches from 2006 to 2017 World Championships	Comparison among single playing categories regarding the relationship between the year, place where the matches were played and activity profiles.
Jiménez et al. (39)	27 men elite/international level badminton players (24.5 ± 4.0 years), 23 women elite/international level badminton players (23.6 ± 3.7 years)	Official badminton match	Comparison among single playing categories regarding the relationship between testosterone and cortisol levels in both sexes and match results (victory and defeat).
Kui et al. (63)	4 highly trained/national level badminton players (2 men, 2 women; 17.5 years)	Simulated badminton match	Comparison among single playing categories regarding descriptive data of technical-tactical actions, activity profiles, and internal loads.
Le Mansec et al. (62)	Men and women elite/international level badminton players of unknown age and sample size	Seven official videos badminton matches from the 2016 European Badminton Championship	Comparison among five playing categories regarding differences of the activity profiles, and comparison among doubles playing categories regarding differences of the technical-tactical actions and activity profiles.
Leong et al. (46)	Men elite/international level and highly trained/national level of unknown age and sample size	14 official badminton matches	Comparison among single playing categories regarding differences of activity profiles between professional and junior players.
Lin et al. (61)	10 men elite/international level Australian badminton players (26.4 ± 5.3 years)	40 simulated badminton matches	Comparison among single playing categories regarding differences of external and internal loads data between before and after the matches.
Nagano et al. (55)	10 women highly trained/national level badminton players (15.8 ± 1.0 years)	Simulated badminton match	Comparison among single playing categories regarding the descriptive of external loads data.
Phomsoupha et al. (50)	12 men world class badminton players (25.3 ± 3.2 years)	Simulated badminton match	Comparison among single playing categories regarding differences of technical-tactical actions, activity profiles, and internal loads in each session (10 min, 20 min, 30 min, 40 min, 50 min, and 60 min of badminton match).
Rojas-Valverde et al. (56)	24 highly trained/national level Spanish badminton players (10 men, 14 women; 16.2 ± 0.8 years)	Official tournament of Badminton World Federation IBERDROLA Spanish 2018	Comparison among single playing categories regarding the relationship of external and internal loads data in the match games and sex-related.
Sales et al. (59)	6 men highly trained/national level Brazilian badminton players (14.4 ± 2.1 years), 6 women highly trained/national level Brazilian badminton players (15.7 ± 1.7 years)	Simulated and official badminton matches	Comparison among single playing categories regarding the internal load data in official matches and the training sessions (multi-shuttlecock, technical-tactical actions, and physical training).
Torres-Luque et al. (51)	Men and women world class badminton players of unknown age and sample size	Official badminton matches in the Rio 2016 Olympic Games	Comparison among five playing categories regarding different match activity profiles in group phase vs. eliminatory phase.
Torres-Luque et al. (52)	Men and women world class badminton players of unknown age and sample size	Official badminton matches in the London 2012 and the Rio 2016 Olympic Games	Comparison among single playing categories regarding the differences of activity profiles between sexes in Olympic Games.
Valldecabres et al. (48)	Men and women world class badminton players of unknown age and sample size	Official badminton matches in the 2015 Badminton World Championship	Comparison among single playing categories regarding the differences of technical-tactical actions, and activity profiles between sexes.
Xiang-Qian Xu et al. (64)	Women world class badminton players of unknown age and sample size	58 official videos badminton matches in the Tokyo 2020 Olympic Games	Comparison among single playing categories regarding different match activity profiles in groups phase vs. eliminatory phase.
Zhang et al. (66)	Women elite/international level badminton players of unknown age and sample size	40 official videos badminton matches from 2018 to 2021 Badminton World Federation World Tour	Comparison among single playing categories regarding different technical-tactical actions in two different singles game formats (two right-handers and opposite handedness).

Min, minutes.

ES = 0.54 ± 0.72) than women. All further differences were small (ES = 0.11–0.20). The overall ES for the external loads was small (ES = 0.27 ± 0.56), favouring men's singles. Regarding internal loads, men had a largely higher energy expenditure (57.4 ± 15.1 vs. 45.4 ± 0.7 kJ/min; ES = 1.08 ± 1.14) and blood lactate (5.4 ± 3.1 vs. 2.2 ± 0.4 mmol/L; ES = 1.16 ± 0.88) than women. All further differences were small (ES = 0.00–0.20). The overall ES for internal loads was small (ES = 0.34 ± 0.50), favouring men's singles.

TABLE 4 Study characteristics of the 34 included studies concerning the match-play outcome measures of singles category in both sexes.

Authors	Outcome (technical-tactical actions)	Outcome (activity profiles)	Outcome (external loads)	Outcome (internal loads)
Men's singles category				
Abián et al. (42)	The differences between any of the shots (smash, clear, drop, net, drive, lob, and error shots) between the Beijing and London Olympics Games were not significant; the lob shot was more common in London (Beijing: 2.31 ± 1.74%, London: 3.92 ± 4.31%, $p = 0.06$) and net shots were more common in Beijing (Beijing: 16.03 ± 6.6%, London: 13.32 ± 5.38%, $p = 0.08$); unforced errors (Beijing: 41.01 ± 9.46%, London: 42.64 ± 8.89%, $p = 0.548$) and the smash (Beijing: 29.09 ± 8.43%, London: 27.84 ± 8.14%, $p = 0.317$) were the most common last shots of a rally	The London Olympic Games had significantly higher values of the following variables than the Beijing Olympics Games: match duration (1,260.3 ± 267.1 vs. 1,124.6 ± 229.9 s, $p < 0.05$), real-time played (354.7 ± 87.5 vs. 306.9 ± 45.7 s, $p < 0.05$), rally time (10.4 ± 2.1 vs. 9.0 ± 1.1 s, $p < 0.05$), shots per rally (11.1 ± 2.2 vs. 9.8 ± 1.1, $p < 0.05$), and rest time between games (145.2 ± 8.8 vs. 128.7 ± 5.9 s, $p < 0.05$)	N/A	N/A
Abian-Vicen et al. (2)	The smash (29.1 ± 8.4 vs. 21.6 ± 9.5%, $p < 0.05$) and drive (6.3 ± 3.9 vs. 2.0 ± 2.7%, $p < 0.05$) were used more frequently in men's singles than in the women's singles as the last shot of a rally; the differences in the frequency distributions of the clear, net, or lob shots between men's and women's singles were not significant	Men's singles had significantly higher values ($p < 0.05$) of the following variables than women's singles: match duration (2,378.0 ± 387.9 vs. 1,696.1 ± 170.4 s), real-time played (613.7 ± 80.1 vs. 493.6 ± 70.2 s), and total points played (68.0 ± 6.7 vs. 62.6 ± 4.9)	N/A	N/A
Abian-Vicen et al. (40)	N/A	N/A	N/A	The differences between the second round and quarterfinals in terms of sweat rate (1.04 ± 0.62 vs. 0.98 ± 0.43 L/h), rate of fluid intake (0.69 ± 0.26 vs. 0.91 ± 0.52 L/h), and dehydration levels (0.47 ± 1.03 vs. 0.23 ± 0.43%) were not significant; urinary protein concentration was significantly higher in the pre-game than in the post-game in both the second round (2.2 ± 7.5 vs. 34.6 ± 55.4) and quarterfinals (14.3 ± 21.3 vs. 51.9 ± 50.4)
Bisschoff et al. (45)	N/A	N/A	N/A	During the match, the average HR was 166.76 ± 13.84 bpm and maximum HR was 192.78 ± 11.31 bpm; in successful players, percentage HR variability of very low band peak frequencies relative power ($p < 0.05$), HR variability of the ratio of natural logarithmic transformation of low band peak frequencies and HR variability of high band peak frequencies relative power expressed as normalised units ($p < 0.02$) were significantly higher than those of less successful players; percentage HR variability of high band peak frequencies relative power ($p < 0.01$), HR variability of the natural logarithmic transformation of high band peak frequencies relative power expressed as normalised units ($p < 0.02$), and HR variability of low band peak frequencies in Hz ($p < 0.02$) were significantly lower for the successful player group than those for the less successful player group

(continued)

TABLE 4 Continued

Bisschoff et al. (44)	N/A	N/A	N/A	The average and maximum HR during the match were 167 ± 14 and 193 ± 11 bpm, respectively; urine shade scale results were moderate (2.76 ± 1.08) and muscle soreness tended to move to the higher side (1.74 ± 0.68); sleep quality was quite high (3.57 ± 1.03: 6.64 ± 1.38 h), and on average, players rated vigour as the most predominant mood state with a score of 11.08 ± 2.96; the correlation between recovery indicators and HR variability related variables was strong and significant (0.96, $p = 0.014$)
Chiminazzo et al. (49)	The serve (84.9 ± 16.9 vs. 74.0 ± 16.2, $p < 0.02$), net (361.2 ± 121.3 vs. 229.4 ± 79.4, $p < 0.01$), and smash shots (115.3 ± 31.8 vs. 96.2 ± 32.7, $p < 0.03$) were significantly more common in the playoffs than in the group stage	Match duration (3,464.0 ± 1,136.0 vs. 2,522.0 ± 721.0 s, $p < 0.01$), total rest time (2,557 ± 829.2 vs. 1,845.0 ± 560.4 s, $p < 0.01$), total points played (84.9 ± 16.9 vs. 74.1 ± 16.2, $p < 0.02$), shots per rally (11.5 ± 2.2 vs. 10.1 ± 1.7, $p < 0.04$), and total shots (1,001.0 ± 349.3 vs. 747.6 ± 205.1, $p < 0.04$) were significantly higher in the playoffs than in the group stage; rally time (9.3 ± 14.3 vs. 10.7 ± 8.7 s, $p < 0.01$, ES = 0.12) and rest time (25.6 ± 21.4 vs. 30.5 ± 23.2 s, $p < 0.01$, ES = 0.23) were significantly lower in the group stage than in the play-offs	N/A	N/A
Gawin et al. (43)	N/A	The total match duration was 0:49:54 ± 0:19:20 h, real-time played was 26.5 (21.4–31.7%), rally time was 9.3 ± 1.5 s, rest time was 23.1 ± 3.9 s, shots per rally were 4/2 (1–28), and shots per second was 0.56 ± 0.03 n/s; in both singles category (men's and women's), the rallies were shorter than those in the men's and mixed doubles ($p < 0.001$)	N/A	N/A
Gómez et al. (58)	N/A	The number of shots were higher during game 3rd than that during games 1st and 2nd ($p = 0.001$); rallies were longer during game 3rd than those during games 1st and 2nd ($p = 0.001$); the knockout stage was longer than the group stage ($p = 0.006$); and rest time in the knockout stage was longer than that during the group stage ($p = 0.04$); the frequency of shots was higher during the group stage than that during the knockout stage ($p = 0.027$); standard entropy increased as the second half (11 to 21 points) progressed in the first (group ACF: 0.67, knockout ACF: 0.54), second (knockout ACF: 0.58), and third (knockout ACF: 0.43) games	N/A	N/A
Phomsoupha et al. (50)	There were no significant differences in technical-tactical action variables in any session: clear ($p = 0.857$), drop ($p = 0.794$), smash ($p = 0.654$), and net shots ($p = 0.728$)	The average rally time, rest time between rallies, and effective playing time were 5.81 ± 0.32 s, 8.04 ± 0.35 s, and 41.54 ± 1.43%, respectively; there was a strong correlation between rally duration and recovery time ($r = 0.742$, $p < 0.001$) and a moderate correlation between shots frequency and rally duration ($r = 0.504$, $p < 0.001$)	N/A	The average HR was 168.3 ± 13.2 bpm (85% HR maximum); the correlation between HR and shots frequency was strong ($r = 0.884$, $p < 0.001$); blood lactate level increased from an initial value of 1.62 ± 0.43 to 6.87 ± 6.33 mmol/L after 10 min of play ($p < 0.001$)

(continued)

TABLE 4 Continued

Torres-Luque et al. (51)	N/A	The difference in match duration ($p < 0.001$) between the group stage (43:81 ± 12:10 min) and eliminatory phase (58:76 ± 18:75 min) was significant; the average longest rally duration in the group stage and eliminatory phase was 43:11 ± 18:04 s and 45:30 ± 10:24 s; rally times in the group stage and eliminatory phase were 9.53 ± 2:58 s and 10.23 ± 1:88 s, respectively; in Set 1st, values of the following variables were significantly higher in the eliminatory phase than in the group stage: duration of set (21:61 ± 5:37 vs. 18:13 ± 4:09, $p < 0:001$) and longest rally (42:30 ± 11:44 vs. 35:27 ± 13:02 s, $p < 0:001$)	N/A	N/A
Torres-Luque et al. (52)	N/A	In the Rio 2016 and London 2012 Olympics Games, the average match durations were 58.76 ± 18.75 vs. 55.87 ± 15.68 min, longest rally was 45.30 ± 10.24 vs. 42.68 ± 12.06 s, highest number of rally shots were 42.76 ± 9.04 vs. 42.00 ± 9.88, rally time was 10.23 ± 1.88 vs. 10.12 ± 2.29 s, and average number of rally shots were 8.92 ± 1.57 vs. 8.25 ± 1.70, respectively; in the Rio Olympics Games, the longest rally was in Sets 1st (42.30 ± 11.44 s) and 3rd (48.00 ± 7.74 s) ($p < 0.01$), and Set 3rd ($p < 0.01$) was longer in duration (29.40 ± 3.80 min) in Rio than in London Olympics Games (25.60 ± 2.63 min)	N/A	N/A
Abdullahi et al. (3)	With regard to shots-related variables, the drive (122.1 ± 27.4, 0.08 ± 0.02) and clear (118.0 ± 32.4, 0.08 ± 0.02) shots were the most common, followed by the serve (68.5 ± 12.8, 0.05 ± 0.01), smash (56.2 ± 23.1, 0.04 ± 0.01), and net shots (54.3 ± 19.7, 0.04 ± 0.01); with regard to foot movement-related variables, the chasse-step (174.6 ± 73.6, 0.12 ± 0.04) and shuffle foot (161.7 ± 66.1, 0.11 ± 0.04) movements were the most common; highly significant correlations were observed between chasse-step foot movements and smash shots ($r = 0.71$, $p < 0.05$) and between backward lunges and net shots ($r = 0.71$, $p < 0.05$)	The average match duration was 1,470.4 ± 341.9 s, real-time played was 432.9 ± 91.6 s, and the percentage of real-time played was 29.8 ± 4.5%; the average rally time was 5.6 ± 5.8 s, with an average of 6.5 ± 1.3 shots per rally during each match, and the average work density during matches was 0.4 ± 0.1 work/rest; players rested for 17.3 ± 4.6 s in-between rallies during each match	N/A	N/A
Abdullahi et al. (5)	N/A	N/A	The average distance cover was 1,763 ± 751.4 m; the furthest distance covered was the low-intensity distance (978.09 ± 331 m), followed by the medium-intensity (616 ± 387 m) and high-intensity (170.07 ± 134.72 m) distances; moderately significant correlations were observed between absolute distance ($r = 0.42$, $p < 0.05$) covered and time spent in the high-intensity zone ($r = 0.44$, $p < 0.05$)	During match-play, the minimum HR was 91.2 ± 17.4 bpm, average HR was 157.1 ± 13.9 bpm, and maximum HR was 188.73 ± 11.7 bpm; the average PL was 187 ± 79.6 (5.3 ± 1.1/s, 5.3 ± 1.1/min) and average peak PL was 10.8 ± 13.9 (0.01 ± 0.01/s); the correlation between PL and HR in the high-intensity zone was moderately significant ($r = 0.44$, $p < 0.05$)
Abián-Vicén et al. (38)	N/A	N/A	N/A	The sweat rate during the badminton match was 1.14 ± 0.46 L/h and rate of fluid intake was 1.10 ± 0.55 L/h; there was a significant loss of body mass during the match (pre-match: 74.4 ± 7.2 kg, post-match: 74.1 ± 7.2,

