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Tennis: Testing and performance

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Tennis: Testing and performance

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Editorial: Tennis: Testing and performance

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KEYWORDS

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Editorial on the Research Topic
Tennis: Testing and performance

The topic of testing has attracted considerable attention in the tennis performance literature (1, 2), and the energetic and skill demands of tennis have also been studied extensively providing a considerable understanding of the game challenges (3). In this context, the main objective of this research topic is to assist in the provision of insight on this area by including a series of novel studies that contribute to the acquisition of further theoretical and practical knowledge which can offer new perspectives for research as well as a direct application on-court.

Crucial to the testing process is the use of normative values as done by Johansson et al. who explored the shoulder rotation strength and range of motion of boys' and girls' junior players and presented a normative database for these aspects. This seminal study showed age and sex differences in both the isometric internal rotation, weakness in external rotation, as well as eccentric external rotation in these competitive athletes. Following the findings from Reid and Schneiker (4) this research emphasised the relevance of strength development through puberty specifically in the girls' tennis players.

The use of technology is gradually becoming a must in the assessment of tennis players (5). However, its application in the provision of information related to the psychological components of the game is still in progress due to the complex nature of mental skills identification in competitive settings. This trend is clearly shown in the study conducted by Havlucu et al. who explored the detection of the achievement of the "zone" in elite players using off-the-shelf wearable technology. They used a neural network to predict the achievement of this state of optimal performance at a relatively low cost. Their findings were successfully applied in a real-life scenario combining wearable technology, expert labels, and machine learning, which could provide all interested with a suitable alternative to the detection of psychological states in tennis players.

The tactical and technical skills constitute the backbone components of the game (6), for the first time ever, Kolman et al. developed a reliable, valid, and feasible tool to assess tactical skills during training and game situations in tennis players. This study supported the psychometric properties of the Tactical Skills Questionnaire in Tennis (TSQT), an instrument by which players can self-assess their tactical skills using reflection on their tactical competencies. This tool can provide useful information to generate specific areas to be worked on during practice sessions. Regarding the testing of the technical aspects, one crucial element in the understanding of the performance of the technical skills in complex match situations. Kolman et al. also explored the development of these skills throughout the various age categories in junior talented players. They used a dedicated tool, the on-court Dutch Technical-Tactical Tennis Test, to find out that skills such as ball speed for males and accuracy in complex situations for both genders develop through adolescence in these players.

As Baiget et al. (7) indicated, the testing of the metabolic and conditional demands of the game provides an unvaluable insight on the profile of this activity. Several articles in this research topic have covered this area. In a systematic review with meta-analysis paper, Lambrich and Muehlbauer quantified and characterised effects of training on physical fitness measures and stroke velocity in youth and adult tennis players. They found training adaptations in adult players for lower-extremity muscle power, upper-extremity muscle strength, and stroke velocity, and endurance adaptations in youth players.

In an applied study, Bjorklund et al. explored the energy expenditure and exercise intensity in four different on-court drills in the line of Reid et al. (8). They concluded that the drills analysed in the study provided energy expenditure per minute values closer to those of similar sports, and that the energy expenditure per meter was considerably greater.

Fatigue is also a capital issue in the tennis testing scenario as stated by Hornery et al. (9). In this context, the relationship between player fatigue and groundstroke type in tennis was studied by Murata and Naito who analysed the physiological demands in simulated matches and hitting tests while considering the translational and rotational kinetic energy ratio of the ball. Findings suggest that players with high lactate levels hit the ball with a greater ratio of rotational kinetic energy to total kinetic energy, which may imply that the type of groundstrokes played is a factor to be considered when testing fatigue in tennis.

The assessment of movement skills in performance players is also extremely relevant due to the great importance of the displacement and court positioning capabilities in today's game (10). In this vein, Reiner Volk et al. explored the correlation of a linear sprint and change of direction test to the current tennis ranking of the player. The authors found that the change of direction test had a moderate and higher impact on tennis performance as compared to the linear sprint. Considering these results, the use of specific change of direction drills in on-court training session was recommended.

From a training programme perspective, the study of the effects of training prescription is extremely relevant (11). Le Sollliec et al. investigated the impact of an 8-week multimodal programme on the thoracic posture, glenohumeral range of motion and serve performance in competitive young players. The programme produced moderately relevant effects to rectify the sagittal thoracic curvature in the sample. It also assisted in regaining the range of motion in glenohumeral rotation without producing an impairment in the performance of the serve.

In conclusion, findings from the articles included in this research topic provide researchers with directions for future studies and facilitate coaches and other professionals with evidence-based methods, procedures and instruments for testing and assessing different components and skills needed for performance tennis. The information presented in this topic can be used in tennis specific testing programmes aimed at increasing the understanding of the mechanisms underlying proper player assessment and evaluation.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication. All authors contributed to the article and approved the submitted version.

Conflict of interest

MC was employed by International Tennis Federation. RG declares 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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Metabolic Demands, Center of Mass Movement and Fractional Utilization of $\dot{V}O_{2max}$ in Elite Adolescent Tennis Players During On-Court Drills

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The aim of the study was to investigate the exercise intensity and energy expenditure during four types of on-court tennis drills. Five female and five male tennis players participated in the study (age: 17 ± 2 years; $\dot{V}O_{2max}$: 54 ± 6 ml·kg^{-1}·min^{-1}). Anthropometric measures were taken for each player and, on separate days, each player performed (i) treadmill running to determine $\dot{V}O_{2max}$ and (ii) four different tennis drills (Drill1-4) during which $\dot{V}O_2$, blood lactate concentration, ratings of perceived exertion (RPE 6–20), and displacement of center of mass (*m*) using 3D kinematics were recorded. The drills were designed to simulate match play with 90 s of rest between each drill. A repeated two-way ANOVA was used for physiological and biomechanical data and Friedman's test for RPE using $< \alpha$ 0.05. Fractional utilization of $\dot{V}O_{2max}$ was greatest during Drill1 81.8 ± 7.0% and lowest during Drill4 72.4 ± 5.2% ($p < 0.001$) with no difference between sexes ($p > 0.05$). The highest energy expenditure was during Drill1 and lowest during Drill4 (77 ± 15 and 49 ± 11 kcal, respectively, $p < 0.05$). Energy expenditure per meter for Drill1–Drill4 was subsequently reduced for each drill with 10.5 ± 2.1, 9.9 ± 2.2, 7.6 ± 1.7, and 8.0 ± 1.6 J·kg^{-1}·m^{-1} ($p < 0.01$). There were no interaction effects for any of these variables. RPE (6–20) and blood lactate concentration post Drill1–Drill4 were 17.5, 15.5, and 13.0 (overall, legs and arms, $p < 0.001$) and 5.9 ± 2.0, 4.9 ± 1.9, 5.6 ± 2.0, and 5.0 ± 2.2 mmol·l^{-1} ($p < 0.05$). The findings of this study demonstrate that the on-court tennis drills performed here are suitable for high intensity training in junior tennis players. The energy expenditure per minute is comparable to similar sports whereas the energy expenditure per meter is notably greater.

Keywords: biomechanics, exercise intensity, motion capture, racket sport, work economy

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INTRODUCTION

Tennis players need to master the complex techniques and sport-specific movements, for example the service motion and the movement patterns on-court, requiring acceleration and deceleration in combination with change of direction (Kovacs, 2006; Kovacs and Ellenbecker, 2011; Hoppe et al., 2014). In addition, tennis has become a true physical challenge requiring strength, speed, power, agility, mobility, aerobic fitness, and anaerobic power output (Baiget et al., 2015). It has been reported that maximal oxygen uptake ($\dot{V}O_{2max}$) of high-level tennis players is in the range of 44–69 ml·kg^{-1}·min^{-1}, and above 50 ml·kg^{-1}·min^{-1} in the majority of cases (Kovacs, 2006). The average fractional of utilization of $\dot{V}O_{2max}$ during intensive rallies corresponds to ∼50–60% of time spent with $\dot{V}O_{2max}$ values above 80% (Fernandez et al., 2006). Armstrong and Welsman (1994) report that female athletes generally have 10% lower $\dot{V}O_{2max}$ than males in childhood and at 16 years of age; the difference often increases to ∼35% between sexes. Relative intensity of simulated tennis play and the responses to different training drills showed that drills were stroke-time-dependent, were an increase in number of strokes per drill required significantly greater heart rate, blood lactate concentrations, and oxygen uptake ($\dot{V}O_2$) up to two–three times of $\dot{V}O_{2max}$ (Botton et al., 2011; Gomes et al., 2016). In addition, intensity distribution and its relation to aerobic fitness in competitive players appears to determine the intensity players can sustain throughout a game (Baiget et al., 2015). To summarize, energy expenditure expressed as $\dot{V}O_2$ and heart rate responses to standardized tennis drills exhibit large various across different drills (Bekraoui et al., 2012).

In tennis, Global Positioning Systems (GPS), Local Positioning Systems (LPS), and video based systems have been used to track players' movement patterns on-court (Reid et al., 2008, 2016; Hoppe et al., 2014; Whiteside and Reid, 2017). These systems have provided valuable information with sufficient accuracy regarding distances traveled and running patterns but cannot always accurately detect short sprints, high intensity actions, and rapid directional changes, which often occurs in tennis (Barris and Button, 2008; Coutts and Duffield, 2010; Waldron et al., 2011; Sathyan et al., 2012; Vickery et al., 2014; Luteberget et al., 2018). Generally, when compared with females male elite players cover a greater distance per match and at higher speeds (Reid et al., 2016; Whiteside and Reid, 2017). Previous studies have reported the total distance covered per match to be between 2,100–3,200 and 1,200–1,400 m for men and women, respectively (Reid et al., 2016; Pereira et al., 2017; Whiteside and Reid, 2017). However, the difference in the total covered distance per match can be explained by the variable formats of five sets for the men verses three sets for the women as the normalized distance per game or set shows now significant difference between sexes.

Both metabolic monitoring and positioning tracking of the players have been used to quantify tennis players exercise intensity and movements on-court. However, to date these methods have not been used simultaneously in tennis to calculate energy expenditure per meter traveled. As previously reported, both running speed as well as the frequency of turning, affect the energy expenditure during change of direction while running (Hatamoto et al., 2014). Due to the nature of tennis, where there is a constant change of direction, the energy expenditure per meter should be exceptionally high compared to linear sports. Therefore, the aims were to combine physiological and biomechanical measurements to quantify the (i) the fractional utilization of $\dot{V}O_{2max}$ and (ii) quantify the overall energy expenditure and per meter during four different on-court tennis drills.

METHODS

Subjects

Ten adolescent elite tennis players from the Swedish national teams, all competing on the International Tennis Federation (ITF) level (five male: age 17 ± 2 years, height 186 ± 7 cm, body mass 73 ± 10 kg; 5 female: age 17 ± 2 years, height 172 ± 3 cm, body mass 69 ± 7 kg), participated in the study. Exclusion criteria were a history of any injuries or illness symptoms during the last 3 months that resulted in rest from training and/or competition for more than 1 week, and/or sickness for more than 3 days during the last 4 weeks before the aerobic and anaerobic tests. All players were right-handed and used two-handed backhand. The calendar year for the players consisted of 20–22 weeks of training with a training volume ranging between 12–20 h per week depending on age; in line with the national recommendations by the Swedish Tennis Association for adolescent elite players. In addition, each player competed for 100–120 matches nationally and/or internationally (ITF) distributed over 22–26 weeks of competition over a calendar year. Therefore, total training and match volume for these players per year accumulates to a range of 500–850 h depending on age and individual schedule. Before any participation, the procedures, and potential risks were explained fully to the subjects. Written informed consent was obtained from each player. The study was in accordance with the Declaration of Helsinki and preapproved by the Regional Ethical Review Board, Stockholm, Sweden (approval no. 2012/1731/2).

Laboratory Tests

The laboratory tests- were initiated with a progressive 10-min warm-up on a treadmill (Katana, Lode, Groningen, the Netherlands) followed by a 3-min rest period.

The first 5-min of the warm-up consisted of a pre-selected speed of 10 km·h^{-1} for all individuals and thereafter adjusted for each player, according to previous self-reported test results at 3,000 m. The running speed was constant throughout the test while the workload increased by inclination in 1-min steps, 2% at the 1-min mark, and subsequently by 1% until the athlete experienced voluntary exhaustion. Capillary blood samples were collected 1 and 3 min after the cessation of the test. Expired gas and ventilation were measured continuously in mixing chamber mode with a metabolic cart (Jaeger Oxycon Pro, Wuerzburg, Germany). Prior to the start of each test, the gas analyser's turbine were calibrated. If two out of the following three criteria had been met $\dot{V}O_{2max}$ was considered to be reached: (1) $\dot{V}O_2$ showed a leveling off, defined as an increase in $\dot{V}O_2$ of <150 ml·min^{-1}, (2) respiratory exchange ratio exceeded 1.10, and (3) maximal blood lactate samples > 8 mmol·l^{-1}. The highest $\dot{V}O_2$ averaged over a period of 60 s was used to calculate $\dot{V}O_{2max}$.

Field Tests

Tennis Drills

The players performed a 15 min warm up on a bike ergometer (LT2, Monark Exercise AB, Vansbro, Sweden) at 2 W per kilo

TABLE 1 | Overview of the drills characteristics.

Drill	Number of sets per drill	Rest between each set (s)	Rest between each drill (s)	Strokes per set	Forehand strokes per set	Backhand strokes per set	Total number of strokes per drill
1	8	25	90	6	4	2	48
2	8	25	90	4	2	2	32
3	8	25	90	3	3	0	24
4*	2	25	90	6,4,3	4,2,3	2,2,0	26

*Combination drill consisting of drill 1,2, and 3, repeated two times.
m, meters; s, seconds.

body mass for the men and 1.5 W per kilo body mass for the women. Following the cycling warm up, the players performed 5 min of individual dynamic movements and stretching, followed by 10 min of hitting warm up. The participants performed three different tennis drills (Drill1-3), divided into 3–6 strokes per set and eight sets per drill and one combination drill (Drill4) of the three previous drills, divided into 3–6 strokes per set and six sets, in total four drills, 30 sets and 130 strokes divided by 90 forehands (69%) and 40 backhands (31%) (**Table 1**). An experienced professional coach, standing in the center of the court following the player, hand-fed new tennis balls to the player at a speed determined by the completion of the previous shot and movement of the player to the next shot (i.e., self-selected; Reid et al., 2008; Fernandez-Fernandez et al., 2017). Ball placement followed a fixed order presented to the players in advance at a frequency of ∼1 ball every 3 s. Each drill was based on movement patters seen in match play and designed by one fitness coach and one ATP coach in agreement. All four drills were carried out consecutively. The start of each set was called out by a research assistant responsible for the timing with a resting time of 25 s between each set and 90 s between each drill. The movement patterns of the three different drills were; Drill1; Spanish Cross) a cross pattern consisting of six strokes, starting position in the center of the court, ball placement starting with a defensive ball on the forehand side, offensive ball on the forehand side, defensive ball on the backhand side, offensive ball on the backhand side, defensive ball on the forehand side, and ending up with an offensive ball on the forehand side, recovery toward the middle of the court after the last shot was instructed to mimic match play. Drill2; Lateral) A lateral pattern consisting of four strokes alternating wide neutral balls to the forehand and backhand side respectively, starting position in the center of the court, starting with a wide ball to the forehand side, ending with a wide ball to the backhand side, recovery toward the middle of the court after the last shot was instructed to mimic match play. Drill3; Inside Out) Inside out forehand, starting position just left of the center of the court, the movement was repeated three times, and recovery toward the middle of the court in between every shot and after the last shot was instructed to mimic match play. Drill 4; Match Simulation) A combination of drill 1, 2, and 3, performed separately and consecutively with 25 s of rest between each set. This was repeated twice. All players were encouraged to move as fast as possible in all four drills and perform strokes with maximal effort, emphasizing the importance to hit the ball inside the court.

Oxygen Uptake

All tennis players were equipped with a portable breath-by breath gas analyser (MetaMax3B_R2; Cortex Biophysik GmbH, Leipzig, Germany). The gas analysers were calibrated between the tests for all player using a two-point calibration for the oxygen (O_2) and carbon dioxide (CO_2) sensors. The two-point calibration for the gas sensors used ambient conditions and a mixture of 15% O_2 and 5% CO_2 (UN 1950 Aerosols, Cortex Biophysik GmbH, Leipzig, Germany). The turbine flow was pre checked with a 3 L syringe (M9474-C, Medikro Oy, Kuopio, Finland). The gas analyser was firmly attached to the tennis players to minimize any inconvenience or disturbance to the normal playing patterns. In addition, the facemask was placed in a manner to avoid potential impairment of the vision.

The calculation of energy expenditure E_{exp} (kcal· min^{-1}) was determined by using oxygen uptake ($\dot{V}O_2$) and respiratory exchange ratio (RER) accordingly to the Weir Equation (Weir, 1949).

$$E_{\exp} = ((1.1 \cdot RER) + 3.9) \cdot \dot{V}O_2$$

Total E_{exp} for each drill was based on the area under the curve for the $\dot{V}O_2$ data. Each single breath was calculated for $\dot{V}O_2$ and RER as previously described and divided by 60 to get E_{exp} in seconds times the duration of the breath. Thereafter the sum of every breath's kcal was calculated to get the total kcal for each separate drill.

Blood Lactate

Capillary blood lactate was collected from fingers on the non-dominant hand. A resting blood lactate was collected before Drill1. Thereafter, collection of capillary blood samples was performed after the completion of each drill. The finger was first wiped with antiseptic solution (Klorhexidin, Fresenius Kabi AB, Uppsala) thereafter capillary blood was sampled using a capillary tube (20 µl) that was dissolved in pre-filled Safe-Lock reaction cup. The pre-filled Safe-Lock cups were then placed in an analyser (Biosen C-line, EKF diagnostic GmhB, Magdeburg, Germany) for blood lactate determination.

Borg Scale

After completion of all four drills, the players rated their subjective exertion using the 6–20 Rating of Perceived Exertion scale (RPE) and were asked to differentiate between overall, legs and arms RPE (Borg, 1990).

FIGURE 1 | Picture of the calibrated measuring volume with the majority of the motion capture cameras visible.

Biomechanical Measurements

All tennis players used their own individual equipment. The male players wore only tight-fitting shorts and the female players, tight fitting shorts, and a sports bra to be able to attach soft reflective markers directly on the skin. Each marker had a diameter of 15 mm and was attached by double-sided tape and additionally fixed with tape around the base to avoid movement of the markers. Markers were placed on the left and right ASIS (Anterior Superior Iliac Spine), the left and right PSIS (Posterior Superior Iliac Spine) and five markers were attached to the racket. The ASIS and PSIS markers were used to define the movement of the pelvis and the markers on the racket were used to detect and define each shot.

Kinematic data were collected within a volume 14 × 13 × 5 m by 12 Qualisys Uqus 7+ cameras (Qualisys AB, Gothenburg, Sweden) at 300 Hz and with a resolution of 12 mega pixels, **Figure 1**. All cameras were places on high tripods around the tennis court, well outside of the sidelines and away from the ball trajectories. The measurement volume was calibrated with a hand-held T-wand, consisting of two reflective markers at each end, with a known distance between them. The orientation of the coordinate system was performed by placing an L-frame at the decided origin which was at the T-point of the baseline. The mean residual for all cameras was 1.4 mm, $SD = 0.3$ mm.

The distance covered by each player per drill, was defined as the horizontal trajectory of the center of mass (COM) in the xy-plane. The position of the center of mass was defined as the center of the pelvis and calculated as the virtual center point of the left and right reflective markers on the ASIS and PSIS. The start of a drill was defined as the first movement of the COM and the end of a drill was defined as the end phase of last shot of the drill. All analyses were performed in Qualisys Track Manager 2019.2 (Qualisys AB, Gothenburg, Sweden), Matlab R2017a (The MathWorks Inc., Natick, MA, USA), and Microsoft Excel (Microsoft Corp. Inc., Redmond, WA, USA).

Statistical Analysis

All data were checked for normal distribution with Shapiro Wilks test before further analysis. Data were analyzed with SPSS (IBM Corp. Released 2017. IBM SPSS Statistics for Windows, Version 25.0. Armonk, NY: IBM Corp) and jamovi (The jamovi project, 2020). Physiological data were analyzed using a two-way factorial ANOVA with repeated measures. For all ANOVA, Mauchly's sphericity test of the data was checked to control for type one errors and if violated the Green House Geisser correct F values were used. If there were global significances for the ANOVA a further Bonferroni *post hoc* analysis was performed. Partial eta squared ($_{\rho}\eta^2$) was used for effect size for the ANOVA. RPE scale outcomes were evaluated with Friedman's test. A Durbin Conover test was applied if the Friedman's test was significant to make pair wise comparisons. All data are presented as mean and ± standard deviation while RPE scale is presented as median and interquartile range (IQR). The α level was set as 0.05 in priori.

TABLE 2 | Percentage of time spent in different running speed ranges.

	Drill1	Drill2	Drill3	Drill4
Speed Range				
$0 \leq 1$ m·s^{-1}	15 ± 2%	14 ± 4%	11 ± 3%	13 ± 2%
$1 \leq 2$ m·s^{-1}	27 ± 5%	30 ± 9%	25 ± 3%	26 ± 6%
$2 \leq 3$ m·s^{-1}	35 ± 3%	42 ± 3%	27 ± 2%	34 ± 5%
$3 \leq 4$ m·s^{-1}	18 ± 4%	15 ± 7%	27 ± 3%	22 ± 5%
> 4 m·s^{-1}	4 ± 2%	1 ± 1%	10 ± 4%	5 ± 4%

RESULTS

The average covered distances were 31 ± 4, 19 ± 3, 27 ± 2, and 25 ± 6 m, the durations were 14.6 ± 1.4, 9.6 ± 0.9, 10.8 ± 0.5, and 11.3 ± 1.9 s and the mean running speeds were 2.1 ± 0.1, 2.0 ± 0.2, 2.5 ± 0.1, and 2.2 ± 0.1 m·s^{-1} for drill one, two, three, and four, respectively. The percentage spent in different ranges of running speeds for the different drills are presented in **Table 2**.

Pre-test Physiological Variables

$\dot{V}O_{2max}$ for women and men was in absolute values 3.43 ± 0.33 vs. 4.22 ± 0.58 l·min^{-1} ($p = 0.03$, 95% CI−1.5 to −1.0), and in relative values 50 ± 6 vs. 58 ± 3 ml·kg^{-1}·min^{-1} ($p = 0.03$, 95% CI−14.0 to −1.1). Maximum HR was for women and men 196 ± 5 vs. 202 ± 4 beats·min^{-1} ($p > 0.05$, 95% CI−12.4 to 0.2) while maximum lactate 12.2 ± 1.6 vs. 12.0 ± 0.7 mmol·l^{-1} ($p > 0.05$, 95% CI−1.6 to 1.9).

Physiological Variables During On-Court Drills

$\dot{V}O_2$ was highest for the first drill both in absolute values and in relative values (**Table 3**). The men showed higher absolute $\dot{V}O_2$ values (l·min^{-1}) compared to women for all drills, but in relative numbers as fractional utilization (percent of $\dot{V}O_{2max}$) there were no differences between sexes. The relative $\dot{V}O_2$ (ml·kg^{-1}min^{-1}) was the greatest at Drill 1 compared to all drills for both women and men while not statistically significant between sexes [$F_{(1,8)} = 0.052$] the effect size indicated a moderate difference ($_{\rho}\eta^2 = 0.395$). There were no differences in heart rate between drills nor between sexes (**Table 3**). Resting blood lactate concentration before the start of the drills were 1.5 ± 0.2 and 1.6 ± 0.2 mmol·l^{-1}

TABLE 3 | Physiological variables during the on court tennis drills.

	Drill1	Drill2	Drill3	Drill4	*F*-values, *P*-values and effect size
Mean VO_2 ($l \cdot min^{-1}$)					
Women	2.8 ± 0.4$^{\#\dagger}$	2.7 ± 0.4$^{*\#}$	2.6 ± 0.5$^{*\#}$	2.6 ± 0.4*†	$^{a}F_{3,24} = 12.6$, $p < 0.001$, $_{\rho}\eta^2 = 0.612$
Men	3.4 ± 0.3$^{\#\dagger}$	3.2 ± 0.4$^{*\#}$	3.3 ± 0.4$^{*\#}$	3.0 ± 0.3*†	$^{b}F_{3,24} = 1.3$, $p = 0.291$, $_{\rho}\eta^2 = 0.141$
Mean VO_2 ($ml \cdot kg^{-1} \cdot min^{-1}$)					
Women	41 ± 4$^{\#\dagger}$	39 ± 4*	38 ± 5*	37 ± 5*	$^{a}F_{3,24} = 13.1$, $p < 0.001$, $_{\rho}\eta^2 = 0.620$
Men	47 ± 4$^{\#\dagger}$	44 ± 3*	45 ± 3*	42 ± 4*	$^{b}F_{3,24} = 1.3$, $p = 0.296$, $_{\rho}\eta^2 = 0.140$
Percent of VO_{2max}					
Women	82 ± 7$^{\#\dagger}$	79 ± 7*	77 ± 10*	75 ± 7*	$^{a}F_{3,24} = 12.7$, $p < 0.001$, $_{\rho}\eta^2 = 0.613$
Men	81 ± 4$^{\#\dagger}$	75 ± 3*	77 ± 3*	72 ± 5*	$^{b}F_{3,24} = 1.0$, $p = 0.406$, $_{\rho}\eta^2 = 0.112$
Percent of HR_{max}					
Women	94 ± 4	94 ± 3	95 ± 3	93 ± 3	$^{a}F_{3,24} = 2.4$, $p = 0.11$, $_{\rho}\eta^2 = 0.323$
Men	91 ± 2	89 ± 4	91 ± 3	91 ± 3	$^{b}F_{3,24} = 1.4$, $p = 0.278$, $_{\rho}\eta^2 = 0.220$
Blood Lactate ($mmol \cdot l^{-1}$)					
Women	5.9 ± 2.4†	5.1 ± 2.0*	6.0 ± 2.2†	5.3 ± 2.1	$^{a}F_{3,24} = 6.1$, $p < 0.01$, $_{\rho}\eta^2 = 0.441$
Men	5.8 ± 1.8†	4.8 ± 1.9*	5.3 ± 1.8†	4.7 ± 2.4	$^{b}F_{3,24} = 0.8$, $p = 0.503$, $_{\rho}\eta^2 = 0.092$

A factorial ANOVA for repeated measurement was used to compare drills and sex with a Bonferroni post-hoc test.
[a] *Factorial ANOVA for repeated measurement of drills (4).*
[b] *Interaction effect between drills and sex (4 × 2).*
[*] *Statistically different from Drill1.*
[†] *Statistically different from Drill2.*
[#] *Statistically different from Drill4.*

respectively for women and men ($p > 0.05$). Blood lactate concentration was above 4.0 $mmol \cdot l^{-1}$ throughout all drills but with a variation between drills while no interaction effect for sexes (**Table 3**). Drill1 had the greatest energy expenditure compared to Drill2 (95% CI = 6.1, 24.1; $p = 0.002$) and Drill4 (95% CI = 19.0, 36.2; $p < 0.001$) but no significant difference compared to Drill3 (CI 95% = −0.7, 23.7; $p = 0.067$. There was no interaction between drill and sex for energy expenditure [$F_{(3,24)} = 0.42$, $p < 0.739$, $_{\rho}\eta^2 = 0.05$]. Further no differences in total energy expenditure was observed for sex [$F_{(1,8)} = 3.3$, $p = 0.108$, $_{\rho}\eta^2 = 0.291$].

Energy Expenditure

The total energy expenditure (kcal) changed between drills 1–4 (**Figure 2A**). The Drill1 had the greatest energy expenditure compared to Drill2 (95% CI = 6.1, 24.1; $p = 0.002$), Drill4 (95% CI = 19.0, 36.2; $p < 0.001$), and almost to Drill3 (CI 95% = −0.7, 23.7; $p = 0.067$. There was no interaction between drill and sex for energy expenditure [$F_{(3,24)} = 0.42$, $p < 0.739$, $_{\rho}\eta^2 = 0.05$] and no differences in total energy expenditure between sexes [$F_{(1,8)} = 3.3$, $p = 0.108$, $_{\rho}\eta^2 = 0.291$]. There was a difference in energy expenditure per meter ($J \cdot kg^{-1} \cdot min^{-1}$) between drills 1–4 (**Figure 2B**). The first drill had the greatest energy expenditure compared to Drill3 (95% CI = 1.6, 4.2; $p < 0.001$), Drill4 (95% CI = 1.4, 3.5; $p < 0.001$) while equal energy expenditure to Drill2 (CI 95% = −0.9, 2.1; $p = 0.199$. There was no interaction between drill and sex for energy expenditure [$F_{(3,24)} = 1.09$, $p < 0.370$, $_{\rho}\eta^2 = 0.258$] and no differences in total energy expenditure was evident between sexes [$F_{(1,8)} = 1.8$, $p = 0.212$, $_{\rho}\eta^2 = 0.224$].

RPE Scale

RPE differed between overall, leg and arm ($\chi^2_2 = 18.0, p < 0.001$) with RPE overall median of 17.5 (IQR = 16.0 – 18.0), RPE leg median of 15.5 (IQR = 13.5 – 16.8), and RPE arm median 13.0 (IQR = 11.5 – 13.0). The RPE overall was greater than RPE leg and RPE arm ($p < 0.001$ for both RPE leg and arm) with RPE arm being the lowest of all ($p < 0.001$ for both RPE overall and leg) (**Figure 3**). RPE between women or men did not differ for either overall, leg or arm.

DISCUSSION

This is the first study that has analyzed the energy expenditure for on-court tennis drills for both total and energy cost per distance. The current study shows that the energy expenditure per distance is exceptionally high for on-court tennis drills and is two to three times greater than linear sports (e.g., running), which substantiate the importance to enhance work economy for tennis players. Additionally, the O_2 demand for the drills used are comparable to previous studies, investigating on-court tennis drills, but in the upper range of previously reported $\dot{V}O_2$ ($\geq$ 40 $ml \cdot kg^{-1} \cdot min^{-1}$). This indicates that the used on-court tennis drills are well-suited for tennis specific high intensity interval training. However, the elevated total energy expenditure per drill suggests that sessions using these drills should be shorter to be able to play with a high technical skill.

Oxygen Uptake and Energy Expenditure

There are numerous studies that have investigated $\dot{V}O_2$ and distance covered, during both simulated match play and various

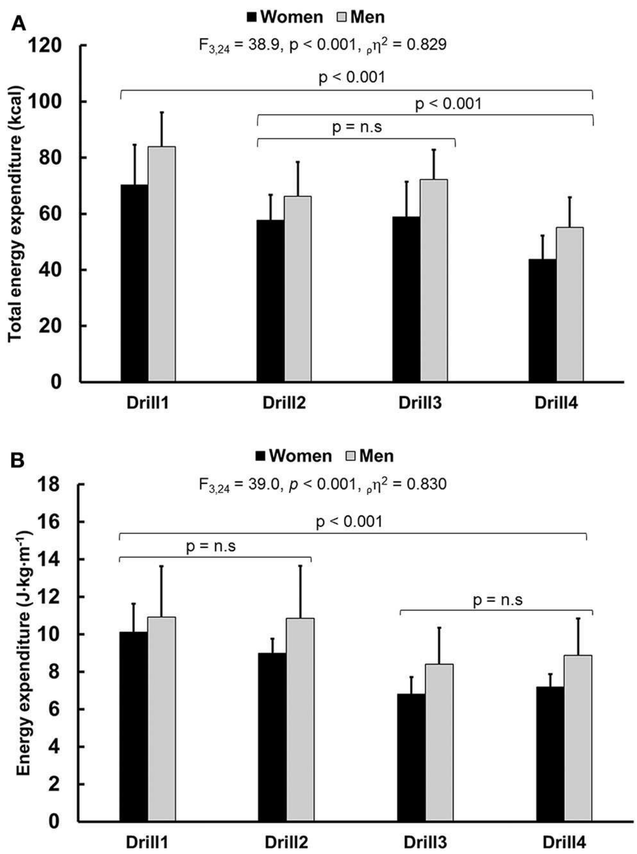

FIGURE 2 | (A) Total energy expenditure (kcal) for Drill1-Drill4. **(B)** Energy expenditure per meter for Drill1-4 expressed as joules relative to body weight per meter (J·kg^{-1}·m^{-1}). Women and men are illustrated using black and gray bars respectively. The *F*-, *P*-values, effect size ($_p\eta^2$) and power values obtained with a two-way ANOVA (Drill × Sex). Non-significant results are presented using n.s. The values given are mean ± *SD*.

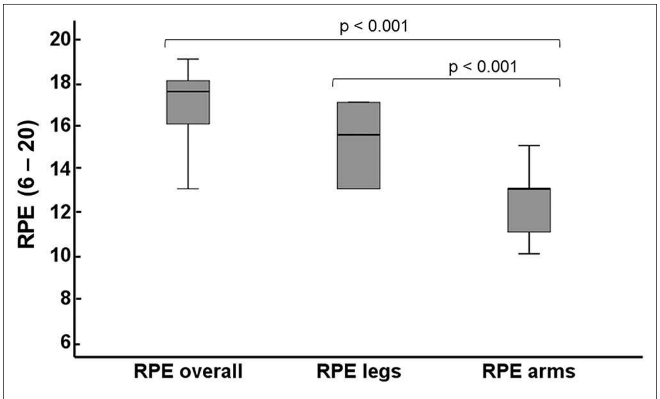

FIGURE 3 | Rate of Perceived Exertion (RPE) for overall, legs and arms. The values given are median and interquartile range (IQR).

on-court tennis drills (Smekal et al., 2001; Novas et al., 2003; Reid et al., 2008; Fernandez-Fernandez et al., 2009). However, this is the first study that has combined both methods for calculating energy expenditure per m. While the average $\dot{V}O_2$ during simulated tennis matches is mostly within a range of 50 – 60% of $\dot{V}O_{2max}$, the present study observed a significantly greater O_2 uptake. The greater average $\dot{V}O_2$ for the drills used in the study is close to 80% of fractional utilization of $\dot{V}O_{2max}$. However compared to other studies using on-court tennis drills, such high utilization of $\dot{V}O_{2max}$ are also reported in longer drills used by Gomes et al. (2016). The explanation clearly seems to be associated to both an increase in number of strokes as well as duration of the drills. These longer drills in the study by Gomes et al. (2016) resembles current study in number of strokes per drill, 7–10 vs. 6–8 as well as length, 14–20 vs. 10–15 s. This indicates the impact of number of strokes as well of the duration of the drills on the increase in O_2 uptake. Although the increase in strokes per minute and an elevated O_2 uptake has been reported previously (Cooke and Davey, 2008; Botton et al., 2011) it was suggested that the limb acceleration is a key factor in this association. While running speed is considered to be of less importance for an greater O_2 demand during ground strokes in tennis (Cooke and Davey, 2008), change of direction should not be overlooked. Studies investigating the cost of turning 180 degrees while running showed that change of direction is a major factor that increases the energy expenditure per distance (Hatamoto et al., 2014; Ciprandi et al., 2018). The reason why such a discrepancy could be the result of the use of O_2 per minute and the energy expenditure per distance. Although there are some studies (Botton et al., 2011; Bekraoui et al., 2012) that have used energy expenditure as definition, they have calculated O_2 uptake, which is not equal to energy expenditure expressed as joules or calories (Shaw et al., 2014). Novas et al. (2003) did calculate energy expenditure during tennis play but did not include respiratory exchange ratio and hence excluded variation in substrate utilization (Shaw et al., 2014). Based on the current study, the average O_2 uptake increases with roughly 20–30% while the energy expenditure per distance increases two to three times compared to level running (Fletcher et al., 2009). Interestingly, as shown by Ciprandi et al. (2018), the change of direction resulted in twice as high energy expenditure per distance, this is similar to the results of the present study. Although previous studies have shown that the O_2 uptake increases with strokes per minute (Cooke and Davey, 2008; Botton et al., 2011), the situation with repeated directional changes is also likely to be a major contributor to the increased O_2 uptake in the present study. Nevertheless, the present study shows that the use of on-court drills, $\dot{V}O_2$ is greater than the average fractional utilization of $\dot{V}O_2$ during simulated tennis play. This indicates that these drills would be of great use for tennis specific high intensity training. Moreover, to estimate and understand work economy of on-court tennis play, energy expenditure per distance should be the preferred method over $\dot{V}O_2$. It is also noteworthy that the total energy expenditure is alike in Drill2 and Drill3. However, even though that the mean running speed is higher in Drill3, the energy expenditure per meter is lower in Drill3 as the covered distance in Drill2 is lower. This suggests that the movement pattern is less efficient since players are moving latterly from side to side. Hence, the use of the forehand on the backhand side is more energy demanding which is worth to consider in training as well as during match play to reserve energy, if needed. Similar inference can be made between drill one and four, where drill four consisted of a combination of the other three drills. Hence, the combination of different drills and movement patterns allow the players to move more efficiently at similar speeds.

Heart Rate and RPE

Heart rate remained at ∼90% of max between drills whereas the O_2 cost varied. The inability of heart rate to mirror O_2 uptake is not a new phenomenon during field settings versus laboratory estimations (Crisafulli et al., 2006). More specifically previous studies confirm this finding during tennis play were average heart rate overestimates the energy expenditure compared with $\dot{V}O_2$ measurements with around 20% (Novas et al., 2003). Due to the similar heart rate between drills in current study, heart rate estimations for energy expenditure would have incorrectly been equal in kcal. The most erroneous drill would have been the last one for energy expenditure calculations with the greatest overestimation. However, the use of heart rate seems adequate for internal load, but one should be cautious to make assumptions of precise energy expenditure calculations during tennis play. RPE has been used in many previous studies in tennis (Novas et al., 2003; Mendez-Villanueva et al., 2010). However, the differentiation of RPE for overall, legs and arms has rarely been used as in current study. As shown in current study the legs seem most affected by the drills compared to the arms. This is probably not surprising as and effective movement pattern on-court is decisive for effective tennis play.

Lactate

While previous studies from simulated tennis matches show rather low blood lactate, concentrations of ∼1.4–4.0 mmol·l^{-1} (Fernandez et al., 2006). Such low values are understandably due to the short rallies with a longer rest. Additionally the time spent above the second ventilator threshold during tennis matches is minimal with <5% (Baiget et al., 2015). The current protocols were performed at a clearly elevated blood lactate concentration (∼6.0 mmol·l^{-1}) compared to tennis match but similar to other on-court drills using similar amount of strokes and rally durations (Gomes et al., 2016). Although the increased lactate response seems to be influenced by the type of drill the most important factor still seems to be rally duration (Reid et al., 2008). Altogether, the drills used in current study clearly stress the anaerobic glycolytic pathways.

On-Court Distance

Previous studies report the average on-court distance to be 2,000–3,200 and 1,200–1,400 m per match, for men and women respectively (Reid et al., 2016; Cui et al., 2017; Pereira et al., 2017; Whiteside and Reid, 2017). The average distance per rally is reported to be 5–11 m with a duration of 5–12 s, which is shorter compared to the drills in the present study (Murias et al., 2007; Reid et al., 2016; Fenter et al., 2017; Pereira et al., 2017). The majority of running in tennis is performed at speeds of 1–4 m·s^{-1}, for both men and women with shorter periods of faster sprints above 3.5 m·s^{-1}, which is similar to the four drills in the present study (Martínez-Gallego et al., 2013; Reid et al., 2016; Pereira et al., 2017; Whiteside and Reid, 2017). However, these were obtained from adult professional tennis players and it is plausible that the data are different for adolescent players, as in our study. Based on 10 Hz GPS data, Hoppe et al. (2014) report a total running distance of 3,362 ± 869 m, with the most occurring running speed of 1–2 m·s^{-1} for adolescent tennis players during simulated matches. They do not present any data for running speeds or distances per rally or game. Still, this running speed is lower compared to the total average speed in the drills in the current study (2–2.5 m·s^{-1}) which might be because Hoppe et al. (2014) included the walking between each rally whereas our results only include the actual rallies. Another feasible explanation is the use of 10 Hz GPS data, as the accuracy of such a system in tennis is debatable as these systems have been shown to only provide acceptable validity and repeatability for straight running and other team sport specific movements which differ compared to on-court tennis movements (Varley et al., 2012; Galé-Ansodi et al., 2016). Furthermore, Vickery et al. (2014) compared 10 Hz GPS data and 3D motion capture data during tennis play and found that the distance measured using a 10 Hz GPS device differed 13% compared to the 3D motion capture data. Hence, the use of a motion capture system to analyse on-court tennis movements is essential for scientific studies in which the highest accuracy, validity, and repeatability are necessary. The current study, as well as other studies (Vickery et al., 2014; Charbonnier et al., 2015; Fenter et al., 2017) used motion capture systems on-court movements in tennis during field measurements. Hence, in contrary to the statement by Hoppe et al. (2014), motion capture systems can without impracticability, be used for scientific field measurements in tennis. In the current study, the mean residual for all 12 cameras was 1.4 ± 0.3 mm, which vouches for high accuracy and repeatability.

Limitations

Tennis is an intermittent sport which makes it difficult to use steady state intensities for estimations of energy estimations. However, the use of are under the curve with a breath-by-breath system was the most valid way to quantify the total energy expenditure. The use of Weir equation could underestimate the energy expenditure to a minor degree (Kipp et al., 2018). However, the Weir equation is robust for relative changed between drills. Ciprandi et al. (2018) stressed the importance of alactacid processes and RER into considerations during exercise with change of directions. The present study is the first that considers RER for on-court tennis play. Nevertheless, Ciprandi et al. (2018) suggested that roughly between 0.4 and 1.0 J·kg^{-1}·m^{-1} is added by alactacid processes when a maximal velocity close to 75% is used during exercise with change of direction. The high blood lactate concentration in the current study indicate that such numbers likely should be added but the low RER values do not. It can also be argued that that the repeatability of the drills could be increased with the use of a ball machine. However, the players move differently between each stroke, which requires individually timed throws. Still, the standard deviations for the distances and times for all drills indicate a high consistency and repeatability that most likely would have been difficult to surpass with a ball machine.

CONCLUSIONS AND PRACTICAL APPLICATIONS

The high energy expenditure during the four different drills indicates that players need to be well prepared to handle the substantial physiological demands of each drill. Furthermore, the overall high demands of $\dot{V}O_{2max}$ and anaerobic power presented in our study indicates the importance of high intensity training on- and off-court to improve aerobic fitness and anaerobic power becomes crucial to withstand central and local fatigue. The high energy expenditure is plausibly caused by the multiple changes of direction in combination with a high stroke frequency. Hence, high intensity training on-court to enhance fatigue resistance whilst maintaining stroke mechanics must be emphasized. It is also shown that these high intensity drills do have different energy expenditure that are independent of covered distance or time duration. This knowledge should be considered when planning training sessions and exercises, suggesting that the length of the drills could be modified to further challenge movement skills in combination with technical skills.

DATA AVAILABILITY STATEMENT

The datasets generated for this study are available on request to the corresponding author.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Regional Ethical Review Board, Stockholm, Sweden (approval no. 2012/1731/2). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

GB, MS, MN, and FJ designed the study. GB, MS, JA, and FJ performed the experiment, analyzed the data, and prepared the manuscript. All authors read and approved the final manuscript. All authors contributed to the article and approved the submitted version.

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Eccentric and Isometric Shoulder Rotation Strength and Range of Motion: Normative Values for Adolescent Competitive Tennis Players

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The aim of this cross-sectional study was to investigate isometric internal rotation (IR), external rotation (ER), abduction (ABD), and eccentric external rotation (eccER) shoulder strength and rotational range of motion (ROM) in adolescent male and female competitive tennis players. Additional aims of the study were to provide a tennis-specific normative database based on a large sample of players to deepen the knowledge regarding shoulder strength and ROM for adolescent competitive tennis players, and to discuss differences based on sex, age, and level of play. Shoulder strength and ROM was assessed in 301 adolescent competitive tennis players, 176 boys and 125 girls with a mean age of 14.6 and 14.4 years, respectively. Outcome variables of interest were isometric IR and ER strength, ABD strength, eccER shoulder strength, intermuscular strength ratios ER/IR and eccER/IR, IR ROM, ER ROM, and total range of motion (TROM). A General Linear Model two-way ANOVA was used to analyze differences in sex, age, and level of play. The findings of this study demonstrated age, side, and sex differences in the shoulder isometric strength, the eccER strength and ROM in adolescent competitive tennis players. Furthermore, when strength was expressed as ratios ER/IR and eccER/IR both sexes showed a lower ratio for eccER/IR in national players (0.95 ± 0.22 and 0.95 ± 0.23) compared to regional players (1.01 ± 0.32 and 1.07 ± 0.29) for male and female players, respectively. In conclusion, this paper presents a tennis-specific normative database for shoulder rotation strength and ROM in adolescent male and female competitive players. The key points in this evaluation are strength values normalized to body mass, intermuscular ratios, and TROM.

Keywords: shoulder, hand-held dynamometry, tennis, adolescent, normative database, range of motion, strength

INTRODUCTION

Tennis is an intermittent sport in which players need to master a range of demands of physical components, such as aerobic and anaerobic capacity, linear sprint and change-of-direction speed, agility, and muscle power to reach the highest levels of performance (Fernandez-Fernandez et al., 2018; Björklund et al., 2020). Furthermore, male and female professional tennis players perform the serve motion to a larger extent compared with their younger counterparts (i.e., high performance junior players) (Myers et al., 2016). At high-performance junior levels, players perform per match an average of 60–70 serves at a speed range from 145 to 160 kph (Kovalchik and Reid, 2017). From a biomechanical point of view the shoulder moves into an external rotation (ER) of 170 degrees in the late cocking phase, followed by a shoulder internal rotation (IR) taking place after ball impact at 2,420 and 1,370°/s for male and female players, respectively (Fleisig et al., 2003). In addition, a strong positive correlation between peak serve speed and shoulder IR and ER strength has been shown (Hayes et al., 2021), highlighting the link between good shoulder capacity and sport-specific performance. The competitive adolescent tennis player has previously been reported to have age related increase in shoulder strength, decreased rotational range of motion (ROM) in IR, increased ER ROM, and decreased total ROM (TROM) in the dominant arm (DA) used for the overhead serve motion, parallel to the growth process (Cools et al., 2014b; Gillet et al., 2017; Fernandez-Fernandez et al., 2019).

Investigations of adolescent tennis players competing on the highest level have reported injury rates of 1.2–2.8 injuries per 1,000 h played (Pluim et al., 2016; Gescheit et al., 2019; Moreno-Pérez et al., 2019) and amongst these injury rates, overuse injuries have been reported to be the most common health complaint among junior tennis players with a weekly prevalence of 12.1%, compared to acute injuries with a weekly prevalence of 3% (Pluim et al., 2016). Moreover, a considerable proportion of these overuse injuries are in the dominant shoulder, with an incidence of 8.2 injuries per 1,000 playing hours in tennis matches, accounting for 15.9% of all overuse injuries in high-performance junior tennis players (Pluim et al., 2006; Fu et al., 2018).

Factors of importance for the origin of injury in overhead athletes such as handball and tennis players, and across all age groups have been reported to be, imbalances in terms of low intermuscular ratios between ER/IR strength, ER weakness, decreased IR ROM and decreased TROM of the shoulder (Saccol et al., 2010; Andersson et al., 2017; Achenbach and Luig, 2020; Asker et al., 2020).

Since adolescent athletes are not yet fully developed, and early onset of adaptations occur, continuous assessments at shoulder level throughout puberty are crucial for the guidance and optimization of the tennis players training regime (Oliver et al., 2020). In view of clinical assessment, field-friendly measurement tools which are reliable, valid, and cost-effective like the hand-held dynamometer (HHD) and smartphone inclinometer have been proposed (Cools et al., 2014b; Mejia-Hernandez et al., 2018). Furthermore, a recent meta-analysis showed good absolute reliability for HHDs in shoulder internal and external rotator strength assessment reinforcing previous studies (Chamorro et al., 2021). Previously, a general reference database based on HHD measurements for tennis players has been published, however, the study sample was relatively small ($n = 65$), the players were 18–50 years old, and a recreational playing level constituted the subjects represented (Cools et al., 2016).

Therefore, the primary aim with our study is to provide normative values at shoulder level for isometric and eccentricER (eccER) strength, intermuscular ratios ER/IR, and rotational ROM for the adolescent competitive tennis player. In addition, we hypothesized that sex, age, side, and level of play differences would exist between test values.

MATERIALS AND METHODS

Participants

Three hundred and one adolescent competitive tennis players, 176 males and 125 females, mean age 14.6 (±2.0) and 14.4 (±2.0) years, respectively, volunteered to participate in the study. Recruitment of the players was performed via all seven tennis regions in Sweden and included both national ($n = 50$) and regional ($n = 251$) level players. A baseline questionnaire was filled out before the testing and an informed consent form was read and signed by the players, if under 15 years of age, the players' legal guardian read and signed the consent form. Inclusion criteria were (1) competitive level of at least regional level in Sweden (2) minimum of 8 h of total training volume per week on average. Subjects were excluded if they had shoulder surgery or dislocation the last 6 months. Subclassification of the tennis players was made based on sex, age, and level of play. Classification for age was divided into (a) 14 years and under and (b) 15 years and over, in accordance with the competing system of Tennis Europe and the International Tennis Federation[1,2] In addition, level of play was divided into regional and national level based on the high-performance program conducted by the Swedish Tennis Association[3].

Ethical Statement

The study was in accordance with the declaration of Helsinki and preapproved by the Regional Ethical Review Board, Stockholm, Sweden (approval no. 2012/1731/2).

Testing Procedure

Prior to the testing procedure, the players body mass was assessed on a digital scale, shoes and heavy clothing were removed and the result was recorded to the nearest decimal fraction. A supervised and standardized warm-up program for 10 min was performed, consisting of several multiplanar shoulder movements including three light elastic band exercises performed 2 sets x 15 repetitions/side and two general flexibility exercises for the thoracic spine and the upper limb was performed 2 sets x 10 repetitions/side by the players prior to the testing. The assessments consisting of both strength and mobility in

[1]https://www.itftennis.com/en/itf-tours/world-tennis-tour-juniors/
[2]https://www.tenniseurope.org/page/12174/Official-Events
[3]https://www.tennis.se/elit-och-landslag/juniorlandslag/

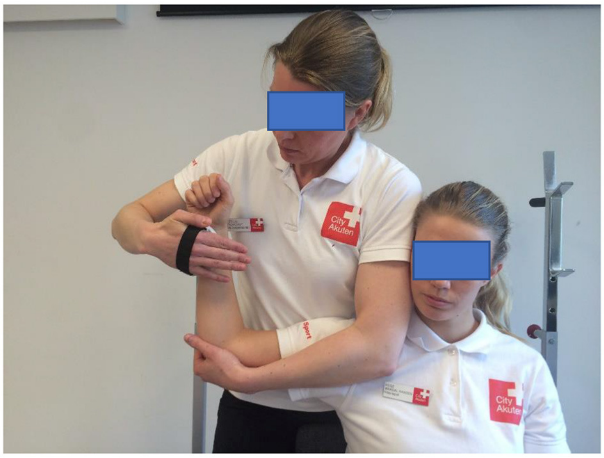

FIGURE 1 | Measurement of isometric muscle strength of the internal rotators using a hand-held dynamometer (CompuFET, Hoggan Health Industries Inc., Groningen, The Netherlands).

FIGURE 2 | Measurement of isometric muscle strength of the external rotators and starting position for eccentric strength measurement using a hand-held dynamometer (CompuFET, Hoggan Health Industries Inc., Groningen, The Netherlands).

a standardized field-based setting were performed on a single visit by three teams of three assessors per team, all teams were trained prior to the testing by an experienced clinician and user of the HHD.

Glenohumeral Muscle Strength

For all strength measurements, the MicroFET© HHD was used (MicroFet 2, Hoggan Health Industries Inc., Biometrics, The Netherlands). To control the testing procedure for learning effects and fatigue, the order of the tests was randomized between sides. The protocol consisting of six different strength tests were performed in both the DA and non-dominant arm (NDA) independently: (1 and 2) isometric shoulder strength of IR and ER at shoulder level with 0° of abduction (ABD), (3 and 4) isometric shoulder strength of IR and ER in 90° ABD, (5) isometric shoulder strength of ABD in the scapular plane, (6) eccER shoulder strength testing in an abducted position from 90° of ER to 0° of ER were included (Clarsen et al., 2014; Cools et al., 2014a). Strength measurements were recorded in Newton (N) by the HHD, and the second examiner registered the test value into the test-protocol. Each test was repeated two times with a pause in between trials of 20 s (Cools et al., 2014a).

Isometric IR and ER testing took place in a seated position, the arm was supported in shoulder position at 90° of ABD and neutral rotation (illustrative **Figures 1**, **2**) (Cools et al., 2014a). Isometric ABD was measured with the player in a standing position with the arm held 30° of ABD in the scapular plane (Clarsen et al., 2014). For all strength tests the participants were asked to build up their force gradually to a maximum voluntary effort over a 2-s period and hold the maximal voluntary effort for 5 s, two sets of trials were performed, and the average value was used for calculation.

The eccER shoulder strength testing was performed in a seated position, starting in 90° of ABD and 90° of ER, with the arm supported by the examiner, the HHD was positioned 2 cm proximal of the processus styloideus ulnae and placed on the dorsal side of the forearm (Johansson et al., 2015b). The participant performed a resisted ER, and the examiner moved the arm into IR for 90° in 3 s (illustrative **Figure 2**).

All testing procedures described above demonstrated good to excellent intra- and inter-rater reliability (Cools et al., 2014a; Johansson et al., 2015b).

Glenohumeral Internal- and External Rotation Range of Motion

Shoulder IR and ER passive ROMs were measured for the dominant and non-dominant shoulder using a smartphone inclinometer app, GetMyROM (version 1.0.3; Interactive Medical Productions, Hampton, NH, USA) and following the methods previously described in the literature (Mejia-Hernandez et al., 2018). Participants were supine with their shoulders positioned in 90° of ABD in the coronal plane. Measurements for IR and ER ROM were performed in the plane of ABD, and a small towel roll was used to maintain the position of the humerus. The inclinometer was positioned on the player's forearm (illustrative **Figure 3**). Two examiners performed the test, examiner one took the shoulder to full ROM without using overpressure, scapular movement was controlled by palpating the coracoid process, examiner two read and noted the ROM in IR and ER. These procedures have previously shown good test-retest reliability (Cools et al., 2014b), and excellent intra- and interrater reliability (Cools et al., 2014b).

Statistical Analysis

To analyze the difference in isometric and eccentric strength and the intermuscular ratios a general linear model two-way analysis of variance (ANOVA) for repeated measures, in which the within-subject factor was side (two levels), and the between-subject factors were sex (two levels), level of play (three levels),

FIGURE 3 | Measurement of glenohumeral internal-rotation range of motion using a smartphone inclinometer application (GetMyROM (version 1.0.3; Interactive Medical Productions, Hampton, NH, USA).

and age category (three levels). The eccentric and isometric strength measurements were analyzed both in Newton and as normalized by body mass. The following isometric muscle strength ratios were also calculated: ER/IR at 0–0° and 90–90° and the functional ratio eccER/isometric IR. For mean calculations and ratios between different measurements, the individual measurements were treated separately and no mean values of the two measurements per individual were used.

To assess the reliability of the strength measurements, the Intraclass correlation coefficients (ICC) (3.1), two-way mixed model, agreement) were calculated, along with their 95% confidence intervals, over the two measurements taken. Standard error of measurement (SEM) was calculated as $SD^*\sqrt{}$ (1- ICC), where SD is the standard deviation of the measurement. Minimum detectable change (MDC95) was calculated as $SEM^*1.96^*\sqrt{}2$.

Interaction effects, as well as main effects were explored. In case of absence of any significant interactions, main effects for (age, side, sex, and level of play) were analyzed. In the ANOVA a $p < 0.05$ was considered statistically significant. *Post-hoc* analyses were performed using a Bonferroni test when a significant difference was found with ANOVA. For the ANOVA analysis, the mean value was taken of the two measurements done for each subject. In case of main effects for sex and side, no *post-hoc* tests were necessary.

TABLE 1 | Characteristic data of the tennis players in the study ($n = 301$).

	Female ($n = 125$)	**Male ($n = 176$)**
Age year, mean (SD)	14.4 (2.0)	14.6 (2.0)
Height cm, mean (SD)	165.2 (7.6)	173.0 (12.3)
Weight kg, mean (SD)	55.1 (9.6)	60.6 (14.1)
Number of players–Age range 14 and under (%)	74 (59)	94 (53)
Number of players–Age range 15 and over (%)	51 (41)	82 (47)
Level of Play–National squad (%)	28 (22)	22 (12.5)
Level of Play–Regional squad (%)	97 (78)	154 (87.5)
Total training h/week, National squad, mean (SD)	14.8 (5.3)	16.1 (3.7)
Total training h/week, Regional squad, mean (SD)	11.3 (5.5)	12.5 (4.2)

SD, standard deviation.
Total Training is the Sum of Tennis and Fitness but no other sports.

Analysis was done in R (version 3.6.1, R Core Team, 2019). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria) and Stata, version 15 (StataCorp. 2017. Stata Statistical Software: Release 15. College Station, TX: StataCorp LLC.).

RESULTS

Anthropometric data, training background and level of play are summarized in **Table 1**.

The results of the reliability study measurement are summarized in **Table 2**.

Supplementary Tables 1, **2** show the results of the isometric strength, eccentric strength, and ER/IR strength ratios and eccER/IR strength ratios testing for male and female players, respectively, and (a) across all ages, (b) divided by age, and (c) divided by level of play.

Tables 3, **4** display the rotational ROM results of male and female players, respectively, and (a) across all ages, (b) divided by age, and (c) divided by level of play. Summarized results for the ANOVA repeated measures statistical analysis and *post-hoc* tests, are displayed in **Table 5**. Furthermore, in **Appendix 1**, ROM, strength values and intermuscular ratios are presented for male and female players as percentiles and in **Appendix 2**, a comparison between male and female players shoulder strength are presented (Figures 4, 5 in **Appendix 2**).

Present results show significant differences for age and sex in all six strength tests. However, the three calculated intermuscular strength ratios based on the strength testing showed a lower ratio in the male players compared to the female players, most likely due to the strong internal rotators seen in male players. Overall, the reported test values of strength in the DA were higher than in the NDA, however, the NDA showed higher values of intermuscular ratios. Moreover, national level players are stronger than their regional counterparts with male players showing the largest difference. Male players increase their strength values with age but when normalized to body mass the

TABLE 2 | Intraexaminer reliability ($ICC_{3,k}$) with their 95% CI, SEM and MDC (N) for the range of motion, isometric, and eccentric strength testing of the rotator cuff.

Position	Dominant arm	SEM	MDC (*N*)	Non-dominant arm	SEM	MDC (*N*)
Passive max ROM IR	0.90 (0.87–0.92)	3.87	10.73	0.91 (0.89–0.93)	3.85	10.68
Passive max ROM ER	0.91 (0.89–0.93)	3.81	10.55	0.87 (0.84–0.90)	4.51	12.50
Isom IR 0–0	0.95 (0.94–0.96)	9.01	24.97	0.96 (0.95–0.97)	7.31	20.27
Isom ER 0–0	0.94 (0.93–0.95)	5.54	15.36	0.93 (0.91–0.95)	5.98	16.58
Isom IR 90–90	0.95 (0.93–0.96)	9.37	25.98	0.93 (0.90–0.95)	9.29	25.76
Isom ER 90-90	0.94 (0.92–0.95)	5.64	15.62	0.92 (0.90–0.94)	6.52	18.06
Ecc ER 90–90 to 90–0	0.94 (0.93–0.95)	7.58	21.01	0.92 (0.90–0.93)	8.95	24.80
Isom ABD 30°	0.95 (0.94–0.96)	6.78	18.80	0.94 (0.92–0.95)	7.29	20.22

ROM, range of motion; Max, maximal; ER, external rotation; IR, internal rotation; Ecc, eccentric; Isom, isometric; 0–0°, 0° abduction 0° external rotation, 90–90° 90° abduction 90° of external rotation (ABER); ABD, abduction; SEM, standard error of measurement; MDC, minimal detectable change; N, Newton.

TABLE 3 | Descriptive analysis (means and SDs) of the results of the Range of Motion (ROM) for the male ($n = 176$) subjects.

	ROM IR		ROM ER		Total ROM	
	D	ND	D	ND	D	ND
MALE						
(a) Across all ages						
Mean	57.2	65.4	98.4	91.3	155.6	156.7
SD	12.2	11.6	12.5	12.8	17.4	17.7
AGE						
(b) Divided per age category						
Under 14 years ($n = 94$)						
Mean	58.8	66.3	97.3	91.5	156.2	157.8
SD	11.8	10.2	12.5	12.5	16.1	16.7
Over 15 years ($n = 82$)						
Mean	55.4	64.5	99.6	91.1	155.0	155.5
SD	12.5	13.0	12.4	13.1	18.7	18.8
LEVEL OF PLAY						
(c) Divided per level of play						
National players ($n = 22$)						
Mean	56.8	63.2	102.5	97.0	159.3	160.2
SD	10.7	9.4	14.2	10.1	15.0	13.2
Regional Players ($n = 154$)						
Mean	57.3	65.7	97.8	90.5	155.1	156.2
SD	12.4	11.9	12.1	13.0	17.6	18.3

ER, external rotation; IR, internal rotation; ROM, range of motion; D, dominant; ND, non-dominant.

increase remains only in isometric ABD strength. In addition, male players are stronger than female players even when strength values are normalized to body mass. Female players increase their strength with age in absolute values but when normalized to body mass the strength results show a decrease. The eccER/isometric IR ratio revealed a decrease with increased age and national players reporting a lower ratio than regional players.

A two-way interaction effect was significant for age x sex and age x playing level for the six strength tests plus the intermuscular strength ratio: isometric ER/IR 0–0 and the eccER/isometric IR 90–90, reflecting that there are differences for age but not for both sexes/playing level or there are differences for sexes/playing level but not for different age groups.

Analysis for three-way interaction effects showed significant strength differences for side x age x playing level in isometric IR and ER at neutral position 0°- 0°. A 3-way interaction effect was also significant for sex x side x playing level regarding ER ROM. Neither of the 3-way interaction effects showed a significant difference in the *post-hoc* Bonferroni analysis. However, the two-way interaction effect, sex x age, remained significant in all strength tests in the *post-hoc* Bonferroni analysis. Lastly, the same significant outcome was noted for isometric IR strength at 0–0 and 90–90 position.

The ER ROM showed significant sex x side x playing level in the three-way interaction effect with male national players showing increased ER ROM in the DA compared to male regional

TABLE 4 | Descriptive analysis (means and SDs) of the results of the Range of Motion (ROM) for the female subjects (n = 125).

	ROM IR		ROM ER		Total ROM	
	D	**ND**	**D**	**ND**	**D**	**ND**
FEMALE						
(a) Across all ages						
Mean	61.5	71.5	98.5	93.5	160.0	165.0
SD	11.6	13.4	13.1	12.5	17.0	17.2
AEG						
(b) Divided per age category						
Under 14 years (n = 74)						
Mean	61.2	71.5	98.2	93.7	159.4	165.2
SD	11.1	13.9	12.2	12.3	16.4	17.6
Over 15 years (n = 51)						
Mean	62.0	71.5	98.8	93.3	160.9	164.8
SD	12.2	12.7	14.2	12.9	17.7	16.7
LEVEL OF PLAY						
(c) Divided per level of play						
National players (n = 28)						
Mean	60.3	70.7	99.4	97.3	159.7	168.0
SD	13.2	13.8	9.5	10.6	17.9	14.8
Regional Players (n = 97)						
Mean	61.9	71.7	98.2	92.4	160.1	164.2
SD	11.0	13.3	13.9	12.9	16.7	17.7

ER, external rotation; IR, internal rotation; ROM, range of motion; D, dominant; ND, non-dominant.

players as well as compared to all female players. Furthermore, the TROM and ER ROM displayed significant differences in the two-way interaction effect for sex x side, with the DA showing increased ER and decreased TROM for both male and female players. Finally, the side x playing level in the two-way interaction effect revealed a significant difference in the IR and TROM in both sexes. The *post-hoc* Bonferroni analysis confirmed the previous results in ROM presented in the two-way interaction effects for side x playing level regarding IR, and sex x side regarding TROM and ER.

DISCUSSION

The main purpose of the study was to establish normative values at shoulder level for isometric and eccentric strength, as well as rotational ROM for the adolescent competitive tennis player. The main results showed, age and sex differences in the isometric as well as the eccER shoulder strength in adolescent competitive tennis players. Secondly, the DA is stronger than the NDA and national players are stronger than their regional counterparts. Thirdly, age, sex, and playing level differences for the intermuscular strength ratio: isometric ER/IR 0–0 and the eccER/isometric IR 90–90 were seen. Finally, both male and female players showed a difference in IR ROM of the DA compared to the NDA, however, male national players revealed higher values in ER ROM in the DA compared to regional players.

Shoulder Rotational Strength

Present results showed that glenohumeral strength values were higher in male players compared with female players, which is in line with previous studies of young tennis players (Cools et al., 2014b; Gillet et al., 2017; Fernandez-Fernandez et al., 2019). Both male and female players are stronger in the dominant side when compared to the non-dominant side confirming the results of a previous study on adolescent tennis players (Cools et al., 2014b) and highlighting the asymmetric nature of the sport (Rogowski et al., 2008). The asymmetry may be a result of playing tennis rather than handedness (Rogowski et al., 2008). Several asymmetric findings in the dominant shoulder have been reported in literature, including both male and female players, adolescent, and professional players, reporting clinical infraspinatus atrophy, early signs of tendinosis in the infraspinatus and supraspinatus tendons, ROM deficits and increased strength in the dominant shoulder (Johansson et al., 2015a; Young et al., 2015; Gillet et al., 2017; Ellenbecker et al., 2020). Therefore, it seems inevitable to not be affected in the dominant shoulder by these high numbers of repetitions. However, if these adaptations are to be considered as normal adaptations, risk factors or to be entitled as maladaptation's needs further investigation. Regarding the development of strength levels, results for both sexes increase with age as seen in other studies (Cools et al., 2014b; Gillet et al., 2017; Fernandez-Fernandez et al., 2019). However, when normalized to body mass, our study shows that the strength values of the female players are leveling out comparing the age group 14 years and under with the age group 15 years plus, whilst male players still increase their relative strength throughout adolescence. In view of rapid anthropometry changes during puberty and the onset of hormones girls are more likely to have a tougher challenge to sustain their strength normalized to body mass

TABLE 5 | Results from the repeated measures ANOVA for all variables.

		Isom IR 0–0		Isom ER 0–0		Isom IR 90–90		Isom ER 90–90		Ecc ER		Isom ABD		Isom ER/IR 0–0		Isom ER/IR 90–90		EccER/isom IR 90–90		ROM IR	ROM ER	ROM total
		ABS	NORM	ABS	NORM	ABS	NORM	ABS	NORM	ABS	NORM	ABS	NORM	ABS	NORM	ABS	NORM	ABS	NORM	ABS	ABS	ABS
	Three-way-interaction																					
Three-way-interaction	Gender x Age x Side	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	Side x Age x Level of play	*	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	Gender x Age x Level of play	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	Gender x Side x Level of play	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS
	Two-way-interaction																					
Two-way-interaction	Gender x Age	***	NS	***	*	***	NS	***	NS	***	NS	***	***	NS	*	NS	NS	NS	*	NS	NS	NS
	Gender x Side	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	**	**
	Gender x Level of play	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	Age x Side	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	Age x Level of play	**	*	NS	NS	**	NS	*	NS	NS	NS	*	NS	*	*	NS	NS	NS	*	NS	NS	NS
	Side x Level of play	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	**	NS	*
	Main effects																					
Main effects	Age	***	NS	***	NS	***	*	***	NS	***	*	***	*	NS	***	NS	***	NS	***	NS	NS	NS
	Side	NS	NS	NS	NS	*	NS	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	***	NS	NS
	Gender	***	***	***	**	***	***	***	**	***	***	***	***	**	***	NS	*	NS	*	**	NS	*
	Level of play	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS	NS
Post-hoc test: Bonferroni																						
Two-way-interaction	Gender x Age	***	NS	***	NS	***	NS	***	NS	***	NS	***	**	NS	NS	NS	NS	NS	*	NS	NS	NS
	Gender x Side	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	*
	Gender x Level of play	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	Age x Side	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	Age x Level of play	**	*	NS	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	Side x Level of play	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	*	NS	NS

**Significant at 0.05 level. **Significant at 0.1 level. ***Significant at 0.01 level. NS, not significant; ABS, absolute strength values; NORM, normative values to body weight.*

in comparison with the boys. From the performance and prevention perspective, it would be recommended that tennis players on the international level in transition from Tennis Europe under 14 to junior ITF 15–18 years with an increased level of competition, improve their shoulder strength within this timeframe. Furthermore, a long-term athlete development strategy is recommended also in the perspective of strength development during this period provided that sufficient time are given to the players by the coaches in the training plan to improve strength.

Playing Level and Strength

In view of the playing level perspective, national players presented higher strength values overall compared to their regional level peers. The difference was especially observed in the isometric IR 90–90 position reporting higher values (134.8 ± 33.4 vs. 126.0 ± 46.0 N and 107.3 ± 21.6 vs. 96.5 ± 25.7 N) in the DA, for male and female players, respectively. Considering that IR at high shoulder elevation angles takes place during the tennis serve motion, the difference in strength results in the IR 90–90 position may reflect the higher volume of sport-specific training seen in national players compared to regional players. Consequently, this repetitive motion in shoulder IR is most likely to develop IR strength over time as the service motion to a great extent engage the internal rotators of the shoulder complex (Escamilla and Andrews, 2009).

Eccentric External Rotation Strength

This is the first study to investigate eccER shoulder strength in a large cohort of adolescent competitive tennis players using an HHD. In our study male players showed eccER strength increase with age, higher values in the DA and a difference between national and regional players. However, female players showed only an improvement in eccER strength with age, no difference was found either for side or level of play. The eccER strength normalized to body mass for male and female players were in our study 2.0 and 1.8 N/kg, respectively. In comparison with a similar cohort in age, investigating competitive adolescent handball players, results were similar, reporting 1.9 and 1.7 N/kg for male and female players, respectively (Asker et al., 2020). Furthermore, a sample of 65 recreational tennis players in the age group 18–25 years reported normalized eccER strength values of 2.2 and 2.1 for male and female subjects, respectively (Cools et al., 2016). In summary, the low ratios in adolescent athletes may reflect the challenge to develop eccER strength in overhead athletes during puberty no matter the sport. In addition, recreational players may not be as fatigued in the shoulder as competitive players regardless of age and therefore reporting higher values in eccER.

Intermuscular Ratios in Dominant and Non-dominant Arm

Results revealed in all three calculations for both male and female players a lower ratio in the DA compared to the NDA. Our results showed an eccER/IR isometric ratio 90–90° of 1.00/1.13 for male players and 1.05/1.23 for female players in the DA and NDA, respectively. These results are in line with previously reported ratios, although reported in an older sample (27.6 ± 8.4 years), results being lower in the DA of tennis player (Cools et al., 2016). In addition, similar results have been reported in a younger cohort of tennis players, reporting lower isometric ER/IR intermuscular ratios in the DA (Gillet et al., 2017; Fernandez-Fernandez et al., 2019). This lower ratio may be explained by several factors. Firstly, the DA is subject to a high number of repetitions and therefore the shoulder internal and external rotator muscles are most likely to be fatigued. Secondly, when calculating ratios, we need to consider the IR strength being more developed in the DA and especially in male players, due to the high numbers of serving compared to the NDA not being used in the overhead motion, therefore affecting the ER/IR ratio calculation. Moreover, intermuscular ratios being lower in the DA of adolescent athletes is a phenomenon seen in other sports as well, such as handball and baseball (Trakis et al., 2008; Asker et al., 2020).

Level of Play and Intermuscular Ratios

In view of level of play, male and female national players in our study presented a lower ratio for the eccER/IR strength ratio compared to regional players. In the light of national players being stronger especially in isometric IR 90–90° this might be the explaining factor for the lower ratio, on the other hand, it should also be highlighted that with more hours per week in match, practice, and fitness, a potential fatigue of the shoulder internal and external rotator muscles may occur. In view of ER/IR ratios, at both positions (0 and 90°) the male and female players regardless of level in our study performed a ratio <0.75. Therefore, it may be of special importance to improve the ER strength of the shoulder since decreased ER strength has been previously reported to be associated with injury in the adolescent and elite handball player (Saccol et al., 2010; Asker et al., 2020). In addition, low ratios of ER/IR have also been reported to increase injury risk in the professional baseball pitcher (Byram et al., 2010).

Range of Motion

In overall the ROM results revealed a difference between sexes with male players showing less IR and TROM compared to female players, both sexes showing less IR and increased ER in the DA compared to the NDA. In addition, female players displayed a decrease in TROM in the DA compared to the NDA. Male players showed a decrease in IR ROM and increase in ER ROM with age. However, TROM was not affected, therefore the results suggesting a shift in the rotational range to be the explanation (Whiteley et al., 2009). In the perspective of level of play, male national players displayed higher ER ROM and higher TROM compared to regional players, IR remained the same for both playing levels. Female players showed no difference either in age or in level of play. This increase in ER ROM in male national players may be a consequence of more training and match volume and thereby a greater number of overhead motions enhancing ROM in ER (Myers et al., 2016). In addition, based on practitioner experience it might reflect a traditional training paradigm with male players practicing more serves on the national level compared with female national players practicing more from the baseline. Previous studies of ROM in tennis players have reported a decrease in IR with an increase in age, TROM remains the same with age, however, a shift is apparent with an increase in ER in combination with a decrease in IR (Cools et al., 2014b; Gillet et al., 2017; Fernandez-Fernandez et al., 2019; Moreno-Pérez et al., 2019).

Strength and Limitations

The strengths of the study were firstly the large cohort including 301 adolescent competitive national and regional tennis players, therefore representing most of the available players. Secondly, the cohort included both male and female players enabling the possibility to investigate and compare the two sexes. Thirdly, the reliability of the clinical measures performed with a HHD was good to excellent, with ICC ranging between 0.87–0.91, SEM 3.81–4.51, and MDC 10.55–12.50, consequently, making the results clinically relevant (Cools et al., 2014a; Johansson et al., 2015b). In addition, the smartphone app used for ROM assessments has also proven to be reliable in the clinical setting (Mejia-Hernandez et al., 2018). Lastly, the present study and its results have high levels of ecological validity and may offer a starting point to suggest practical applications to tennis-specific fitness and prevention training.

However, this study has some limitations. Firstly, it should be highlighted that the reference values suggested here only is comparable in the clinical setting provided that the clinician is using the HHD as an assessment tool. Moreover, no standardized threshold in force output was used between the two trials, potentially this could affect the results if one of the trials being a submaximal effort or if there was a learning effect. This would be recommended for future assessments, however, in view of the large cohort it was not possible due to time management. In addition, when assessing stronger players, it may require stronger assessors to resist the strength of the player's push and obtain reliable results (Croteau et al., 2021). