

Effects of a 12-week integrated core and plyometric training program on tennis skills, agility, strength, and balance in adolescent tennis players

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Abstract

Background and Study Aim Tennis performance in adolescents depends on the development of agility, strength, balance, and sport-specific skills. During the growth period, optimizing training strategies is essential to enhance performance without increasing injury risk. There is a growing interest in combining core and plyometric exercises within structured training programs. This study aimed to examine the effects of a 12-week integrated core and plyometric training program on tennis-specific skills (ITN score), agility, lower-body strength, and dynamic balance in adolescent tennis players aged 12–14 years.

Material and Methods Twenty-two junior male players were recruited and block-randomized into two groups: an experimental group (integrated core and plyometric training plus regular tennis) and a control group (regular tennis only). Five participants withdrew from the study. The final sample consisted of 17 players (experimental $n = 8$, control $n = 9$). Pre- and post-tests included the ITN, Pro-Agility Test, Squat Jump (SJ), Countermovement Jump (CMJ) using the BTS SportPlate™, and the Star Excursion Balance Test (SEBT). Shapiro-Wilk tests confirmed that all variables were normally distributed, satisfying the assumptions for parametric testing. Data analysis included repeated measures ANOVA, post hoc comparisons, effect sizes, and Pearson correlation coefficients.

Results Repeated measures ANOVA revealed significant group \times time interactions for ITN score ($F = 12.34$, $p = 0.003$, $\eta^2 = 0.45$), Pro-Agility Test ($F = 7.45$, $p = 0.015$, $\eta^2 = 0.38$), and SEBT ($F = 6.56$, $p = 0.018$, $\eta^2 = 0.35$). No significant interactions were found for SJ or CMJ. Pairwise comparisons showed large effects for ITN improvement (experimental group: Mean Diff = -1.2 , $p = 0.001$, $d = 1.20$) and Pro-Agility time (experimental group: -0.23 s, $p = 0.004$, $d = 0.85$). SEBT scores increased by 6.1 points ($p = 0.003$, $d = 0.92$). A moderate negative correlation ($r = -0.52$, $p < 0.05$) was found between agility gains and ITN improvements.

Conclusions The 12-week integrated program significantly improved tennis skills, agility, and dynamic balance compared to regular training alone. However, it had minimal impact on vertical jump performance. These results support incorporating core and plyometric training into youth tennis programs to enhance sport-specific performance.

Keywords: core training, plyometric exercises, youth tennis players, agility performance, dynamic balance.

Introduction

Youth sport performance is shaped by a combination of physiological and motor control factors that evolve during growth and maturation. In tennis, the ability to perform rapid directional changes, maintain postural stability, and generate explosive movements is especially critical for success on the court. For adolescent players, improving such qualities presents a complex challenge, as training must balance the demands of physical development with age-appropriate load

management. This complexity underscores the importance of designing training processes that address multiple interrelated physical components.

Participating in sports and regular physical activity not only shapes the body but also acts as a transformative experience that supports overall physical fitness and mental well-being [1, 2]. Developing strength and power is widely recognized as essential for success in most competitive sports, including tennis [3]. Over recent decades, tennis has evolved from a primarily technical sport to one that demands high levels of speed, power, and agility [4]. Players must now combine precise shot-making with explosive movement, efficient court

coverage, and quick adaptability during dynamic matches [5]. Achieving this performance level depends on strong muscles and joint stability to produce powerful strokes and serves while reducing injury risk, especially in areas like the shoulders and hips [6]. Sufficient flexibility and joint mobility are also crucial for executing full swings and rapid directional changes. Conditioning methods such as plyometric training and resisted sprint drills have been shown to effectively develop these physical qualities [7, 8]. However, there is still no consensus on a single best approach for developing strength and power in tennis, underscoring the need for sport-specific research and program design.

In racket sports, technical and tactical skills are key to reaching elite levels and directly influence performance [9, 10]. These skills, including serves, groundstrokes, and tactical decision-making, are strongly associated with competitive success [11, 12, 13, 14]. At the same time, cardiovascular fitness, sprint rehearsal ability, change of direction speed, muscle strength, and muscle power are among the essential physical components required for successful tennis performance [5, 15, 16]. A stronger physical foundation provides more opportunities to develop technical, tactical, and psychological skills [17, 18, 19], as well as to prevent injuries [20]. Moreover, it is widely acknowledged that players need enhanced physical fitness to perform advanced strokes and compete effectively against stronger opponents [4].

Tennis is a dynamic and demanding sport that requires a combination of athletic qualities, including speed, explosive power, agility, and the ability to maintain high performance levels under competitive pressure. In this context, the study by [21] highlights the significant benefits of high-intensity interval training (HIIT) on various performance metrics in adolescent tennis players. It demonstrates marked improvements in aerobic capacity, agility, and sport-specific skills. To succeed in modern tennis, players need technical mastery supported by high physical fitness. This requires training approaches tailored to the sport's demands, such as plyometric training, which can boost both skills and physical performance [22]. Several types of exercise interventions can enhance performance in tennis players. For instance, resistance training can increase serve velocity [23], while strength training can enhance forehand and backhand hitting speed [24]. In addition, core training, balance training, and sprint training are known to improve speed and strength in tennis players [8, 25, 26]. High-intensity interval training also improves aerobic performance in young tennis athletes [27].

Among the many kinds of exercises, plyometrics assist in developing power, a foundation from which the athlete can refine the skills of their sport [28]. Muscle strength is a key factor for maintaining high-

level tennis performance during competition [29]. Core muscles play an essential role in stabilizing the spine and body during dynamic movements such as jumping, running, and throwing [30], while also supporting balance and lower-limb performance [31]. Because tennis involves constant directional changes and complex kinetic chain actions, a strong core is critical for transferring force efficiently from the ground through the body to the racket [32, 33].

In modern tennis, rotational movement has become a key factor in performance [34], requiring training that addresses strength, speed, balance, coordination, and flexibility in a three-dimensional approach [6, 35]. Players must maintain explosive leg and upper body strength, visual tracking, and attentional focus during long matches [36]. Core training should therefore build stability, posture, and injury prevention into every tennis-specific program [32]. For youth athletes, training should strengthen the abdominal, back, and spinal muscles first to create a solid base for limb movements, especially during growth [37]. Research supports that core training can improve shoulder rotation, serve speed, and reduce overuse injuries [38, 39]. Manchado et al. [40] found improved throwing speed in handball, while Afyon et al. [41] noted speed and agility gains in footballers. However, other studies found no significant agility benefits [42, 43].

Analysis of research findings has shown that various training methods, including core and plyometric exercises, contribute to improving physical performance indicators relevant to tennis. Researchers emphasize that the effectiveness of such interventions may depend on how well they are integrated into sport-specific training, especially during periods of rapid growth in adolescent athletes. Given the complexity of physical demands in tennis and the multiple components involved in performance development, further exploration of structured training combinations remains a meaningful direction. Within this context, examining the combined impact of core and plyometric training on key performance metrics in youth players becomes particularly relevant.

It is reasonable to assume that a structured combination of core and plyometric exercises may produce greater improvements in tennis-specific performance compared to conventional training alone, particularly during early adolescence when physical adaptations are most responsive. Targeted interventions that address both stability and explosive movement patterns could be especially effective in enhancing agility, balance, and lower-body strength in young athletes. This study aimed to examine the effects of a 12-week integrated core and plyometric training program on tennis-specific skills (ITN score), agility, lower-body strength, and dynamic balance in adolescent tennis players aged 12–14 years.

Materials and Methods

Participants

A total of twenty-two male tennis players, aged 12 to 14 years, were initially recruited to participate in this quasi-experimental study. All participants had a minimum of two years of consistent tennis training experience and were actively competing at the junior level in local tournaments. Participants were randomly allocated using block randomization to either the experimental group, which received an integrated core and plyometric training program in addition to regular tennis training, or the control group, which continued with standard tennis training only.

Due to injuries, scheduling conflicts, and non-compliance with the intervention protocol, five participants withdrew from the study during the first two weeks. Therefore, the final sample comprised seventeen participants, with eight in the experimental group and nine in the control group. Informed consent was obtained from all parents or legal guardians prior to participation, in line with the Declaration of Helsinki.

Study Design

The research was conducted in the southern region, and all sessions were supervised by certified strength and conditioning coaches. An a priori power analysis was conducted using G*Power 3.1 software [44] to determine the minimum required sample size for the planned 2 (Group: Experimental vs. Control) × 2 (Time: Pre vs. Post) repeated measures ANOVA. Based on an anticipated medium effect size ($f = 0.25$), an alpha level of 0.05, and a desired power ($1-\beta$) of 0.80, the analysis indicated that a minimum of 16 participants would be needed to detect significant main and interaction effects. To account for potential attrition, 22 participants were initially recruited, resulting in a final sample of 17 after withdrawals.

Table 1 presents the descriptive characteristics of the participants in the experimental and control groups. The two groups were well matched in terms

of age, height, weight, and training experience at baseline. The participants had comparable demographic profiles, with no major differences observed between the groups. All had at least two years of consistent tennis training and were actively competing at the junior level. This baseline similarity supports the assumption that any post-intervention effects are likely attributable to the training protocol rather than pre-existing group differences. No notable outliers or imbalances were identified, strengthening the internal validity of the study.

Measurement Tools

Tennis Skills. Players' tennis skill levels were assessed using the International Tennis Number (ITN) rating protocol, developed by the International Tennis Federation [45]. The ITN provides a standardized measure of playing ability based on serve consistency, groundstrokes, volleys, and physical mobility in various game situations. Scores were calculated from a composite of performance tests and used to assign an ITN number.

Agility. Agility performance was measured using the Pro-Agility Test, also known as the 5-10-5 Shuttle Run [46]. Participants sprinted laterally to cones positioned 5 yards (4.57 m) to the left and right of a starting line. Timing was recorded using electronic photocells for precision. Each participant performed a 180° turn at each cone, emphasizing change of direction speed.

Strength. Explosive leg strength was evaluated using the Squat Jump (SJ) and Countermovement Jump (CMJ), performed on the BTS SportPlate™ system (BTS Bioengineering) [47]. The SportPlate™ provides high-precision force-time data and jump height analysis, ensuring valid and reliable measurement of lower-limb power output. For the SJ, participants squatted to 90° knee flexion with hands on hips and jumped vertically without countermovement. For the CMJ, participants began from an upright standing position, performed a rapid downward movement to 90°, and then jumped vertically using an arm swing.

Dynamic Balance. To provide additional insight into functional stability, the Star Excursion

Table 1. Demographic Characteristics of Participants (N = 17)

Variable	Experimental Group (n = 8)	Control Group (n = 9)
	M ± SD	M ± SD
Age (years)	12.8 ± 0.6	13.1 ± 0.7
Height (cm)	158.4 ± 5.5	160.2 ± 6.0
Weight (kg)	47.5 ± 6.3	48.8 ± 7.1
Training Experience (years)	2.6 ± 0.5	2.6 ± 0.5

Note. Values are presented as mean ± standard deviation (SD). Groups were similar at baseline.

Balance Test (SEBT) was used [48]. The SEBT required participants to maintain balance on one leg while reaching with the other leg in eight different directions. Maximum reach distances were normalized to leg length and averaged across directions.

Procedures

The integrated training protocol was implemented over a 12-week period and was designed to progressively develop core strength, stability, and explosive power. Each two-week phase targeted specific physical qualities, with core and plyometric exercises selected to match the developmental focus. Exercise intensity, volume, and rest intervals were adjusted accordingly to support adaptation while minimizing injury risk. An overview of the training structure is presented in Table 2.

Baseline testing was conducted one week before the intervention to establish pre-training measurements. All participants completed the ITN Tennis Skills Test, Pro-Agility Test, Squat Jump (SJ), Countermovement Jump (CMJ) using the BTS

SportPlate™, and the Star Excursion Balance Test (SEBT) in a fixed sequence to avoid fatigue bias. Testing sessions were held indoors under consistent conditions, with the same surface, time of day, and environmental factors for all participants. Each test was preceded by a standardized 10-minute dynamic warm-up and was supervised by trained assessors blinded to group allocation. Sufficient rest intervals of 2–3 minutes were provided between tests and trials to ensure valid results. The SEBT was practiced during a familiarization session to reduce learning effects. After the 12-week training program, all post-tests were conducted within one week using identical protocols and the same blinded assessors. Equipment was calibrated before each session. All data were double-checked for accuracy immediately after testing.

Statistical Analysis

All statistical analyses were performed using IBM SPSS Statistics Version 27.0. Prior to conducting inferential tests, data were screened for normality using the Shapiro–Wilk test for each dependent variable at both pre- and post-intervention time points. Variables were considered

Table 2. 12-week integrated core and plyometric training program

Week(s)	Focus	Core Exercises	Plyometric Exercises	Sets × Reps	Intensity
1–2	Foundational strength and mechanics	Front plank, Bird dog, Dead bug, Basic crunch	Jump squat, Double-leg lateral hops	3 sets × 12–15 reps	Bodyweight only. Focus on form and control. Rest 45–60 s between sets.
3–4	Movement control and stability	Side plank (right and left), Swiss ball crunch, Russian twist (bodyweight), Hip bridge	Single-leg hops, Skater jumps	3–4 sets × 10–12 reps	Light resistance introduced (medicine ball 2–3 kg for twists). Rest 60 s between sets.
5–6	Strength endurance and load progression	Hanging knee raises, Cable rotational pulls, Swiss ball roll-out, Plank with alternating leg lift	Bounding drills (20 m), Depth jumps (20–30 cm box)	4 sets × 8–12 reps	Resistance increased using bands or cable at approximately 40–50% of 1RM for rotational pulls. Plyometrics: soft landings. Rest 75–90 s.
7–8	Advanced stability and power	Medicine ball rotational throws (seated and standing), Stir-the-pot (Swiss ball), Plank shoulder taps, Hanging leg raise	Hurdle hops (4–6 hurdles, 30–40 cm), Tuck jumps	4–5 sets × 8–10 reps	Medicine balls 3–5 kg. Plyometrics: higher box heights and controlled landings. Rest 90–120 s between sets.
9–10	Sport-specific power and integration	Single-arm cable chop, Side plank with hip dip, Medicine ball slam, Swiss ball pike	Tennis footwork drill with plyometric burst (split step plus drop jump), Reactive lateral cone hops	5 sets × 6–8 reps	Power-focused: moderate load and explosive tempo. Short ground contact time. Rest 120 s between sets.
11–12	Peak power, agility, and transfer	Rotational plank walks, Standing anti-rotation press (Paloof press), Medicine ball overhead throw, Partner-resisted plank	Multi-directional depth jumps (40–50 cm box), Reaction drop jumps with visual cue	5 sets × 5–8 reps	High intensity: medicine balls 5–6 kg. Maximum effort, explosive execution. Extended rest 2–3 min between sets.

normally distributed if $p > .05$, thus meeting the assumptions required for parametric analyses. Descriptive statistics (means \pm standard deviations) were computed separately for the experimental and control groups.

To examine the effects of the 12-week intervention, a series of 2 (Group: Experimental vs. Control) \times 2 (Time: Pre vs. Post) Repeated Measures ANOVAs were conducted for each outcome variable: International Tennis Number (ITN) score, Pro-Agility time, Squat Jump (SJ) height, Countermovement Jump (CMJ) height, and the Star Excursion Balance Test (SEBT) composite score. This allowed assessment of main effects for group and time, as well as the Group \times Time interaction, which determined whether performance changes differed between groups.

Effect sizes for ANOVA results were calculated using partial eta squared (η^2p), with interpretation thresholds of .01 (small), .06 (medium), and .14 (large) according to Cohen (1988). For post hoc within-group comparisons, Cohen's d was calculated to assess the magnitude of change over time, with effect size interpretations of 0.2 (small), 0.5 (medium), and 0.8 (large). Ninety-five percent confidence intervals (95% CI) were reported for all mean differences to enhance interpretability.

To explore interrelationships among the primary outcome measures, Pearson product-moment correlation coefficients (r) were calculated for change

scores (Post-Pre). These included relationships between changes in ITN and Pro-Agility, SEBT, SJ, and CMJ scores. All variables satisfied the assumptions of linearity, homoscedasticity, and normality required for correlation analysis.

Results

Table 3 presents the results of the Shapiro-Wilk test, confirming that all key dependent variables, including ITN scores, Pro-Agility times, Squat Jump, Countermovement Jump, and SEBT scores, were normally distributed at both pre- and post-test points. All p -values exceeded the 0.05 threshold, indicating that none of the variables deviated significantly from normality. This confirms that the dataset met the necessary assumptions for conducting parametric analyses. Consequently, Repeated Measures ANOVA and Pearson's correlations were appropriately applied across all outcome measures. This strengthens the validity and consistency of the statistical approach used in the study.

Table 4 summarizes the results of the Repeated Measures ANOVA, showing main effects of group, time, and the crucial group \times time interaction for each variable. For the ITN score, significant main effects for time ($F = 18.34, p = 0.001$) and group \times time interaction ($F = 12.34, p = 0.003$) indicate that the experimental group improved significantly more than the control group over time. Pro-Agility time

Table 3. Shapiro-Wilk normality test statistics for each dependent variable

Variable	W Statistic	p-value
ITN Pre	0.97	0.50
ITN Post	0.96	0.40
Pro-Agility Pre	0.95	0.45
Pro-Agility Post	0.94	0.38
Squat Jump Pre	0.97	0.52
Squat Jump Post	0.96	0.47
CMJ Pre	0.95	0.49
CMJ Post	0.94	0.43
SEBT Pre	0.95	0.48
SEBT Post	0.94	0.46

Note. W = Shapiro-Wilk statistic. $p > .05$ indicates that the data are normally distributed, confirming that the data meet the assumption of normality for parametric analysis.

Table 4. Repeated measures ANOVA summary for group, time, and interaction effects

Variable	F (Group)	p (Group)	F (Time)	p (Time)	F (Group \times Time)	p (Group \times Time)	Partial η^2
ITN Score	4.56	0.05	18.34	0.001	12.34	0.003	0.45
Pro-Agility	3.21	0.09	9.12	0.008	7.45	0.015	0.38
Squat Jump	2.10	0.16	1.55	0.22	0.89	0.36	0.05
CMJ	1.89	0.19	1.12	0.29	0.76	0.42	0.04
SEBT	3.45	0.08	12.87	0.002	6.56	0.018	0.35

Note. F = F statistic; partial η^2 = effect size; $p < .05$ indicates statistical significance.

showed a similar pattern, with a significant time effect ($F = 9.12, p = 0.008$) and interaction effect ($F = 7.45, p = 0.015$). SEBT performance also showed a significant interaction ($F = 6.56, p = 0.018$), reflecting meaningful improvements in dynamic balance in the experimental group. Partial eta squared values for these outcomes ranged from 0.35 to 0.45, indicating medium to large effect sizes. Squat Jump and CMJ did not show significant interaction effects, suggesting that the core and plyometric program had limited impact on vertical jump performance.

Table 5 presents pairwise comparisons that clarify where significant changes occurred. The experimental group demonstrated a substantial reduction in ITN score (Mean Diff = -1.2 , 95% CI [$-1.7, -0.7$], $p = 0.001$, Cohen's $d = 1.20$), confirming meaningful tennis skill improvements. The control group showed only a slight ITN score reduction ($-0.2, p = 0.040$), indicating a small effect. For Pro-Agility, the experimental group's time improved by -0.23 seconds ($p = 0.004, d = 0.85$), while the control group's change was negligible and non-significant. The SEBT score in the experimental group increased by 6.1 points ($p = 0.003, d = 0.92$), demonstrating significant gains in dynamic balance. These post hoc results emphasize the practical benefits of the 12-week integrated training program for tennis-specific performance, agility, and balance.

Table 6 shows the relationships between change scores across key performance measures. A moderate negative correlation ($r = -0.52, p < 0.05$) was found between ITN score improvements and Pro-Agility improvements, indicating that as agility performance increased, tennis skill scores also improved. Similarly, a positive correlation ($r = 0.52$)

was observed between changes in SEBT and ITN, suggesting that improvements in dynamic balance may contribute to better tennis performance. The Squat Jump and CMJ changes were highly correlated ($r = 0.85$), which is expected given that both assess lower-body explosive power. These correlations support the idea that gains in agility and balance are functionally related to tennis skill development in young players. Overall, the correlation matrix helps explain how different physical qualities interact to enhance on-court performance.

Discussion

The present study examined the impact of a 12-week integrated core and plyometric training program on tennis-specific skills, agility, strength, and dynamic balance among players aged 12–14 years. The results supported the hypothesis, showing that the combined training group achieved greater gains than the control group. Significant group \times time interactions were found for ITN score ($p = 0.003$), agility ($p = 0.015$), and balance ($p = 0.018$), all with large effect sizes. This confirms that the integrated program was more effective than standard training alone. Furthermore, extending the training duration from eight to twelve weeks contributed to significant improvements in ITN scores, agility performance, and dynamic balance in the experimental group, while jump-related strength gains remained modest. These findings align with prior research supporting the role of core-focused interventions in enhancing functional performance and sport-specific abilities.

Consistent with the findings of [49], who reported significant improvements in forehand and

Table 5. Post hoc pairwise comparisons with 95% confidence intervals and effect sizes

Comparison	Mean Difference	95% CI	p-value	Cohen's d
ITN Exp Pre–Post	-1.2	[-1.7, -0.7]	0.001	1.20
ITN Con Pre–Post	-0.2	[-0.4, 0.0]	0.040	0.25
Pro-Ag Exp Pre–Post	-0.23	[-0.35, -0.11]	0.004	0.85
Pro-Ag Con Pre–Post	0.05	[-0.04, 0.14]	0.580	0.10
SEBT Exp Pre–Post	6.1	[4.0, 8.2]	0.003	0.92

Note. Cohen's d represents effect size for within-group comparisons; $p < .05$ indicates significant change.

Table 6. Correlation Matrix of Change Scores Between Performance Measures

Change Variable	ITN	Pro-Agility	Squat Jump	CMJ	SEBT
ITN	1.00	-0.52*	0.12	0.10	0.52*
Pro-Agility		1.00	0.18	0.15	0.35
Squat Jump			1.00	0.85*	0.28
CMJ				1.00	0.22
SEBT					1.00

Note. Values are Pearson correlation coefficients. Correlations marked with * are statistically significant at $p < .05$. ITN = International Tennis Number; CMJ = Countermovement Jump; SEBT = Star Excursion Balance Test.

backhand groundstroke speeds, static balance, and throwing performance in adolescent tennis players following an 8-week core training program, the present study observed clear advancements in ITN scores. This underscores the value of extended core training for tennis skill enhancement. Similarly, the improvement in agility aligns with the results of [50] among surfers, where an 8-week core training regimen led to notable gains in agility and balance. However, our study suggests that a 12-week duration may amplify these adaptations, particularly for quick directional changes, which are essential in tennis.

Regarding agility performance, our results correspond with previous observations by [51], who found significant improvements in dynamic balance, core strength, and serve accuracy in volleyball players following 6 weeks of core training. The consistent enhancement in agility across studies reinforces the functional role of trunk stability in supporting rapid, multi-directional movements required in racket sports [51].

A distinctive aspect of this study is the inclusion of dynamic balance measurement through the Star Excursion Balance Test (SEBT). Our findings revealed meaningful improvements in SEBT scores after 12 weeks, indicating that integrated core and plyometric exercises can effectively enhance postural control and single-leg stability. This aligns with the systematic review by [48], which highlights the SEBT as a valid and reliable tool for detecting changes in dynamic balance following training interventions. Interestingly, similar to the findings of [49, 52, 53], no significant gains were observed in vertical or countermovement jump height. While [54, 55] reported improvements in jump performance in footballers and children following core training, our results suggest that such gains may be less pronounced in tennis players. This may reflect the sport's primary demands for horizontal quickness and directional changes rather than vertical power [56, 57].

The variation in jump improvements across sports highlights the importance of tailoring training programs to the specific biomechanical requirements of each discipline. Plyometric training has been shown to enhance explosive actions such as jumping and sprinting, which are vital for tennis players. An 8-week plyometric program improved performance in countermovement jumps and medicine ball throws, indicating increased power and strength in young tennis players [58]. Core training, particularly when periodized, significantly improves service velocity. One study demonstrated a 6.6% increase in serve speed among young tennis players following an 8-week core stabilization program, underscoring the importance of core strength in executing powerful serves [39]. A combined training approach, including tennis-specific sprints and plyometric exercises, has been shown to improve

agility and motor skills. Participants in such programs exhibited better performance in agility tests like the Illinois agility test and T-test, which are critical for quick directional changes on the court [59].

Training programs that incorporate both core and plyometric exercises contribute to improved balance and strength. For instance, a study on badminton players showed significant improvements in balance and strength metrics, which are transferable to tennis [60]. In addition to these primary findings, further evidence highlights the broader benefits of combining core stability and plyometric exercises.

Behm et al. [61] emphasized that training on unstable surfaces can activate deeper trunk muscles, enhancing core endurance and functional transfer to sport movements. Similarly, Markovic and Mikulic [62] demonstrated that plyometric training induces favorable neuromuscular and musculoskeletal adaptations, which can translate to improved agility and reactive strength. Myer et al. [63] noted that integrating balance tasks alongside plyometrics may optimize power production and landing mechanics, aligning with the improvements in agility and balance observed in this study. Furthermore, Leetun et al. [64] highlighted that greater core stability can reduce the risk of lower extremity injuries, an important practical consideration for adolescent tennis players. Together, these findings reinforce the notion that a well-designed, longer-duration core and plyometric program can positively affect multiple performance domains relevant to tennis development.

A recent study by Liu et al. [65] demonstrated that combining functional and traditional training effectively enhanced multiple performance variables in adolescent athletes, including sprinting ability, agility, and coordination. This supports the current study's approach of integrating core and plyometric training to target similar multi-dimensional performance gains. Such evidence reinforces the value of combined, sport-specific training for youth athletes.

The study by Arslan and Ergin [66] demonstrated that 8 weeks of core training resulted in significant improvements in ITN scores ($p = .001$) and agility ($p = .004$) among 10- to 14-year-old tennis players. Their experimental group also outperformed the control group across these variables, affirming the effectiveness of supplementary core work. These findings directly support the current study's emphasis on integrated conditioning to enhance tennis-specific performance outcomes.

Recent findings by Kumar et al. [67] emphasize that gender and BMI significantly influence motor competence in children, highlighting the need for tailored interventions. This aligns with the present study's focus on customized training to support optimal skill development in young tennis

players. Further, a study by Choudhary et al. [68] demonstrated that perturbation-based balance training significantly improved dynamic stability in university basketball players. This reinforces the value of targeted balance exercises and supports our finding that dynamic balance can be enhanced through integrated core and plyometric training in youth tennis players. These findings are consistent with those of Choudhary et al. [69], who demonstrated that a 12-week structured yoga intervention significantly improved flexibility, static balance, and joint kinematics in university athletes. Their results emphasize the efficacy of structured neuromuscular training in enhancing movement efficiency and postural control.

This study contributes to the existing literature by applying a 12-week integrated core and plyometric training program specifically to adolescent tennis players aged 12 to 14 years. Unlike prior research that typically focuses on shorter interventions or single-mode training, this study extends the duration beyond the common 6–8 week protocols and combines core and plyometric elements. Furthermore, it provides a multidimensional assessment by simultaneously measuring tennis skill (ITN score), agility, vertical jump performance, and dynamic balance (SEBT). While similar training modalities and outcome measures have been reported previously [26, 49, 58, 60, 61, 63, 66], the extended duration, population specificity, and integrated performance profile offer an incremental yet meaningful advance in the field.

Overall, extending the intervention duration from eight to twelve weeks facilitated greater improvements in tennis skill ratings, agility, and dynamic balance, while vertical power gains remained limited. These results underscore the practical relevance of integrated core and plyometric training for tennis players, emphasizing the importance of efficient force transfer, rapid lateral movements, and postural stability in optimizing on-court performance.

Limitations and Future Research Directions

This study has several limitations that should be acknowledged. First, the relatively small sample size and the focus on male adolescent tennis players aged 12 to 14 may limit the generalizability of the findings to other age groups, females, or different competitive levels. Second, the study did not include a long-term follow-up to assess the sustainability of the training effects beyond the 12-week intervention period. Third, although multiple performance outcomes were measured, other relevant factors such as psychological variables, injury incidence, or sport-specific tactical skills were not examined. Future research should consider larger and more diverse samples, including female athletes and different age categories, to enhance the external validity. Additionally, studies with extended follow-up periods are needed to evaluate the retention

of training benefits. Incorporating psychological assessments and sport-specific tactical evaluations could provide a more comprehensive understanding of how integrated training influences overall tennis performance and athlete development.

Conclusions

This study demonstrated that a structured 12-week integrated core and plyometric training program produced meaningful improvements in tennis-specific performance variables among adolescent tennis players aged 12–14 years. Specifically, the program resulted in significant enhancements in ITN scores, agility, and dynamic balance, highlighting the combined benefit of core stability and explosive movement drills for young tennis athletes. While no substantial gains were observed in vertical and countermovement jump performance, this outcome aligns with the sport's emphasis on lateral movement and quick directional changes rather than vertical power output.

By extending the intervention duration from previous 6- or 8-week models to 12 weeks, this study provides additional evidence that a longer training period may amplify gains in skill-specific and functional measures crucial for on-court success. The incorporation of dynamic balance assessment through the SEBT further expands understanding of how core and plyometric training can improve postural control, which may translate to better stability during rapid play situations.

Overall, these findings suggest that tennis coaches and conditioning specialists should consider integrating progressive core and plyometric exercises into young athletes' training routines to optimize agility, balance, and tennis skill development. Future research is encouraged to investigate complementary interventions, longer follow-up durations, and the potential impact on injury prevention.

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Conflict of Interest

The authors declare that there are no conflicts of interest related to this study.

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