(continued)

TABLE 4 Continued

				$p < 0.05$)—with dehydration 0.32 ± 0.83% in the former and 0.37 ± 0.50% in the latter—and a significant decrease in the urinary pH after the match (pre: 7.20 ± 1.08, post: 6.28 ± 1.05, $p < 0.05$); the post-match nitrite (pre: 0.4%, post: 52.2%) and protein concentrations (pre: 8.6%, post: 60.9%) were significantly higher ($p < 0.05$) than those were pre-match
Faude et al. (37)	N/A	N/A	N/A	The average VO_2 was 46.0 ± 4.5 ml/kg/min, HR was 166 ± 6 bpm, blood lactate level was 1.9 ± 0.1 mmol/L, RER was 0.99 ± 0.06, V_E was 94.3 ± 6.4 L/min^{-1}, b_f was 47.4 ± 5.9 min^{-1}, and EE was 68.0 ± 7.5 kJ/min; men's singles had higher values ($p < 0.05$) of VO_2 (46.0 ± 4.5 vs. 36.4 ± 2.8), V_E (94.3 ± 6.4 vs. 61.1 ± 8.7), and EE (68.0 ± 7.5 vs. 45.9 ± 6.7) than women's singles; players who won and those who lost matches did not differ significantly ($p > 0.41$) in terms of VO_2 and HR
Hoffmann et al. (65)	N/A	The year affected all variables from 2006 to 2017, except for the total points played. Concretely, game duration, rally time, rest time, rest time at point 11 and rest time between games increased by 54.0% ($p = 0.002$), 62.2% ($p = 0.000$), 49.3% ($p = 0.000$), 44% ($p < 0.001$) and 74.9% ($p = 0.000$), respectively	N/A	N/A
Jiménez et al. (39)	N/A	N/A	N/A	Regarding sex influenced testosterone levels ($p = 0.0001$), men's singles had higher testosterone levels than women's singles before the competition ($p = 0.007$); in men's singles, testosterone level rose in winners ($p < 0.0001$ and $p = 0.019$) and dropped in losers ($p < 0.0001$ and $p = 0.016$); after the competition, cortisol levels were higher in losers ($p < 0.0001$ in men's singles); however, there was no variation in winners ($p > 0.9$ in men's singles)
Le Mansec et al. (62)	N/A	There was no significant main effect among five playing categories on the duration of the match (average: 42.0 ± 11.6 min); for rally duration, men's singles were longer ($p < 0.001$) than men's doubles and mixed doubles; for effective playing time, men's singles were greater ($p < 0.001$) than men's doubles, women's doubles, and mixed doubles; for shots per second, men's singles were greater ($p < 0.001$) than women's singles, men's doubles, and mixed doubles	N/A	N/A
Leong et al. (46)	N/A	The differences between professional and junior players in terms of mean match duration (1,449.2 ± 434.6 vs. 1,066.3 ± 152.0 s, $p < 0.001$), number of shots per rally (12.3 ± 8.6 vs. 8.2 ± 5.9, $p < 0.001$), real-time played (419.9 ± 101.9 vs. 306.7 ± 62.72 s, $p < 0.001$), and rally duration (11.9 ± 8.04 vs. 8.1 ± 5.3 s, $p < 0.001$) were significant	N/A	N/A

(continued)

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TABLE 4 Continued

Lin et al. (61)	N/A	N/A	The total number of lunges per player in a match was 160–240 (average, 194 ± 18); the knee extension MVC torque decreased significantly (by 12.7 ± 2.9% from 278.4 ± 50.8 Nm before the match, $p < 0.05$); knee extensor voluntary activation in the dominant leg decreased significantly ($p < 0.05$) from before (90.4 ± 1.9%) to after (80.0 ± 2.2%) matches	Average VO_2, HR, RPE, and pre-match and post-match blood lactate level were 44.3 ± 8.6 ml/kg/min (80% of VO_{2max}), 162.0 ± 10.6 bpm, 84% of maximum HR, 7.0 ± 2.0, and 1.8 ± 0.3 mmol/L, 7.2 ± 1.3 mmol/L, respectively
Valldecabres et al. (48)	The most common shots were net shots (36.09%), and men's singles showed a higher use of smashes (11.46%) and lobs (22.08%) shots; in men's or women's singles, the smash was the most successful shot, and net shots were least successful	The values of total real-time played (880.473 vs. 772.564 s), average rally time (12.061 vs. 10.033 s), shots per rally (6.452 vs. 5.403), average rest time (45.550 vs. 36.591 s), and total shots (471 vs. 416) were all higher for men's singles than those for women's singles	N/A	N/A
Fernandez-Fernandez et al. (41)	N/A	The average match duration was 1,411 ± 422 s and average effective playing time was 36.6 ± 4.3%; men's singles had higher rally duration (6.8 ± 4.8 vs. 5.7 ± 3.1 s, $p < 0.05$, ES = 0.81), rest time between rallies (10.5 ± 8.8 vs. 8.8 ± 7.2 s, $p < 0.05$, ES = 0.81), and shots per rally (6.4 ± 4.8 vs. 4.7 ± 2.8, $p < 0.001$, ES = 1.56) values than women's singles	N/A	Internal load variable: HR: 170 ± 9 bpm, blood lactate levels: 3.2 ± 1.8 mmol/L, RPE: 14.6 ± 1.8; the differences between men's and women's singles in terms of any internal load variables were not significant (all p values >0.05, ES: 20.33–0.08)
Fu et al. (57)	N/A	N/A	There were no significant differences between men's and women's singles in terms of decelerations (46.38 ± 29.91 vs. 68.17 ± 29.86), change of direction, left (144.13 ± 40.76 vs. 165.67 ± 75.82), changes of direction, right (82.25 ± 35.25 vs. 70.00 ± 11.54), or jumps (27.63 ± 16.17 vs. 31.50 ± 19.58) or between the victorious and defeated players in terms of accelerations, decelerations, changes of direction (left or right), or jumps	The average glycolytic system contribution was 13.62 ± 11.04 kJ, aerobic energy contribution was 832.07 ± 175.63 kJ, total energy contribution was 920.82 ± 164.26 kJ, and average rate of lipid oxidation was 0.67 ± 0.16 g/min; the average HR was 162.38 ± 18.35 bpm, maximum HR was 194.50 ± 15.00 bpm, absolute PL was 111.85 ± 19.77 AU, and relative PL was 5.02 ± 0.26 AU; men's singles had higher anaerobic lactic capacity (45.04 ± 10.04 vs. 28.55 ± 5.14 kJ, $p = 0.008$) and average rate of carbohydrate oxidation (1.56 ± 0.69 vs. 0.96 ± 0.12 g/min, $p = 0.044$) than women's singles
Green et al. (60)	N/A	Rally duration (6.1 ± 3.9 vs. 5.3 ± 3.5 s, $p = 0.005$), shots per rally (5.9 ± 3.5 vs. 5.3 ± 3.7, $p = 0.012$), work density (0.53 ± 0.17 vs. 0.48 ± 0.23 work/rest, $p < 0.001$), and effective playing time (33.8 ± 7.4 vs. 30.9 ± 9.0%, $p < 0.001$) were higher in the second game than in the first game	N/A	During match-play, the average HR was 151 ± 12 bpm, blood lactate levels during breaks was 2.42 ± 0.44 mmol/L, post-match blood lactate level was 3.33 ± 0.83 mmol/L, RER was 0.84 ± 0.07, EE was 46.7 ± 4.4 kJ/min, and VO_2 was 39.2 ± 3.9 ml/kg/min (62% of VO_{2max} during the 20-m shuttle run test)
Kui et al. (Wei Sheng (63)	The shots with the highest win rates were the smash (men's singles number 1: 42.50%, number 2: 28.57%) and net shots (men's singles number 1: 17.5%, number 2: 22.86%)	Average activity profile data: average shot frequency: 0.99 ± 0.05 s, average shots per rally: 7.28 ± 1.14, total match duration: 48.15 min, average rally duration: 6.98 ± 1.09 s, and average time of rest: 20.92 ± 3.77 s	N/A	Average HR: men's singles number 1 (Set 1st: 114, Set 2nd: 153, Set 3rd:152 bpm), number 2: (Set 1st: 112, Set 2nd: 150, Set 3rd: 149 bpm)
Rojas-Valverde et al. (56)	N/A	N/A	Average relative distance: 46.23 ± 3.73 m/min (1st game), 45.36 ± 2.90 m/min (2nd game), 42.55 ± 3.82 m/min (3rd game), and 44.13 ± 3.99 m/min (4th game); average relative acceleration: 26.33 ± 2.01 N/min (1st game), 26.38 ± 1.75 N/min (2nd game), 25.53 ± 1.93 N/min (3rd game), and 25.26 ± 1.98 N/min (4th game,	Average HR: 1st game, 172 ± 8.92 bpm; 2nd game, 177.92 ± 10.09 bpm; 3rd game, 174.46 ± 9.77 bpm; and 4th game, 178.55 ± 8 bpm. There was no significant interaction (sex vs. games) for the average HR as an internal load variable

(continued)

TABLE 4 Continued

			average maximum acceleration: 3.84 ± 0.36 (1st game), 3.88 ± 0.32 (2nd game), 3.89 ± 0.33 (3rd game), and 3.85 ± 0.32 (4th game); and average maximum speed: 10.84 ± 1.46 km/h (1st game), 10.81 ± 1.44 km/h (2nd game), 10.74 ± 0.99 km/h (3rd game), and 11.03 ± 1.74 km/h (4th game); relative and maximum accelerations were significantly higher ($p = 0.01$) for men than women players	
Sales et al. (59)	N/A	N/A	N/A	During official matches, the men's singles remained in zones 4 (at 80%–90% maximum HR) and 5 (at 90%–100% maximum HR) longer than in zone 1 (at <60% maximum HR) ($p < 0.05$, $\eta^2 = 0.52$); men's and women's singles did not differ in terms of zone HR during official ($p = 0.4$, $\eta^2 = 0.22$), and simulated matches ($p < 0.05$, $\eta^2 = 0.22$)
Deka et al. (47)	N/A	N/A	The total step count was 2,404 ± 360; the mean numbers of steps during the first and second 15 min of match-play did not differ significantly, with 1,264 ± 176 and 1,140.7 ± 206, respectively	The mean VO_2 was 34.4 ± 5.8 ml/kg/min, metabolic equivalent was vigorous intensity (9.8 METS), and average HR during match-play was 166.2 ± 9.23 bpm; the HR in the last 10 min was significantly higher than that in the first 10 min ($p < 0.001$); blood lactate levels and RPE were significantly higher at 15 and 30 min ($p < 0.001$)
Women's singles category				
Abian-Vicen et al. (2)	Drop shots (3.8 ± 3.5 vs. 9.0 ± 6.0%, $p < 0.05$) were used more frequently by the women's singles; unforced errors were more frequent in women's singles than in men's singles (48.6 ± 9.0% vs. 41.0 ± 9.4%, $p < 0.05$)	The percentage of time played was higher for women's singles ($p < 0.05$) than that for men's singles; rallies were significantly more frequent ($p < 0.05$) between 3 and 6 s; comparing the course of each game, women's singles had higher values for work density (game 1st: 0.45 ± 0.05, game 2nd: 0.44 ± 0.04 work/rest vs. game 1st: 0.38 ± 0.06, game 2nd: 0.36 ± 0.04 work/rest) than men's singles ($p < 0.05$)	N/A	N/A
Abian-Vicen et al. (40)	N/A	N/A	N/A	There were no significant differences between the second round and quarterfinal matches in terms of sweat rate (1.04 ± 0.62 vs. 0.98 ± 0.43 L/h), rate of fluid intake (0.69 ± 0.26 vs. 0.91 ± 0.52 L/h), and dehydration level (0.47% ± 1.03 vs. 0.23 ± 0.43%), respectively; pre-game urinary protein concentration was significantly higher than post-game urinary protein concentration in both the second round (2.2 ± 7.5 vs. 34.6 ± 55.4) and quarterfinals (14.3 ± 21.3 vs. 51.9 ± 50.4)
Gawin et al. (43)	N/A	Total match duration: 0:47:28 ± 0:16:35 h, performance time: 29.2 (24.1–32.9%), rally time: 9.2 ± 1.4 s, rest time: 19.4 ± 3.4 s, and shots per rally: 4/2 (1–21); the lowest value of shots per second was observed in the women's singles (0.49 ± 0.02); in both singles category (men's and women's), the rallies were shorter than those in the men's doubles and mixed doubles ($p < 0.001$, $r = 0.81$)	N/A	N/A
			N/A	N/A

(continued)

TABLE 4 Continued

Gómez-Ruano et al. (54)	Approximately 49.6% of the points were won by the serving player; the type of serve was not significantly ($p > 0.05$) associated with winning the point when serving; opponents showed significant relationships ($p < 0.001$) between type of serve and winning the point serving when using the forehand flick and forehand short serve	Match duration was 41.8 min, set 1 duration was 22.1 min, set 2 duration was 20.7 min, set 3 duration was 41.8 min, rally time was 7.87 s, rest time was 22.1 s, shots per rally were 8.0, and frequency was 1.01 s; in 27.3% of cases, medallists played the rally, which lasted 12.3 s and had a shots frequency of 0.98		
Torres-Luque et al. (51)	N/A	The differences ($p < 0.001$) between the group stage and eliminatory phase in terms of match duration (40:11 ± 11:88 vs. 50:66 ± 13:75 min), average rally shots (6.64 ± 1.40 vs. 7.58 ± 1.28), and shuttles used (9:59 ± 3:16 vs. 14:83 ± 6:22) were significant; in Set 1st, the eliminatory phase had higher values than the group stage for the following variables: duration of the set (21:58 ± 4:32 vs. 17:76 ± 3:92 min, $p < 0.001$), longest rally shots (31:00 ± 9:99 vs. 25:52 ± 7:26, $p < 0,02$), and average rally shots (7:83 ± 1:43 vs. 6:97 ± 1:51, $p < 0.001$)	N/A	N/A
Torres-Luque et al. (52)	N/A	In the Rio 2016 and London 2012 Olympics Games, the average match duration was 50.66 ± 13.75 vs. 48.92 ± 14.62 min, longest rally was 38.50 ± 7.37 vs. 31.71 ± 13.15 s, number of shots in the longest rally was 34.16 ± 9.22 vs. 32.07 ± 7.26, and the average number of shots in a rally was 7.58 ± 1.28 vs. 7.07 ± 1.30; the length of rallies in a match was longer ($p < 0.05$) in Rio (10.50 ± 1.74 s) than in London (8.71 ± 2.94 s); the Rio Olympic Games had a longer duration of all sets ($p < 0.05$) and a higher number of shots per rally than London Olympic Games ($p < 0.05$)	N/A	N/A
Xiang-Qian Xu et al. (64)	N/A	The average results of the women's singles players (game duration, longest rally, average rally and total points played) particularly in the elimination phase, are higher ($p < 0.020$) than the average results of the group stage	N/A	N/A
Abián-Vicén et al. (38)	N/A	N/A	N/A	Sweat rate during a badminton match was 1.02 ± 0.61 L/h; the reduction in body mass between the pre-match and post-match conditions was significant (pre: 60.7 ± 4.1, post: 60.5 ± 4.1 kg, $p < 0.05$), with dehydration of 0.32 ± 0.83% in the former and 0.37 ± 0.50% in the latter; compared with before the match, after the match urinary pH values were significantly reduced (pre: 7.2061.21, post: 6.2560.87, $p = 0.059$); contrarily, nitrite (pre: 0.0%, post: 58.3%) and protein concentrations (pre: 10.0%, post: 66.7%) increased significantly ($p < 0.05$)
Faude et al. (37)	N/A	N/A	N/A	The average VO_2 was 36.4 ± 2.8 ml/kg/min, HR was 170 ± 10 bpm, blood lactate level was 1.9 ± 0.9 mmol/L, RER was 0.99 ± 0.08, V_E was 61.1 ± 8.7 L/min^{-1}, b_f was

(continued)

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TABLE 4 Continued

				44.9 ± 5.9 min^{-1}, and EE was 45.9 ± 6.7 kJ/min; women's singles had lower ($p < 0.05$) values of VO_2 (36.4 ± 2.8 vs. 46.0 ± 4.5), V_E (61.1 ± 8.7 vs. 94.3 ± 6.4), and EE (45.9 ± 6.7 vs. 68.0 ± 7.5) than men's singles; players who won vs. those who lost matches did not differ HR
Jiménez et al. (39)	N/A	N/A	N/A	In women' singles, regarding sex influenced testosterone levels ($p = 0.0001$), testosterone levels rose in winners ($p = 0.019$) and dropped in losers ($p = 0.016$); after the competition, cortisol levels rose in losers ($p = 0.005$), whereas there was no variation in winners ($p > 0.6$)
Le Mansec et al. (62)	N/A	There was no significant main effect among five playing categories on the duration of the match (average: 42.0 ± 11.6 min); for effective playing time, women's singles were greater ($p < 0.001$) than men's doubles, women's doubles, and mixed doubles; for shots per second, women's singles were greater ($p < 0.001$) than men's doubles, women's doubles, and mixed doubles	N/A	N/A
Valldecabres et al. (48)	The most commonly used shots were net shots (28.13%); the use of the drive (8.89%) and drop shots (12.02%) were more common among women's singles; in both women's and men's singles category, the smash was the most successful shot, and net shots were the least successful	Work density (0.274 vs. 0.265 work/rest), shot frequency (0.538 vs. 0.535), and rest time between games 1–2 (163.320 vs. 152.424 s) were all greater in the women's singles than in men's singles category	N/A	N/A
Zhang et al. (66)	Overhead shots of two right-handers' games were significantly higher than those of opposite handedness's games with a small effect size ($p < 0.05$, ES = 0.492)	N/A	N/A	N/A
Fernandez-Fernandez et al. (41)	N/A	Average total match time was 1,026 ± 108 s, effective playing time was 39.2 ± 3.5%, rally duration was 5.7 ± 3.1 s, rest time between rallies was 8.8 ± 7.2 s, and shots per rally were 4.7 ± 2.8	N/A	Average internal load variable values: HR: 174 ± 7 bpm, blood lactate level: 2.5 ± 1.3 mmol/L, and RPE: 14.2 ± 1.9; the differences between men's and women's singles in any internal load variables were not significant (all p values > 0.05, ES: 20.33–0.08)
Fu et al. (57)	N/A	N/A	Compared to men's singles, women's singles showed greater acceleration (72.50 ± 18.63 vs. 41.75 ± 14.92 N, $p = 0.005$); there were no significant differences between men's and women's singles in terms of decelerations (46.38 ± 29.91 vs. 68.17 ± 29.86 N), changes of direction, left (144.13 ± 40.76 vs. 165.67 ± 75.82 N), changes of direction, right (82.25 ± 35.25 vs. 70.00 ± 11.54 N), and jumps (27.63 ± 16.17 vs. 31.50 ± 19.58 N) or between victorious and defeated players in terms of accelerations, decelerations, changes of direction (left or right), and jumps	The average ATP-PCr system contribution was 28.55 ± 5.14 kJ, glycolytic system contribution was 7.30 ± 3.19 kJ, aerobic energy contribution was 826.76 ± 226.96 kJ, total energy contribution was 862.62 ± 224.83 kJ, average rate of carbohydrate oxidation was 0.96 ± 0.12 g/min, and average rate of lipid oxidation was 0.52 ± 0.08 g/min; the mean HR was 171.17 ± 8.93 bpm, maximum HR was 198.50 ± 4.76 bpm, and relative PL was 4.92 ± 0.86 AU; women's singles showed greater workloads in terms of absolute PL than men's singles (147.82 ± 31.24 vs. 111.85 ± 19.77, $p = 0.029$)
Kui et al. (63)	The clear (40.54%) and drop (38.5%) shots were the most common	Average activity profiles: average shot frequency: 0.82 ± 0.06 s, average shot per rally: 6.72 ± 1.41, total match duration: 50.86 min, average rally time:	N/A	Average HR in women's singles number 1: Set 1st: 147, Set 2nd: 179, and Set 3rd: 180 bpm and in women's

(continued)

TABLE 4 Continued

		8.13 ± 1.15 s, and average duration of rest: 14.30 ± 3.61 s		singles number 2: Set 1st: 130, Set 2nd: 136, Set 3rd: 157 bpm
Nagano et al. (55)	N/A	N/A	The top five movements were lunging with the dominant hand-side leg during an underhand stroke, landing the non-dominant hand-side leg after an overhand stroke, landing on the dominant hand-side leg after an overhand stroke, cutting from a split step using the non-dominant hand-side leg, and cutting from a split step using the dominant hand-side leg; overhand stroke landings on the dominant leg resulted in greater acceleration than other movements ($p < 0.001$); lunging with the dominant hand-side leg during an underhand stroke involved lesser vertical acceleration than the other movements ($p < 0.001$); and lunging with the dominant hand-side leg during an underhand stroke involved greater anteroposterior acceleration than landing on the dominant and non-dominant hand-side legs after an overhand stroke and cutting from a split step using the non-dominant hand-side leg ($p < 0.001$)	N/A
Rojas-Valverde et al. (56)	N/A	N/A	The average relative distances were 44.54 ± 4.46 m/min (1st game), 44.01 ± 5.69 m/min (2nd game), 42.75 ± 5.31 m/min (3rd game), and 42.85 ± 5.39 m/min (4th game); average relative accelerations were 24.77 ± 2.36 n/min (1st game), 24.41 ± 1.76 n/min (2nd game), 24.57 ± 1.81 n/min (3rd game), and 24.96 ± 1.86 n/min (4th game); average maximum accelerations were 3.41 ± 0.37 (1st game), 3.48 ± 0.42 (2nd game), 3.43 ± 0.38 (3rd game), and 3.54 ± 0.39 (4th game); and average maximum speeds were 10.60 ± 1.65 km/h (1st game), 10.36 ± 1.37 km/h (2nd game), 10.68 ± 0.97 km/h (3rd game), and 11 ± 2.15 km/h (4th game)	The average HR of women's singles during the 1st, 2nd, 3rd, and 4th games was 172.68 ± 11.86, 175 ± 11.59, 172.85 ± 15.71, and 172.15 ± 22 bpm, respectively; there was no significant interaction (sex vs. games) in average HR as an internal loads' variable
Sales et al. (59)	N/A	N/A	N/A	Women's singles spent more time in zones 3 (at 70%–80% of the maximum HR) and 4 (at 80%–90% of the maximum HR) than in zones 1 (at <60% HR maximum), 2 (at 60%–70% the maximum HR), and 5 (at 90%–100% the maximum HR) during the simulated match ($p = 0.006$); women's singles spent more time in zone 5 than that in zones 1, 2, and 3 during official matches ($p < 0.02$); EE was 10.74 ± 0.53 kcal min^{-1}; no difference was observed between women's and men's singles in terms of zone HR during official ($p = 0.4$, η^2: 0.22) and simulated matches ($p < 0.05$, η^2: 0.22)

ACF, autocorrelation function; ATP-PCr, adenosine triphosphate phosphocreatine; AU, arbitrary units; b_f, breathing frequency; BPM, beats per minutes; EE, energy expenditures; ES, effect sizes; g/min, gram per minute; HR, heart rate; Hz, hertz; h, hours; kg, kilogram; kJ/min, kilojoule per minute; kJ, kilojoule; km/h, kilometre per hour; L/h, liters per hour; MVC, maximal voluntary isometric contraction; METS, metabolic equivalents; m, meter; min, minutes; m/min, meter per minute; mmol/L, millimole per liter; ml/kg/min, millilitres per minute per kilogram; N, newton; N/A, not available; Nm, newton per meter; N/min, newton per minute; n/s, number per seconds; η^2, partial eta squared; pH, potential of hydrogen; PL, player loads; r, correlation volume; RER, respiratory exchange ratio; RPE, rate of perceived exertion; s, seconds; V_E, minute ventilation; VO_2, oxygen uptake; VO_{2max}, oxygen uptake maximum.

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TABLE 5 Study characteristics of the 34 included studies concerning the match-play outcome measures of the doubles category in both sexes and mixed.

Authors	Outcome (technical-tactical actions)	Outcome (activity profiles)	Outcome (external loads)	Outcome (internal loads)
Men's doubles category				
Abián-Vicén et al. (4)	N/A	Average match duration was Beijing: 2,657.0 ± 755.7, London: 2,903.8 ± 859.7, Rio: 3,900.4 ± 899.2 s; average real-time played was Beijing: 478.3 ± 153.8, London: 569.9 ± 135.2, Rio: 616.3 ± 146.9 s; average rest time between games was Beijing: 135.4 ± 8.3, London: 132.9 ± 8.8, Rio: 147.4 ± 17.6 s, and average work density was Beijing: 0.25 ± 0.06, London: 0.28 ± 0.06, Rio: 0.21 ± 0.03 work/rest; the number of shots-per rally was higher in London than in Beijing ($p = 0.039$, ES = 1.6) higher values were recorded in the shortest intervals (0–3 and 3–6 s)	N/A	N/A
Gawin et al. (43)	N/A	The total match duration was 0:45:55 ± 0:16:27 h, performance time was 20.4 (17.2–24.5%), rally time was 6.7 ± 1.5 s, rest time was 23.3 ± 3.7 s, shots per rally was 4/2 (1–34), and shots per second was 0.76 ± 0.03 n/s; no statistically significant differences was found in average resting times among the playing categories ($p = 0.10$); the difference in shots per second between men's doubles and mixed doubles was not significant (0.76 ± 0.03 vs. 0.72 ± 0.03, respectively)	N/A	N/A
Torres-Luque et al. (51)	N/A	All match-related variable values were higher in the eliminatory phase than in the group phase ($p < 0.05$); the average match duration in the group stage and eliminatory phase was 48:68 ± 17:87 and 68:94 ± 11:76 min, average of the longest rally in the group stage and eliminatory phase was 42:30 ± 19:96 and 33:94 ± 10:20 s, and the average rally in the group stage and eliminatory phase was 6:70 ± 2:16 and 7:23 ± 1:67 s; men's doubles had longer matches as well as sets (set 1st: 23:00 ± 5:63 and set 2nd: 29:94 ± 11:36), and average rallies (set 1st: 7:70 ± 1:31 and set 3rd: 6:66 ± 0:98)	N/A	N/A
Apriantono et al. (53)	A total of 350 rallies in three matches; the drive shot was most common (466 shots), followed by the drop (337 shots) and lob shots (298 shots)	N/A	N/A	Blood lactate: pre-match (after warming-up): 3.05 ± 1.13 mmol/L, post-match: 4.6 ± 1.11 mmol/L
Le Mansec et al. (62)	For all types of doubles, the player who played the most shuttlecocks in the rear part of the court performed more smash shots than his/her partner ($p < 0.05$); in men's doubles, player who played the most shuttlecocks in the rear part of the court performed a lesser proportion of nets than his partner ($p < 0.01$)	There was no significant main effect among five playing categories on the duration of the match (average: 42.0 ± 11.6 min); for effective playing time, men's doubles were greater ($p < 0.001$) than women's doubles	N/A	N/A
Women's doubles category				
Abián-Vicén et al. (4)	N/A	The average match durations was Beijing: 2,840.6 ± 652.7, London: 559.5 ± 884.3, Rio: 4,037.4 ± 1,053.9 s; average of the real time played was Beijing: 767.7 ± 242.2, London: 608.5 ± 213.2, Rio: 913.5 ± 240.5 s; average of rest time between games was Beijing: 148.3 ± 19.2, London: 135.1 ± 10.5, Rio: 147.6 ± 10.7 s; and average work density was Beijing: 0.41 ± 0.07, London: 0.36 ± 0.06, Rio: 0.34 ± 0.07 work/rest; the percentage of time played was higher in the women's doubles than that in the men's doubles in the three Olympics Games (Beijing: 95% CI: 5.5–11.8%, $p < 0.001$, ES = 2.6, London: 95% CI: 0.7%–7.0%, $p = 0.016$, ES = 1.4, Rio: 95% CI: 4.0–10.2%, $p < 0.001$, ES = 2.4). in all the Olympics Games analysed, work density was higher ($p < 0.001$) and shot frequency was lower ($p < 0.001$) in women's doubles	N/A	N/A

(*Continued*)

TABLE 5 Continued

Authors	Outcome (technical-tactical actions)	Outcome (activity profiles)	Outcome (external loads)	Outcome (internal loads)
Gawin et al. (43)	N/A	The total match duration was 0:40:04 ± 0:10:40 h, performance time was 30.1 (23.4–37.2%), rally time was 10.1 ± 3.2 s, rest time was 20.0 ± 5.3 s, shots per rally were 4/2 (1–41), and shots per second were 0.62 ± 0.05, there were no statistically significant differences in average resting time among all playing categories ($p = 0.10$); shots per rally in women's doubles were higher than those in the men's doubles ($p = 0.01$), women's singles ($p < 0.01$), and mixed doubles ($p < 0.01$)	N/A	N/A
Torres-Luque et al. (51)	N/A	All match-related variable values were significantly higher in the eliminatory phase than in the group phase ($p < 0.05$); the average match duration in the group phase and eliminatory phase was 47:75 ± 13:00 and 68:62 ± 17:13 min; the average of the longest rally in the group phase and eliminatory phase was 54:33 ± 18:58 and 51:87 ± 13:77 s, and the average rally in the group phase and eliminatory phase was 10:33 ± 2:23 and 10:37 ± 1:99 s, respectively	N/A	N/A
Le Mansec et al. (62)	For all types of doubles, the player who played the most shuttlecocks in the rear part of the court performed more smash shots than his/her partner ($p < 0.05$); there was no difference between the player who played the most shuttlecocks in the rear part of the court and her partner of proportional net shots in women's doubles	There was no significant main effect among five playing categories on the duration of the match (average: 42.0 ± 11.6 min); for rally duration, women's doubles were greater ($p < 0.001$) than men's doubles and mixed doubles; for rest time, women's doubles were greater ($p < 0.001$) than mixed doubles; for effective playing time, women's doubles were greater ($p < 0.001$) than men's doubles and mixed doubles; for shots per second, women's doubles were greater ($p < 0.001$) than men's doubles and mixed doubles	N/A	N/A
Mixed doubles category				
Gawin et al. (43)	N/A	The total match duration was 0:40:33 ± 0:09:14 h, performance time was 19.4 (17.1–21.5%), rally time was 5.6 ± 0.5 s, rest time was 20.6 ± 3.2 s, shots per rally were 3/2 (1–23), and shots per second were 0.72 ± 0.03; the average resting time was not statistically significant in any playing category ($p = 0.10$); the difference in identical shots per second between mixed doubles and men's doubles was not significant (0.72 ± 0.03 vs. 0.76 ± 0.03 n/s)	N/A	N/A
Torres-Luque et al. (51)	N/A	All match-related variable values were significantly higher in the eliminatory phase than in the group phase ($p < 0.05$); the average match duration in the group stage and eliminatory phase were 47:45 ± 16:36 and 44:25 ± 6:19 min, the average of the longest rally in the group stage and eliminatory phase were 32:66 ± 10:97 and 37:00 ± 6:96 s, and average rally in the group stage and eliminatory phase were 7:58 ± 1:79 and 7:87 ± 1:20 s, respectively	N/A	N/A
Le Mansec et al. (62)	For all types of doubles, the player who played the most shuttlecocks in the rear part of the court performed more smash shots than his/her partner ($p < 0.05$); in mixed doubles, player who played the most shuttlecocks in the rear part of the court performed a lesser proportion of nets than his/her partner ($p < 0.01$)	There was no significant main effect among five playing categories on the duration of the match (average: 42.0 ± 11.6 min); for effective playing time, mixed doubles were greater ($p < 0.001$) than women's doubles; for shots per second, mixed doubles were greater ($p < 0.001$) than men's doubles	N/A	N/A

ES, effect sizes; h, hours; N/A, not available; min, minutes; mmol/L, millimole per liter; n/s, number per seconds; s, seconds; 95% CI, 95% confidence interval.

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TABLE 6 Descriptive overview of the match-play outcome measures according to the five playing categories in badminton (means and standard deviations).

Variables	Categories				
Technical-tactical actions	**Men's singles**	**Women's singles**	**Men's doubles**	**Women's doubles**	**Mixed doubles**
Net shots (%)	24.5 ± 7.5 (12.2–36.1)	23.3 ± 6.8 (18.5–28.1)	N/A	N/A	N/A
Drop shots (%)	12.7 ± 5.2 (3.8–16.9)	17.7 ± 13.9 (9.0–38.5)	N/A	N/A	N/A
Drive shots (%)	9.9 ± 11.9 (1.4–27.5)	4.6 ± 3.7 (2.0–8.9)	N/A	N/A	N/A
Clear shots (%)	16.4 ± 5.3 (7.3–26.6)	22.6 ± 12.3 (13.7–40.5)	N/A	N/A	N/A
Smash shots (%)	20.3 ± 9.4 (11.5–42.5)	14.6 ± 6.3 (9.4–21.6)	N/A	N/A	N/A
Activity profiles	**Men's singles**	**Women's singles**	**Men's doubles**	**Women's doubles**	**Mixed doubles**
Match duration (s)	2,364.2 ± 1,020.9 (1,066.3–4,047.0)	2,618.2 ± 716.6 (1,026.0–3,680.0)	3,106.2 ± 665.0 (2,405.0–4,174.0)	3,040.1 ± 743.0 (2,402.0–4,142.0)	2,653.0 ± 176.5 (2,433.0–2,865.0)
Rally time (s)	8.8 ± 2.0 (5.3–12.1)	9.3 ± 2.0 (5.7–13.9)	6.5 ± 0.7 (5.3–7.3)	9.7 ± 0.9 (7.7–10.4)	6.8 ± 1.1 (5.6–7.9)
Real-time played (s)	512.9 ± 208.9 (306.7–880.5)	555.4 ± 193.8 (400.0–772.6)	553.9 ± 57.4 (478.3–616.3)	752.7 ± 126.3 (608.5–913.5)	N/A
Effective playing time (%)	34.1 ± 5.3 (27.8–41.5)	29.0 ± 6.6 (20.9–39.2)	19.2 ± 2.3 (15.8–21.6)	27.2 ± 5.0 (22.9–35.1)	N/A
Longest rally (n)	41.7 ± 1.7 (39.2–42.8)	32.2 ± 4.1 (28.6–37.6)	42.9 ± 0.6 (42.4–43.3)	57.4 ± 1.4 (56.4–58.4)	39.0 ± 3.1 (36.8–41.3)
Shots per rally (n)	8.9 ± 2.1 (5.3–12.3)	6.9 ± 1.1 (4.7–8.6)	9.5 ± 1.3 (8.2–10.7)	11.8 ± 1.7 (9.8–12.9)	N/A
Shots per second (n/s)	1.0 ± 0.2 (0.6–1.1)	0.8 ± 0.2 (0.5–1.0)	1.5 ± 0.0 (1.4–1.5)	1.3 ± 0.1 (1.1–1.3)	N/A
Total points played (points)	77.0 ± 7.5 (68.0–84.9)	42.3 ± 20.6 (31.2–79.0)	88.1 ± 7.9 (79.4–98.5)	84.5 ± 10.4 (74.5–96.7)	N/A
Rest time between games (s)	134.2 ± 9.5 (128.7–145.2)	147.1 ± 22.9 (130.9–163.3)	138.6 ± 7.8 (132.9–147.4)	143.7 ± 7.4 (135.1–148.3)	N/A
Rest time between rallies (s)	22.9 ± 10.6 (8.0–45.6)	17.2 ± 4.4 (8.8–22.1)	24.9 ± 3.4 (21.4–30.0)	22.8 ± 4.0 (18.7–28.6)	N/A
Work density (work/rest)	0.4 ± 0.1 (0.3–0.5)	0.4 ± 0.1 (0.3–0.5)	0.2 ± 0.0 (0.2–0.3)	0.4 ± 0.0 (0.3–0.4)	N/A
External loads	**Men's singles**	**Women's singles**	**Men's doubles**	**Women's doubles**	**Mixed doubles**
Distance covered (m/min)	44.6 ± 1.6 (42.6–46.2)	43.5 ± 0.9 (42.8–44.5)	N/A	N/A	N/A
Jumps (N/min)	0.9 ± 0.0 (0.9–0.9)	0.8 ± 0.1 (0.7–0.9)	N/A	N/A	N/A
Accelerations (N/min)	25.9 ± 0.6 (25.3–26.4)	24.7 ± 0.2 (24.4–25.0)	N/A	N/A	N/A
Peak speed (km/h)	10.9 ± 0.1 (10.7–11.0)	10.7 ± 0.3 (10.4–11.0)	N/A	N/A	N/A
Internal loads	**Men's singles**	**Women's singles**	**Men's doubles**	**Women's doubles**	**Mixed doubles**
Peak heart rate (bpm)	192.3 ± 2.5 (188.7–194.5)	189.2 ± 12.5 (180.3–198.0)	N/A	N/A	N/A
Average heart rate (bpm)	162.6 ± 9.9 (138.3–175.7)	168.6 ± 10.5 (141.0–175.0)	N/A	N/A	N/A
Energy expenditure (kJ/min)	57.4 ± 15.1 (46.7–68.0)	45.4 ± 0.7 (44.9–45.9)	N/A	N/A	N/A
Blood lactate (mmol/L)	5.4 ± 3.1 (1.9–10.1)	2.2 ± 0.4 (1.9–2.5)	N/A	N/A	N/A
Fluid intake (L/h)	0.9 ± 0.2 (0.7–1.1)	0.9 ± 0.2 (0.7–1.0)	N/A	N/A	N/A
Sweat rate (L/h)	1.1 ± 0.1 (1.0–1.1)	1.0 ± 0.0 (1.0–1.0)	N/A	N/A	N/A
pH (level)	6.5 ± 0.2 (6.3–6.7)	6.5 ± 0.2 (6.3–6.7)	N/A	N/A	N/A
Dehydration level (%)	0.3 ± 0.1 (0.2–0.5)	0.3 ± 0.1 (0.2–0.5)	N/A	N/A	N/A

Minimum two studies or one study with minimum two data groups were used to calculate the mean.
BPM, beats per minutes; kJ/min, kilojoule per minute; km/h, kilometre per hour; L/h, liters per hour; m/min, meter per minute; mmol/L, millimole per liter; N/A, not available; N/min, newton per minute; n, number; n/s, number per seconds; pH, potential of hydrogen; s, seconds.

3.4.2 Differences between the doubles category in both sexes and mixed

Figure 3 shows the individual and overall ESs for differences in doubles categories between sexes and mixed activity profiles. Regarding activity profiles between men's and women's doubles categories, men's doubles categories performed largely more shots per second (1.5 ± 0.0 vs. 1.3 ± 0.1 n/s; ES = 2.90 ± 1.31) than women's doubles. Furthermore, men's doubles had moderately higher rest time between rallies (24.9 ± 3.4 vs. 22.8 ± 4.0 s; ES = 0.48 ± 0.72) than women's doubles. All further differences were small (ES = 0.07–0.15). The overall ES for the activity profiles was small (ES = −0.15 ± 0.24), favouring women's doubles. Regarding activity profiles between men's and mixed doubles categories, men's doubles had a moderately higher match duration (3,106.2 ± 665.0 vs. 2,653.0 ± 176.5 s; ES = 0.49 ± 0.72) than mixed doubles. All further differences were small (ES = 0.23). The overall ES for the activity profiles was moderate (ES = 0.54 ± 0.45), favouring men's doubles. Regarding activity profiles between women's and mixed doubles categories, women's doubles had a largely higher rally time (9.7 ± 0.9 vs. 6.8 ± 1.1 s; ES = 0.97 ± 0.75), and longest rally (57.4 ± 1.4 vs. 39.0 ± 3.1 n; ES = 0.90 ± 1.10) than the mixed doubles. Furthermore, women's doubles had moderately higher match duration (3,040.1 ± 743.0 vs. 2,653.0 ± 176.5 s; ES = 0.44 ± 0.72), than the mixed doubles. The overall ES for activity profiles was moderate (ES = 0.50 ± 0.45), favouring women's doubles.

3.4.3 Differences between singles and doubles categories in both sexes

Figure 4 shows the individual and overall ESs with respect to differences in the single- and double-categories between sexes regarding activity profiles. In men's activity profiles, singles categories had a largely higher effective playing time (34.1 ± 5.3 vs. 19.2 ± 2.3%; ES = 3.32 ± 1.19) and work density (0.4 ± 0.1 vs.

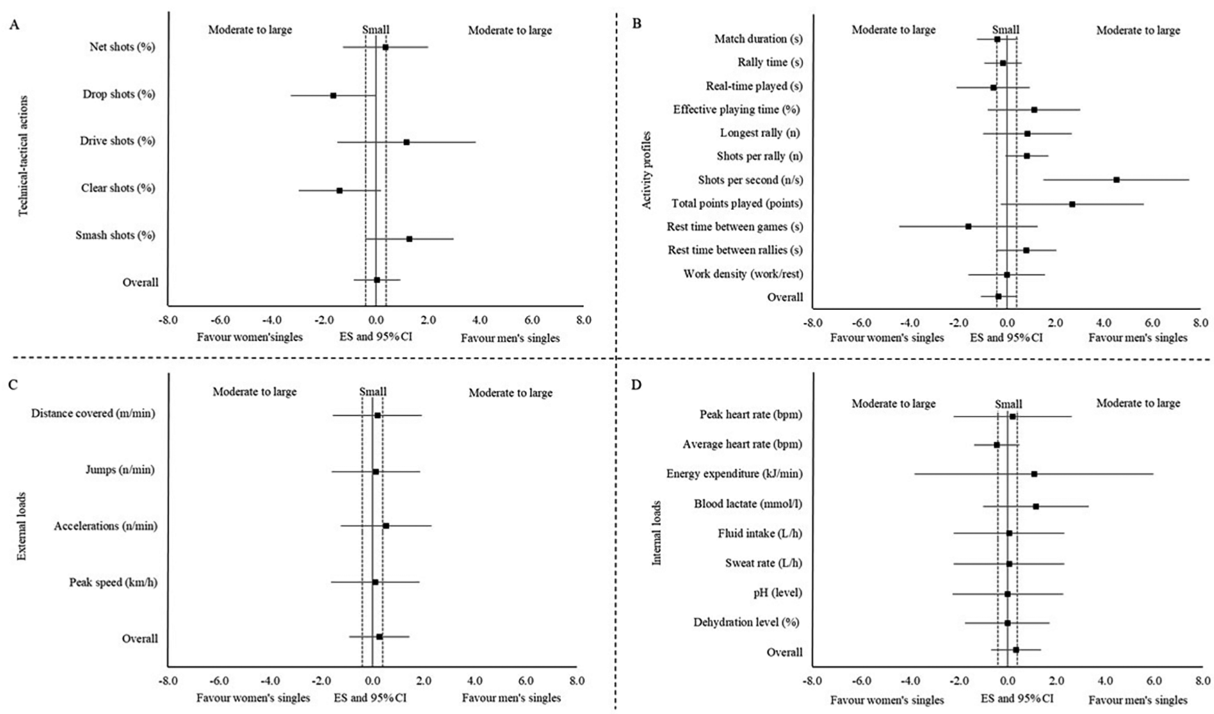

FIGURE 2
Individual and overall ESs and associated 95% confidence intervals with respect to differences between singles category in both sexes regarding (A) technical-tactical actions, (B) activity profiles, and (C) external and (D) internal loads. The dashed vertical lines present thresholds for small effect sizes; solid lines present zero effect sizes. BPM, beats per minutes; kJ/min, kilojoule per minute; km/h, kilometre per hour; L/h, liters per hour; m/min, meter per minute; mmol/L, millimole per liter; n/min, newton per minute; n, number; n/s, number per seconds; pH, potential of hydrogen; s, seconds.

0.2 ± 0.0 work/rest; ES = 2.00 ± 0.85) than doubles categories. Furthermore, singles categories had moderately higher rally time (8.8 ± 2.0 vs. 6.5 ± 0.7 s; ES = 0.69 ± 0.48) than doubles categories. The overall ES for activity profiles was large (ES = -0.90 ± 0.20), favouring doubles categories. No large differences were observed in women's activity profiles. All further differences were small (ES = 0.00–0.38). The overall ES for activity profiles was large (ES = -0.76 ± 0.21), favouring doubles categories.

4 Discussion

This systematic review is the first to investigate differences in match-play data according to the five playing categories in badminton. The main finding was that each playing category places specific demands on the players, which are important to consider when optimising training and testing procedures.

No previous systematic review of match-play data in badminton directly supports our findings. The only previous systematic review of badminton focused on health outcomes (19). Additionally, two other previous reviews focused on a similar topic to ours, but one of them was conducted narratively (1) and the other solely focused on internal loads across several racquet sports (20). In our review, we discovered that most studies investigated men and world-class players during official matches. Compared with other playing categories, men's singles were investigated most often. Moreover, most studies focused on activity profiles as an outcome measure. Therefore, research on women, recreationally active players, doubles categories, and external load measures is lacking. This research gap should be addressed by future studies. With this in mind, advanced methodological approaches may be helpful to investigate match-play data more profoundly in each of the five playing categories during the next years. For example, conducting cross-sectional and longitudinal studies on women, recreationally active players, and doubles categories by utilizing wearable technology such as local positioning systems (67) for external, and also extrapolated internal (metabolic) load measures (68) may contribute to close the here observed research gab.

In the men's singles category, the overall ESs for match-play data regarding technical-tactical actions, activity profiles, and external and internal loads showed only small differences (ES = -0.34 to 0.34) compared with women's singles (Figures 2A–D). However, some individual ESs showed up to large differences (ES ≤ 4.52), favouring the men's single category. For instance, men performed moderately to largely more drive shots, smash shots, accelerations, effective playing time, longest rallies, shots per rally, shots per second, total points played, and rest time between rallies than women. Additionally, men had a largely higher energy expenditures and blood lactate than women (Figure 2D). These observations are supported by a previous review stating that men's singles exhibit more aggressive attacking characteristics and are more physically demanding than women's singles (1, 2, 41–43, 48, 52). Thus, men's singles often

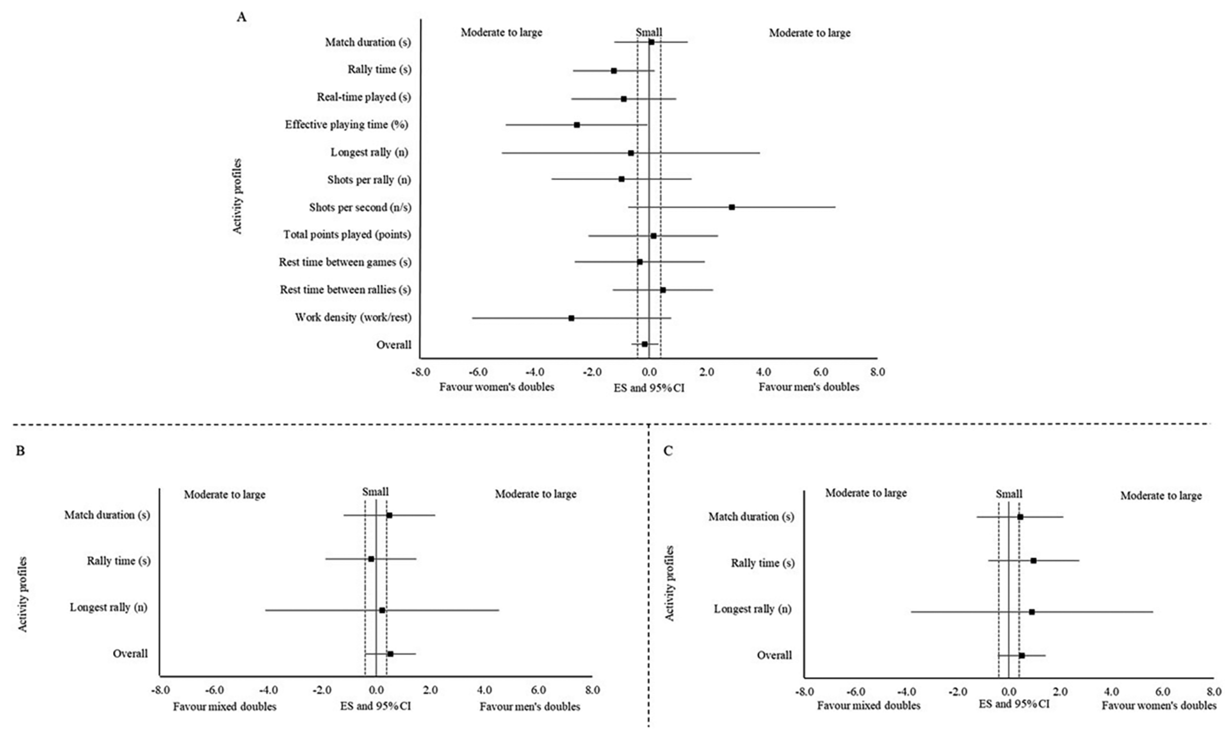

FIGURE 3
Individual and overall ESs and associated 95% confidence intervals with respect to differences between the doubles category in (A) both sexes, (B) men's and mixed, and (C) women's and mixed regarding the activity profiles. The dashed vertical lines present thresholds for small effect sizes; solid lines present zero effect sizes. n, number; n/s, number per seconds; s, seconds.

require longer rest times between rallies (1). Differences in particularly muscular performance between men and women can explain these findings (69). A larger muscle mass allows men to engage in more aggressive play than women (69). Consequently, men's singles players need longer recovery time to maintain high energy levels for continued aggressive attacks (1, 70). Overall, these outcomes suggest that men's singles matches are characterised by more aggressive attacks at higher intensities during rallies, interspersed with longer recovery times than women's singles.

Regarding sex differences in the singles categories, some individual ESs also showed up to large differences (ES ≤ -1.63), favouring the women's single category (Figure 2A). For instance, women performed moderately to largely more drop shots, clear shots, real-time play, rest time between games and had a higher average heart rate than men (Figures 2B, D). These results are supported by previous studies stating that the women's singles category tends to be more defensive with a dominance of smoother shots than men's singles, resulting in longer real-time play (1, 2, 41, 43, 51, 52). In contrast, Valldecabres et al. (48)

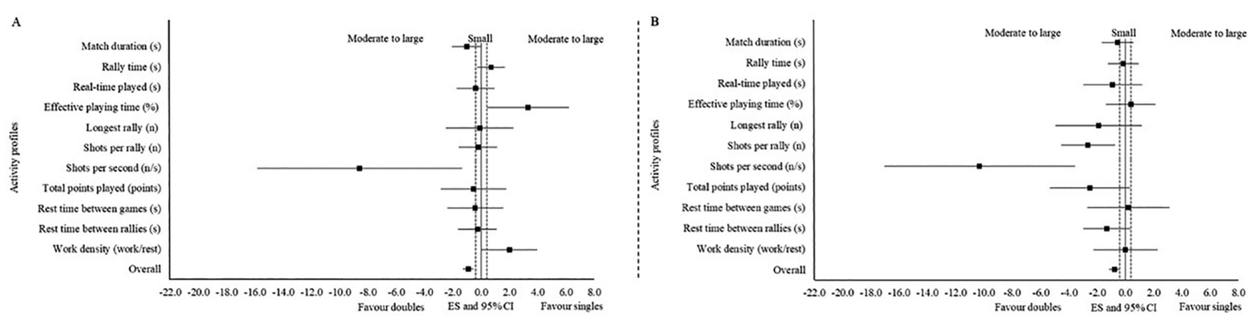

FIGURE 4
Individual and overall ESs and associated 95% confidence intervals with respect to differences between singles and doubles categories in (A) men and (B) women regarding the activity profiles. The dashed vertical lines present thresholds for small effect sizes; solid lines present zero effect sizes. n, number; n/s, number per seconds; s, seconds.

showed that the women's singles category was dominant in executing powerful shots (such as drive shots) compared with the men's singles category. However, this study (48) was based only on final matches, whereas other studies focused on matches across all phases (43, 51, 52). Sex differences in muscle masses (71) and hormones (69, 72) as well as cardiovascular (73) and neuro-muscular characteristics (74) including aerobic and anaerobic capacities (75) may contribute to the variations observed the in activity profiles between women and men. For example, women's singles players, characterized by lesser muscle mass, engage in less aggressive play with longer rallies (69). Consequently, defensive characteristics are more evident in women's singles (1, 2). Overall, the outcomes suggest that the women's singles category is characterised by a more defensive play with smoother shoots, leading to longer real-time plays than in men's singles.

In the doubles category, the overall ESs for the activity profiles were small to moderate (ES = −0.15, 0.50), favouring women's doubles over men's and mixed doubles, respectively (Figures 3A, C). Specifically, some individual ESs showed up to large differences (ES ≤ −2.72), favouring the women's doubles category (Figure 3A). The overall ES for activity profiles was moderate (ES = 0.54), favouring men's doubles over mixed doubles (Figure 3B). In contrast, the overall ESs for activity profiles were large (ES = −0.76 to −0.90), favouring the doubles category for both sexes (Figures 4A, B). These results are supported by previous studies (4, 43, 51, 53). For example, Gawin et al. (43) stated that the work density of women (30.1%) was greater than that of men and mixed doubles (approximately 20% for each). This statement supports our findings, where our results (ES = −2.72) showed that women's doubles had a largely higher work density than men's doubles (Figure 3A). No comparison of work density between women and mixed doubles was observed; however, rally time (ES = 0.97) was largely higher in women's doubles than in mixed doubles. A previous study assumed that shortening coverage areas could intensify match play by increasing shot frequency (4). This statement is supported by our findings, where shots per rally and shots per seconds showed up to large differences (ES ≤ −10.31), favouring the doubles category for both sexes (Figure 4B). These results suggest that the shortening coverage area prompts double players to hit the shuttlecocks earlier, thereby increasing shot frequency. Overall, the outcomes suggest that women's doubles categories have greater work density and rally time than men's and mixed doubles categories. Additionally, the results of activity profiles showed an increase in shot frequency for the doubles compared to the singles category, but no clear conclusion concerning the playing demands in doubles are possible due to a lack of external and internal load measures on an individual player level yet.

Overall, these findings support that badminton shares some demands in common with further racquet sports as tennis and squash (76). However, our subgroup analysis indicates that each category in badminton places specific demands on players. From a practical perspective, our results can serve as a framework to design training, testing and talent identification procedures in badminton. As a general implementation, we carefully recommend such practical aspects based on our main findings summarized in Table 7. Specifically, these recommendations were derived from our match-play data outcomes measure of each category. Therefore, suggested energy contributions serve as foundation for guiding training and testing procedures, which should be worked out by badminton experts. However, our general recommendations should be treated with caution due to the large 95% confidence intervals of some ESs (e.g., longest rally, shots per second, and energy expenditure), indicating a large heterogeneity of the underlying data, which limits a generalization. Therefore, more research is needed not only to prove the observed heterogeneity, but also to evaluate the provided general recommendations, as we have not investigated them here.

TABLE 7 General practical recommendations for training and testing procedures for men's and women's singles according to main findings of our study.

Categories	Main findings of match-play outcome measures	Suggested energy contributions	Recommended training procedures	Recommended testing procedures
Men's singles	• More drive and smash shots • More shots per second and total played points as well as longer rest time between rallies • More accelerations • Higher energy expenditure and lactate concentration	• Aerobic↑ • Anaerobic (alactic and lactic)↑↑	• High-intensity interval training or drill shots with shorter work and longer recovery • High-load resistance training with few repetitions focused on muscular power and additional plyometric training	• Ramp-like running protocol to determine maximum oxygen uptake and ventilatory thresholds • Repeated non-linear sprint ability protocols with shorter work and longer recovery to determine maximum and mean sprint times • Muscular power protocols to determine rate of force development
Women's singles	• More drop and clear shots • Longer real-time played • Higher heart rate	• Aerobic↑↑ • Anaerobic (alactic and lactic)↑	• Moderate-intensity interval training or drill shots with longer work and shorter recovery • Moderate-load resistance training with numerous repetitions focused on muscular endurance and additional plyometric training	• Ramp-like running protocol to determine maximum oxygen uptake and ventilatory thresholds • Repeated non-linear sprint ability protocols with longer work and shorter recovery to determine maximum and mean sprint times • Muscular endurance protocols to determine time to failure

General practical recommendation for the doubles categories could not be provided due to lack of available match-play data outcomes.
↑– Relative amount of energy contribution.

This systematic review had several limitations. First, a meta-analysis could not be conducted due to the large heterogeneity of the included studies and their data. However, ESs were calculated as an established alternative statistical approach (27, 28). Second, we did not investigate differences in playing levels between players, because this would have significantly exceeded the scope of our review. Therefore, further studies are needed to address these issues.

5 Conclusion

There are differences in match-play data according to the five playing categories in badminton, each category placing specific demands on the players. Men's singles are characterised by explosive movements at high intensity, indicating that not only a high aerobic, but also a sufficient amount of anaerobic capacity is needed. In contrast, women's singles are characterised by more defensive play and smoother shoots, suggesting a greater aerobic demand compared to men's singles. In the doubles category, the frequency of shots is increased, but no clear conclusion concerning the playing demands are possible due to a lack of outcome measures on an individual player level. Nevertheless, specific training and testing procedures are essential for the players to prepare them according to the specific demands of each category, what should be considered by scientists and coaches.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

BW: Conceptualization, Data curation, Investigation, Methodology, Visualization, Writing – original draft. JB: Methodology, Validation, Writing – review & editing. TA: Data curation, Investigation, Writing – review & editing. MH: Conceptualization, Data curation, Investigation, Methodology, Supervision, Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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New alternative proposal in physical education: Touchtennis as a racket sport in schools

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In the last decade, the subject of Physical Education has undergone significant transformations, exploring new teaching alternatives for students to acquire interest and enthusiasm for sport. The main objective of this descriptive study is to bring Touchtennis to schools as an innovative and alternative racket sport, which has attracted interest in the sports field. In terms of methodology, an intervention proposal is presented, designed for the subject of Physical Education, through a methodological sequence, in order to get to know the basic contents of the sport and to improve the physical, psychological, social and emotional components of the student. To date, Touchtennis lacks scientific evidence to support its effects. Consequently, a pedagogical proposal is presented in order to open up a promising field for future research, which could reveal its potential in the educational and sporting sphere. It is therefore essential that, on the basis of this research, empirical tests are carried out to analyse the effect of this sport.

KEYWORDS

racquet sport, didactic intervention, alternative sport, Touchtennis, physical activity

1 Introduction

Within the current educational context, the subject of Physical Education must incorporate high quality programmes in order to acquire significant learning and encourage the regular practice of physical activity, emphasising the importance of the health and physical well-being of students (1, 2). In fact, there are many studies that have shown that the practice of exercise or physical activity leads to an improvement in students' academic performance, which reaffirms that the subject of Physical Education should be a fundamental pillar in people's education (3–6).

From this perspective, it is relevant to highlight the role of teachers in teaching spaces, as they must motivate schoolchildren to practice sport by employing different methodologies and attractive and innovative activities that allow for greater commitment and dedication to practice (7–9). In this line, different educational models oriented towards constructivism have emerged significantly, leaving conventional teaching behind (10). These avant-garde approaches are incorporated into the contemporary educational framework to improve the quality of the teaching process and increase motivation towards the subject, with the teacher being the guide and facilitator of the learning process and the student being the protagonist of his or her own learning (11).

In this sense, the teacher must opt to use more innovative methodologies and practices for teaching content and acquiring competences (12, 13), with the aim of increasing the interest and enthusiasm of the student towards the subject. In relation to new practices, Spanish educational legislation has undergone several adaptations in curricular elements, highlighting the incorporation of alternative sports as content within the subject of Physical Education (14).

While it is true that alternative sports or games are understood as those attractive and novel recreational practices that favour the complete and integral development of students (15, 16) and provide improvements in motor skills (17). It is also stated that they experience numerous advantages, as they increase motivation and enjoyment towards the subject, create bonds of friendship (18), acquire positive values and behaviours (19), develop an inclusive and equal understanding (20), foster cooperation and decision-making, and provide alternative and different practices to the traditional ones (21). In this way, it can be inferred that these types of sports, which are totally recent and innovative, represent a new vision within the Physical Education community, due to their wide variety of characteristics, multiple benefits and the facilities they provide when adapted to different contexts (22).

In this context, racket sports are progressively appearing in teaching plans (23) as an educational potential that not only provides a great motor richness (24), but also improves the perceptive, affective and social components of the schoolchild (25, 26). In fact, Varea (27) stated that, through practice, they improve observation skills, foster understanding and decision-making at a personal and group level, promote education in values and strengthen relationships between peers, creating a positive climate that encourages continuous learning.

Thanks to their great popularity in recent years, they are currently positioned as a relevant and alternative teaching content in education (28). In this regard, Castellar et al. (29), highlighted them as a pedagogical option for their development in the subject of Physical Education. However, the school situation reveals that not all racket sports are implemented by specialist teachers, due to a lack of theoretical/practical knowledge about the sport itself, or the practice of racket sports that are better known or easier to adapt to the teaching environment (30). In this sense, it is recommended that teachers be trained in this sport modality, as its implementation can benefit and improve the quality of teaching (31). Furthermore, Quintas et al. (32) stress that it is necessary for teachers to be trained in new disciplines and emerging trends to enrich teaching programmes and incorporate more varied and up-to-date experiences.

However, in order to teach these sports at school, it is essential to apply the game-based methodology (33). In fact, Wilson (34) has promoted this methodology, given that it provides multiple benefits for the overall learning of schoolchildren. In particular, his philosophy is not based on teaching basic and directed strokes as was the case with traditional teachings (35), but seeks to foster technical and tactical learning through a structured and well-organised gradual progress, in order to perform game-based performances that provide greater efficiency (36). Therefore, the game becomes a valuable tool for the teacher due to its great capacity to promote a more dynamic and motivating environment (37).

In addition to the above, Villamizar (38) indicated that teaching through play is a methodology that is based on the active participation of the student through exploration and discovery, linked to fun and interest in practice. In fact, Carrillo-Ojeda et al. (39) found that learning and play are closely related. Thus, play-based teaching is an essential methodology, as its application demonstrates an improvement in physical, cognitive, social and emotional aspects, facilitating an integral development in the student.

Another pedagogical model used in current teaching is the comprehensive model or Teaching Games For Understanding (TGFU) (40–42). Specifically, this methodology is based on the comprehensive teaching of the game through real situations, where the player learns to make decisions generating more effective results (43). In this way, tactical awareness is a determining factor (44), since knowing only the learning of technique is not enough to be effective in the game (45). Therefore, the TGFU focuses on constructivist learning that favours cognitive aspects through the teaching of game tactics in particular combined (46, 47).

Therefore, the main objective of this research work is to provide the educational community with a pedagogical intervention proposal based on a racket sport, called Touchtennis, in order to inculcate this sport in educational centres in a novel and transformative way, using the game as an educational resource.

2 Pedagogical framework

Over time, the educational field has undergone several adaptations in the curricular elements, highlighting the incorporation of alternative or emerging sports as teaching content within the area of Physical Education (14, 18).

From the Spanish legislative point of view, Royal Decree (48), specifically cites softball, pallados, ultimate and pickleball, as sports considered as alternative, as examples of sports that could be implemented in the classroom. Similarly, there are several Autonomous Regional Decrees that set out this need, such as the Decree of the Region of Murcia (49) and the Decree of the Principality of Asturias (50), among others.

In addition to the above, the Order of the Autonomous Community of Aragon (51), refers to the following alternative sports: touchball, indiaka, dodgeball, kin-ball, colphol and korfball. All of them are characterised as alternative or emerging.

In this respect, the Decree of Castilla y León (52), refers to alternative sports or games from the third year of Primary Education onwards. For its teaching, it is necessary to apply pedagogical methodologies adapted to the contents and the particular needs of each group, allowing a competent and quality development during the student's learning process (53). In this sense, León-Díaz et al. (12) and Sierra-Díaz et al. (54) pointed out that the methodological strategies that are implemented must be adapted to the particularities of each environment, that is, they must be adapted to the characteristics of the student, the materials and facilities available and especially to the curricular elements of the educational law. In addition, they stated that these methodologies should encourage motivation with the aim of creating adherence to sports practice and improving motor behaviour and its development, creating active and healthier lifestyles.

In this perspective, the Touchtennis modality has recently arrived in Spain with its first circuit organised by the Royal Tennis Federation (55). However, no evidence of its implementation in Spanish schools has been found. For this reason, it is interesting that it is integrated into new groups of practitioners, in order to get to know a new and attractive discipline. Moreover, Touchtennis has interesting aspects, as it is easy to learn and can be applied quickly and economically. Therefore, this sport can be an effective resource to introduce in the educational environment (56).

3 Learning environment

Touchtennis is a split-court racket sport, which maintains the essence of conventional tennis in a shortened version. This sport makes it unique, due to its striking adaptability and accessibility at an early age, making it a suitable choice for inclusion in the educational environment.

Specifically, it is a sport that is played individually or in pairs, positioned on both sides of the court and divided by a net. The main objective of the game is to win points through a rally, in which the aim is to force the opponent to make a mistake or to hit a winning shot. However, it has similarities to conventional tennis in that it focuses on a game of precision, strategy and control, rather than speed and intensity. In this sense, thanks to its particularities, it facilitates its practice being accessible to all ages regardless of the characteristics of each individual. Moreover, thanks to the modifications in the dimensions of the court, it allows the sport to be more dynamic and entertaining. In fact, a court can be installed on the vast majority of indoor and outdoor surfaces. However, one of the practical barriers that the sport can have in educational settings is the cost and accessibility of sports equipment. However, Touchtennis equipment is easily adaptable to different types of racquets and cheaper balls. As for the court, it can be played informally by adapting the court with tape or by converting it into a Pickleball court. In this way, it is a sport that can be easily adapted in schools.

For these reasons, it is characterised as an innovative and inclusive racket sport, as it encourages motivation and enjoyment towards the practice of physical activity, making it a favourable option to incorporate in education and specifically in Physical Education classes.

3.1 Playing field

The Touchtennis court is divided into two halves of 6 m, a reduced version of the tennis court. The official dimensions are $12\ m \times 5\ m$ for singles and $12\ m \times 6\ m$ for doubles, with a net height between the two halves of no less than 0.80 m. However, variations in the dimensions of the court of up to 1 m are accepted, with the aim of offering greater variety and accessibility.

3.2 Equipment

In terms of equipment, a ball with a uniform surface made of a foam material with a diameter of 8 cm is required, which facilitates hitting, reduces the speed and intensity on the court and minimises the impact on the player's joints.

On the other hand, the 21-inch racquet with a strung weight of 195 g and a head size of 85 inches, is characterised by its light and reduced size, favouring its handling, movement and technique of the sport.

3.3 Participants

Touchtennis is an inclusive discipline, so it is designed to be participatory and accessible to all those who wish to practice a new form of racket. In addition, it is an emerging discipline that seeks an initiation to the practice of a sport regardless of skill level, whether beginners or experienced players. In this way, the practice of Touchtennis facilitates the introduction of conventional tennis, but with a more motivating and attractive factor for the participant.

However, this initiative can be used in different centres, thanks to its flexibility and adaptability in any particular context or situation. It can also be adjusted to any type of age, space and material, as long as there are modifications according to the real need and context, due to the multitude of options it presents.

3.4 Touchtennis rules

The rules of Touchtennis are internationally regulated by Touchtennis Pro Limited (57) and integrated in the Royal Spanish Tennis Federation (56). For your enquiry, they are detailed on the official Touchtennis website (58).

3.5 Pedagogical format

In the following, a Touchtennis methodological sequence is proposed for the purpose of presenting and introducing a new alternative racket sport in Physical Education classes.

For this purpose, based on the methodological sequence provided by Sánchez-Alcaraz et al. (59), a game-based methodology has been applied, integrating a global strategy for teaching sport. However, another suitable methodology that could be used would be the comprehensive model or TGFU for understanding the internal logic of import.

Specifically, the proposal is designed through a structural and gradual sequence with different global practice situations. First of

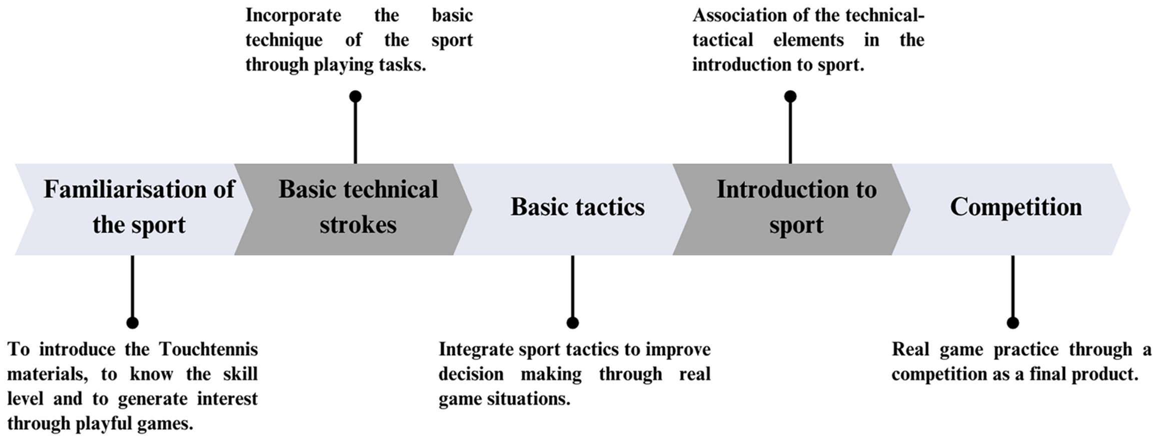


FIGURE 1
Diagram of the methodological sequence for the teaching of Touchtennis.

all, it is recommended to start with playful activities to familiarise with the sport and its materials. Subsequently, the teaching of basic strokes will be essential to learn the technique from a general approach. Next, training in basic tactics is proposed in accordance with the internal logic of the sport, followed by playing tasks that reproduce real game situations based on technical-tactical skills and, as a final product, a Touchtennis competition is proposed, in order to associate the contents learned during the methodological sequence.

Consequently, it aims to increase motor engagement time and promote participation and cooperation among all students, acquiring an active role in their learning (Figure 1 and Table 1).

4 Results

Through the intervention proposal, it is intended that the schoolchildren acquire basic knowledge about Touchtennis through active, playful and meaningful learning based on the game as an educational resource. Likewise, with its dissemination, the aim is to get to know a new racket sport that encourages active participation through the application of different strategies and motor experiences during sport practice, with the aim of creating enriching experiences in the student's learning process. In addition, one of the main characteristics is that the basic technical-tactical aspects of this sport are similar to the best known racket sports, such as tennis and paddle tennis.

In a specific way, Touchtennis offers new motor proposals for sport initiation that stand out for being inclusive, providing a universal language among its practitioners. As a result, this alternative sport provides significant motor experiences, acquiring a high didactic potential and a high pedagogical quality to the educational system.

Finally, in terms of evaluation, the aim is to gather information on the student's teaching-learning process, assessing their progress and evolution in order to analyse and make a judgement on the student's performance. To this end, the procedural, conceptual and attitudinal components are evaluated, through different procedures and varied and adapted instruments, in order to know to what extent the expected results are achieved.

5 Discussion

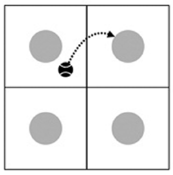
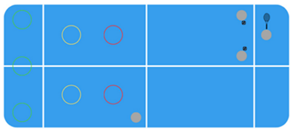
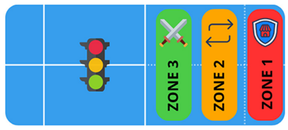
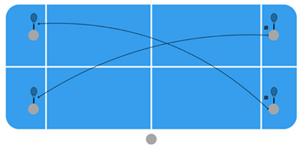
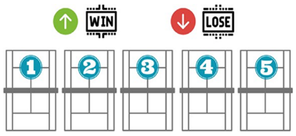
The main objective of this research work was to provide the educational community with a proposal for a pedagogical intervention based on a racket sport, called Touchtennis, with the aim of inculcating these sports in educational centres in a novel and transformative way using play as an educational resource.

In relation to racket sports, Herrero et al. (23) stated that badminton and alternative sports are the most demanded by teachers in Physical Education classes. In fact, the results of Ruiz-Malagón et al. (60) showed that racket sports are appropriate for increasing motivation and decreasing anxiety in Physical Education classes. In this regard, Pradas and Castellar (61) revealed that they are considered as a key, beneficial and highly recommended content due to their multiple pedagogical facilities and possibilities.

However, Lara-Bocanegra and Galán-López (62) pointed out that it is essential that racket sports training begins in higher education, with the intention that future teachers practice and obtain extensive knowledge to implement them in their programmes.

As a result of the above, evidence supports the argument that students at any educational stage, acquire an increase in motivation and interest when including new or alternative sports, as they propose a closer and more interesting experience, away from other more recurrent proposals where the same sports disciplines are usually taught (63, 64). However, situations and strategies should be created that promote participation, increase enjoyment and interest in the subject (65) and prove to be

TABLE 1 Intervention proposal based on Touchtennis' methodological sequence.

Methodological sequence	Didactic objectives	Task played	Graphic description
Familiarisation with the implements of the sport	To master the elements of the sport (ball, racket and racket/ball). To develop the pupils' manipulative skills. To improve the coordination aspects of the pupils.	The introductory game consists of hitting the ball and bouncing it into one of the squares. To do this, four squares are formed and one student is placed in each of them. The objective is to cooperate among all members until a minimum number of hits is achieved. The sequence would start with hand strokes followed by racket and ball strokes.	
Learning basic strokes	To know and practice the basic technique of ground strokes (forehand and backhand), net strokes (forehand and backhand volley) and the serve. To learn the technique from a global strategy, using the game as a methodological resource.	The example of a game task based on the practice of the basic technique is based on the practice of different ground strokes, net strokes and serves to the coloured hoops distributed on the other side of the court. Each hoop will have a score and the objective will be to reach a minimum score between all members.	
Development of basic tactics	Knowing the areas of the court applying the strategy and the appropriate stroke according to the game situations (attack and defence). Recognise the spatial position according to the direction of play. Know the basic tactics of the sport, applying the processes of perception, decision and execution appropriate to the internal logic of the game.	In order to practise tactics, the traffic light theory is used. The game consists of a parallel rally between pairs. The aim is to prepare the point in the defence zone, force the opponent in the yellow zone and finish by hitting a winning shot in the green zone.	
Introduction to the sport	To learn the rules in a practical way, encouraging fair play and sportsmanship among students. To integrate the strokes learnt in order to internalise them, improving the precision of the strokes and the handling of the implements through a real situation.	The task played consists of a rally between the two pairs diagonally. Once it fails, the point will be played between the four participants. The referee will keep track of the strokes and the scoring of the game, in order to learn the Touchtennis scoring system: 15–30–40-game.	
Final competition	Put into practice the technical-tactical aspects learnt during the methodological sequence as a final product.	In order to associate the contents, a real game situation is proposed through a Touchtennis competition. Different matches will be played on the proposed courts, the winning pair will move up a level and the losing pair will move down a level. A fair play programme will be implemented to ensure inclusion, equal opportunities and to foster a peaceful and healthy competitive spirit. To this end, the aim will be to comply with the rules, penalise unsportsmanlike conduct and harmful behaviour.	

decisive for the development of physical, cognitive, social and psychological skills (66–68).

At present, the scientific base includes a scarce amount of research related to alternative sports (69). For this reason, Pérez-Pueyo and Hortigüela (70) expressed the need to apply pedagogical interventions to discover their true contributions and move away from current trends that simply value them as different from the standard.

Moreover, these sports emerge to address the current problem of stereotypes and achieve a more egalitarian component in the subject of Physical Education (71). In fact, Hernández et al. (14) added that such sports promote integration and sportsmanship. In the same perspective, Aznar (72) underlined the importance of racket sports in terms of coeducation, equity and interculturality.

In this sense, research by Van Acker et al. (73) showed that the female gender maintained the same prominence as the male gender, and even had greater participation during practice. Therefore, implementing these sports in the educational community can have a positive impact (74) and, consequently, resolve one of the most widespread concerns in the educational context (75).

Therefore, supporting this idea, Robles and Robles (21) indicated that these sports generate greater enjoyment, unlike more traditional and habitual sports in Physical Education sessions. Likewise, the studies by Jaquete and Ramírez (76) showed that during the practice of alternative sports, more empathy and cooperation was generated among students.

In reference to the above, the findings of Menescardi and Villarrasa-Sapiña (77) showed an increase in intrinsic motivation after having practised different alternative sports in Physical Education sessions. For these reasons, its implementation is necessary as content to be taught in Physical Education classes, in addition to continuing to expand new knowledge about its benefits (19).

Specifically, the study carried out by González-Cutre and Sicilia (78) pointed out the importance of implementing novel strategies in order to obtain positive effects on adherence to physical activity. These results are in line with the research obtained by Kalajas-Tilga et al. (79), as they identified the enjoyment factor as essential and, consequently, the increase of intrinsic motivation of the schoolchildren towards the subject.

For these reasons, Touchtennis is a striking and optimal modality for incorporation into teaching programmes, which means that teachers should seek new pedagogical alternatives (17) by applying avant-garde strategies and using new experiences such as alternative sports, in order to generate improvements in motor commitment (80) and increase motivation towards the subject (20, 81).

6 Conclusion

Physical Education has undergone remarkable advances in its pedagogical process resulting in a high impact on education. This change has included a growing trend in the inclusion of alternative sports in its programmes, as a reflection of a need that offers new and more enriching experiences for the student. Among them, Touchtennis stands out as a sport of initiation to racket sports supported by the Royal Spanish Tennis Federation and being an unknown sport in the field of education and sport. In this sense, its impact can be attractive in the field of Physical Education, as it offers multiple advantages, including its simple learning, adaptability in the reduced and accessible material for educational centres and its enjoyment after practice as it does not require a high level of motor involvement. For these reasons, its learning introduces a new alternative sport, providing a wide variety of content in educational programmes.

The main limitation of the study is the lack of empirical data to support the pedagogical proposal. In this sense, the present study aims to create a basis for future lines of research that, through the practical application of the pedagogical proposal, will support empirical evidence and sustain a theoretical framework specific to sport. In this regard, further research is intended to analyze, firstly, the motor behavior and the impact on the physical condition of the student, through the measurement of heart rate or physical tests adapted to the sport. Secondly, the psychological and social aspects such as, for example, the level of motivation and interest caused by Touchtennis as a sport in educational programs and, finally, to analyze the didactic methodology used for an ideal development of the methodological sequence. In addition to the above, its application on a large scale at various educational levels is required, avoiding a biased sample, to verify possible differences and support the benefits of incorporating a new sporting experience in teaching programs.

For this reason, the aim is to bring an innovative practice based on a racket sport through the development of a pedagogical proposal, so that the student has the basic knowledge of an alternative sport that breaks with conventional practices and that begins to be carried out from an early age. It also promotes teamwork, mutual support, values such as fair play, sportsmanship and respect for diversity.

In short, there is a need to expand racket sports that are not very common in the educational itinerary, so that new practice options are known that enrich the sporting experience of the schoolchildren.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

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The effects of tennis on depressive symptoms and pro-social behaviors in university students: the mediating role of appreciative social support

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Aims: This research aimed to explore the impact of tennis on depressive symptoms and pro-social behaviors among college students, while also delving into the intermediary function of social support navigation.

Materials and methods: Utilizing a suite of psychological evaluations and social support instruments, the study compared the levels of depressive symptoms and pro-social behaviors between collegiate tennis athletes and their non-athlete peers.

Results: The findings revealed an inverse relationship between the duration of tennis engagement and the presence of depressive symptoms ($\beta = -0.234$, $p < 0.001$), alongside a direct positive association with pro-social tendencies ($\beta = 0.222$, $p < 0.001$). Further scrutiny uncovered a substantial link between the degree to which participants valued social support and their experiences of depressive symptoms (*indirect effect* = −0.212, *95%CI* = −0.036 ~ −0.009) and pro-social behaviors (*indirect effect* = 0.025, *95%CI* = 0.009 ~ 0.044). Notably, the valuation of social support served as a conduit for the beneficial effects of tennis on these outcomes within the collegiate population. Consequently, the evidence from this investigation underscores the salutary influence of tennis on the psychological well-being and social conduct of college students, highlighting the pivotal role of understanding and leveraging social support.

Conclusion: These insights offer valuable direction for fostering mental health and social proficiency in the university setting and advocate for the integration of sports as a viable component in mental health strategies.

KEYWORDS

tennis, university student, depressive symptom, pro-social behavior, appreciating social support

1 Introduction

Over recent decades, depression has emerged as a significant mental health concern, drawing considerable scholarly interest worldwide. This issue is particularly acute within the college demographic, where the incidence of depression raises alarm (Husky et al., 2023). College students, navigating an era marked by an explosion of knowledge and rapid social transformation, encounter a myriad of stressors, including academic demands, career

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uncertainties, and complex social dynamics, all of which can precipitate depressive symptoms (Spatafora et al., 2022; Lei et al., 2021). Consequently, identifying effective strategies to mitigate these symptoms and bolster the mental well-being of university students has become a critical area of inquiry within mental health research.

Physical activity is universally acknowledged as a potent tool for enhancing mental health and diminishing the effects of depression (Pascoe and Parker, 2019; Dauwan et al., 2021). Tennis with its blend of collective physical exertion, skillful challenge, and social engagement, merits consideration for its potential mental health benefits. Beyond the physical benefits, tennis fosters social interaction, a key element in supporting the mental health of college students (Wang et al., 2019; Yaneva et al., 2020).

Moreover, tennis may influence depressive symptoms indirectly by bolstering perceived social support. Recognizing social support—the awareness of care and assistance from others—stands as a crucial buffer against mental health challenges (Khoury et al., 2021; Qi et al., 2020). Within the tennis milieu, players not only engage in physical activity but also experience camaraderie and encouragement, thereby enhancing their sense of social support. Social support has been highlighted as a key factor affecting mental health outcomes (Diotaiuti et al., 2021).

Additionally, fostering pro-social behaviors such as helping, sharing, and cooperating is vital among college students. These behaviors are instrumental in building positive social connections and are essential for successful social integration (Wang et al., 2021). Team-oriented sports like tennis create an optimal setting for nurturing these pro-social tendencies. Despite this, research exploring the influence of tennis on depressive symptoms and pro-social behaviors through the lens of perceived social support remains scarce. This study seeks to bridge this gap by investigating how tennis participation can alleviate depressive symptoms and encourage pro-social behaviors in college students by augmenting their perception of social support.

2 Materials and methods

2.1 Objects of study

A total of 150 general college students who play tennis (M = 20.62, SD = 1.67), and 150 professional tennis players (M = 20.65, SD = 1.72) participated in this study. The specific demographic information is shown in Table 1. The data were collected from 22 February to 3 March 2023 Participants in this study were completely voluntary and were not compensated. The study questionnaire was distributed electronically to participants through APP Survey Star (Changsha Ranxing Technology, China). The study was approved by the ethics committee of the first author's institution. Participants were recruited through university-wide email invitations and posters displayed on campus. Data collection was conducted over a two-week period, during which participants completed an online survey hosted on Wenjuanxing. To ensure data quality, participants were required to provide informed consent before proceeding and were instructed to complete the survey in a single sitting. Measures were administered in a randomized order to minimize response bias. This study was approved by the Suzhou University of Science and Technology of Ethics Committee at Suzhou University of Science and Technology, with the approval number UTS2024001. All participants provided informed consent prior to participation, and the study adhered to the ethical guidelines outlined in the Declaration of Helsinki.

2.2 Research tools

2.2.1 Appreciating social support

The Perceived Social Support Scale (PSSS) revised by Jiang (1999) was used. The scale contains 12 entries and is scored on a 7-point scale, with higher scores indicating a higher level of social support felt by the individual. The Cronbach's alpha coefficient in this study was 0.92.

2.2.2 Depressive symptoms

The revised Centre for Epidemiological Studies Depression Scale (CES-D) by Chen et al. (2009) was used, which consists of 20 items and is scored on a 4-point scale, with higher total scores indicating a higher degree of depressive symptoms in an individual. The Cronbach's alpha coefficient in this study was 0.89.

2.2.3 Pro-social behavior

The Prosocial Tendencies Measure (PTM) was developed by Carlo and Randall (2002). The scale consists of 23 items with six dimensions and is assessed on a five-point scale, with higher scores indicating stronger tendencies for pro-social behavior. Kou et al. (2007) revised the Chinese version of the scale, which still retained the six dimensions of openness, anonymity, altruism, adherence, emotionality, and urgency, with a total of 26 items, and a Cronbach's alpha coefficient of 0.88. The PTM was used as a proxy for the PTM.

2.3 Statistical analysis

All statistical analyses were conducted using SPSS 25.0 and PROCESS macro 3.4. Gender and socioeconomic status were

TABLE 1 Correlation of variables and descriptive statistical results.

	AB	PSS	DS	PSB
AB	1			
PSS	0.278**	1		
DS	−0.234**	−0.405**	1	
PSB	0.222**	0.437**	−0.138*	1

AB, Age of the Ball; PSS, Perceived Social Support; DS, Depressive Symptoms; PSB, Pro-Social Behavior. *$p < 0.05$; **$p < 0.01$.

TABLE 2 Difference analysis table.

	Rank	N	Mean	SE	*t*	*p*	Cohen's *d*
AB	Non-tennis player	150	3.41	2.03	−2.38	0.018	−0.275
	Tennis player	149	3.97	2.04			
PSS	Non-tennis player	150	3.94	0.71	−2.34	0.020	−0.269
	Tennis player	149	4.13	0.70			
DS	Non-tennis player	150	2.55	0.46	0.501	0.617	0.070
	Tennis player	149	2.52	0.39			
PSB	Non-tennis player	150	2.93	0.46	−2.57	0.011	−0.292
	Tennis player	149	3.06	0.43			

included as control variables in all models to account for their potential confounding effects. Bootstrapping with 5,000 resamples was applied to test the significance of indirect effects in the mediation analysis, as well as to calculate confidence intervals for correlation and t-test results. Key coefficients obtained from the analyses were interpreted qualitatively to provide insights into their practical implications. For example, a standardized regression coefficient of 0.35 indicates a moderate positive relationship between appreciative social support and prosocial behavior.

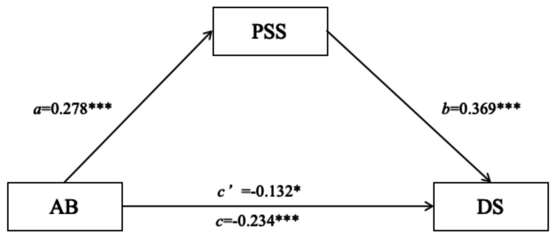

FIGURE 1
The mediating role of social support between playing age and depressive symptoms. *$p < 0.05$, ***$p < 0.001$.

3 Results

3.1 Correlation and descriptive statistics of variables

Table 1 presents the results of the correlation analysis and descriptive statistics between the variables, as shown by the significant positive correlation between the age of the ball and perceived social support, the significant negative correlation between the age of the ball and depressive symptoms, and the significant positive correlation between the age of the ball and pro-social behavior. There was a significant negative correlation between navigational social support and depressive symptoms and a significant positive correlation between navigational social support and pro-social behavior. There was a significant negative correlation between depressive symptoms and pro-social behavior.

3.2 Analysis of differences between professional and non-professional players on each variable

Table 2 presents the differences between ordinary college students and professional tennis players, and it was found that the age of tennis players was significantly higher than that of ordinary college students ($t = -2.380$, $p = 0.018$), the level of perceived social support was significantly higher than that of ordinary college students ($t = -2.340$, $p = 0.020$), and the level of pro-social behaviors of tennis players was significantly higher than that of ordinary college students ($t = -2.570$, $p = 0.011$). There was no significant difference between the levels of depressive symptoms of ordinary university students and tennis players.

3.3 Analysis of the role of intermediaries

3.3.1 Appreciation of the mediating role of social support in the relationship between ballistic age and depressive symptoms

Age had a significant positive effect on perceptual social support ($\beta = 0.278$, $p < 0.001$), i.e., the longer the time spent playing tennis, the higher the level of perceptual social support. Age ($\beta = -0.132$, $p = 0.017$) and perceived social support ($\beta = -0.369$, $p < 0.001$) had a significant negative effect on depressive symptoms, i.e., the longer the time spent playing tennis, the lower the level of depression, and the higher the level of perceived social support, the lower the level of depression. Thus, it can be shown that comprehending social support partially mediates the relationship between ballistic age and depression (Figure 1; Tables 3, 4).

3.3.2 The mediating role of appreciative social support in the relationship between ballroom age and pro-social behavior

Age had a significant positive effect on perceptual social support ($\beta = 0.278$, $p < 0.001$), i.e., the longer the time spent playing tennis, the higher the level of perceptual social support. Age ($\beta = 0.109$, $p = 0.045$) and perceived social support ($\beta = 0.407$, $p < 0.001$) had a significant positive effect on pro-social behavior, i.e., the longer the time spent playing tennis, the higher the pro-social behavior, and the higher the level of perceived social support, the higher the pro-social behavior. It can therefore be shown that comprehending social support partially mediates the relationship between ball age and pro-social behavior (Figure 2; Tables 5, 6).

TABLE 3 The mediating role of social support between playing age and depressive symptom.

Variable	DS			PSSS			DS		
	β	95%CI	*p*	*β*	95%CI	*p*	*β*	95%CI	*p*
AB	−0.234	−0.345 ~ −0.123	<0.001	0.278	0.168 ~ 0.388	<0.001	−0.132	−0.239 ~ −0.024	0.017
PSS							−0.369	−0.477 ~ −0.261	<0.001
R	0.234			0.278			0.425		
R2	0.055			0.077			0.18		
F	17.208***			24.868***			32.544***		

Mediating effect (a*b) = −0.102. ***$p < 0.001$.

TABLE 4 Bootstrap.

	Effect	BootSE	LLCI	ULCI	Percent
Total	−0.234	0.056	−0.345	−0.123	100%
Direct effect	−0.132	0.055	−0.239	−0.024	56.4%
AB→PSS → DS	−0.102	0.036	−0.178	−0.039	43.6%

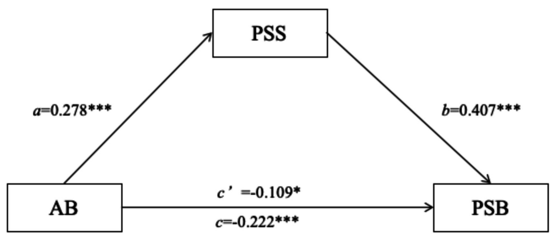

FIGURE 2
The mediating role of social support between playing age and prosocial behavior. *$p < 0.05$, ***$p < 0.001$.

4 Discussion

The results of this study suggest that playing age can significantly reduce depressive symptoms and also significantly increase prosocial behaviors in athletes. It is understood that social support plays a mediating role in it.

4.1 Influence of age of ball on depressive symptoms in tennis players

In evaluating the influence of tennis-playing duration on depressive symptoms among university students, our study found a noticeable correlation. The longer the duration that students had been playing tennis, the lesser were their depressive symptoms. This relationship between physical activity and depression has been well-documented in literature, reinforcing our findings (Craft and Perna, 2004). The relationship can be partially explained by the biological theory which suggests that physical activities like tennis lead to the release of endorphins, also known as "feel good" hormones, in the brain (Dinas et al., 2011). Regular release of these endorphins through sustained involvement in tennis could therefore potentially decrease depressive symptoms over time. Moreover, the psychological theory posits that physical activities provide a distraction from worries and negative thoughts that feed depression (Scully et al., 1998). Given the mental concentration required in tennis, it is plausible that longer duration of play provides a greater respite from such negative cognitions, thus reducing depressive symptoms. Furthermore, the social interaction theory suggests that sports like tennis, which require interpersonal communication and cooperation, provide an opportunity for social interaction, helping to combat feelings of loneliness and isolation that are often associated with depression (Paluska and Schwenk, 2000). Long-term tennis players are likely to have established a solid social network within the sport, which may provide them with strong social support, thereby acting as a buffer against depression. However, it is important to note that while our study and the aforementioned literature suggest a protective effect of long-term tennis playing against depressive symptoms, it does not necessarily imply causality. Other factors, such as individual personality traits and external support systems, might also play significant roles in this context (Nimrod and Kleiber, 2007).

In conclusion, our findings suggest that the longer duration of tennis playing could potentially reduce depressive symptoms in university students, possibly through the combined effects of biological, psychological, and social factors. These findings underscore the importance of promoting regular and long-term participation in sports like tennis for the mental wellbeing of university students.

4.2 Influence of age of ball on pro-social behaviors in tennis players

In our study, we observed that the duration of tennis participation positively correlated with pro-social behaviors among university students. This suggests that the longer a student had been involved in playing tennis, the more likely they were to demonstrate pro-social behaviors such as cooperation, sharing, and helping others. This finding is consistent with prior research suggesting that involvement in team sports promotes pro-social behavior (Eime et al., 2013). One potential explanation for this relationship is the social nature of tennis. Tennis often involves doubles play, where cooperation and communication with a partner are essential. These repeated interactions over time can foster a sense of teamwork and mutual understanding, which are key components of pro-social behavior (Bruner et al., 2014). Further, longer-term involvement in tennis may also

TABLE 5 The mediating role of social support between playing age and prosocial.

Variable	PSB			PSS			PSB		
	β	95%CI	*p*	*β*	95%CI	*p*	*β*	95%CI	*p*
AB	0.222	0.111 ~ 0.333	<0.001	0.278	0.168 ~ 0.388	<0.001	0.109	0.002 ~ 0.215	0.045
PSS							0.407	0.301 ~ 0.513	<0.001
R	0.222			0.278			0.45		
R2	0.049			0.077			0.202		
F	15.384***			24.868***			37.484***		

Mediating effect (a*b) = 0.113. ***$p < 0.001$.

TABLE 6 Bootstrap.

	Effect	BootSE	LLCI	ULCI	Percent
Total	0.222	0.057	0.111	0.333	100%
Direct effect	0.109	0.054	0.002	0.215	49.1%
AB→PSS → PSB	0.113	0.042	0.042	0.209	50.9%

provide more opportunities for athletes to develop and refine their social skills. Social interaction is an inherent part of tennis, and over time, players may become more adept at negotiating, compromising, and empathizing with others - all of which are important aspects of pro-social behavior (Kavussanu and Boardley, 2009). However, it is worth noting that while our findings suggest a positive relationship between tennis-playing duration and pro-social behaviors, it does not imply causality. Other factors such as individual personality traits, coaching styles, and team dynamics could also influence the development of pro-social behaviors in athletes (Hodge and Lonsdale, 2011).

In conclusion, our study adds to the body of evidence suggesting that long-term participation in sports like tennis may enhance pro-social behaviors in university students. However, further research is needed to fully understand the underlying mechanisms of this relationship.

4.3 The mediating role of perceive social support

Our study also sought to understand the mediating role of appreciative social support in the relationship between tennis-playing duration and both depressive symptoms and pro-social behaviors. The results demonstrated that appreciative social support significantly mediated these relationships, a finding consistent with previous research (Rees and Hardy, 2000). Appreciative social support, derived from the tennis environment, could be a critical factor in reducing depressive symptoms. The social interactions and positive reinforcement received from coaches, teammates, and even spectators might foster a sense of belonging and acceptance (Sarason et al., 1997). This feeling could counteract feelings of isolation and loneliness, common triggers for depressive symptoms. Over time, continued involvement in tennis and the associated social support could potentially lead to a decrease in depressive symptoms (Cohen and Wills, 1985). Similarly, appreciative social support could play a significant role in enhancing pro-social behaviors among tennis players. The social nature of tennis often requires cooperation and mutual understanding, and positive social support could encourage these behaviors. Players who feel appreciated and supported are likely to reciprocate these positive behaviors toward others, promoting a cycle of pro-social behavior within the tennis community (Bandura, 1977). However, it is important to consider other factors such as personality traits and socio-economic status which can also influence the perception and effect of social support (Lakey and Cohen, 2000). More research is needed to fully understand the complexity of these relationships.

In conclusion, our findings highlight the potential mediating role of appreciative social support in the relationship between tennis-playing duration, depressive symptoms, and pro-social behaviors. It suggests that fostering a supportive environment in sports settings could be beneficial for athletes' mental health and social interactions.

4.4 Limitation

This study has several limitations. First, the sample was limited to college students in a specific region, possibly limiting the generality of the results. Second, the data relies largely on self-reporting, which can lead to social expectation effects or memory biases. The cross-sectional design of the study did not allow causal relationships to be established, only correlations between variables were revealed. In addition, only the effects of tennis were examined, and the potential effects of other sports types were not considered. Understanding social support as a mediating variable may be influenced by unmeasured factors, such as personality traits or socioeconomic status. Finally, without considering the effects of long-term participation in tennis, short-term studies may not reflect long-term effects, and insufficient consideration of the impact of cultural context on social support and mental health may limit the applicability of the results in different cultural contexts.

5 Conclusion

The aim of this study was to investigate the effects of tennis on depressive symptoms and pro-social behavior in university students and to examine the mediating role of comprehending social support.

By collecting relevant psychological assessments and social support questionnaires from the participants, we reached the following conclusions: (1) Tennis has a significant mitigating effect on depressive symptoms in college students. The results of the study showed that the longer the time spent playing tennis, the less depressive symptoms. This suggests that tennis, as a physical activity, has a positive impact on improving the mental health of college students. (2) Tennis has a positive impact on the pro-social behavior of university students. The results of the study showed that the longer the time spent playing tennis, the higher the level of pro-social behavior. This suggests that by participating in tennis, university students are more inclined to be socially active, caring and supportive. (3) Appreciation of social support mediated the effects of tennis on college students' depressive symptoms and pro-social behavior. Through further analyses, we found significant correlations between participants' perceptions of social support and depressive symptoms and pro-social behavior during tennis training. This suggests that participants' level of appreciation of social support is an important factor in the impact of tennis on their mental health and pro-social behavior.

In summary, the results of this study indicate that tennis has a significant mitigating effect on college students' depressive symptoms and promotes the development of pro-social behaviors. In addition, comprehending social support plays a mediating role in this process. These findings provide theoretical and practical guidance for the mental health and social development of college students, as well as empirical support for the application of sport in the field of mental health. Provide more actionable recommendations for college administrators and mental health professionals to suggest specific strategies for integrating tennis or similar activities into wellness programs. Summarize how this study extends existing literature to highlight the practical importance of creating a supportive environment in sport.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

Research involving humans has been approved by Suzhou University of Science and Technology. The studies were conducted in accordance with local legislation and institutional requirements. Participants provided written informed consent to participate in this study.

Author contributions

RS: Writing – original draft, Conceptualization, Investigation, Methodology, Software, Validation. TL: Writing – original draft, Conceptualization, Investigation, Methodology, Software. ML: Writing – original draft, Methodology, Validation. LM: Writing – review & editing, Supervision.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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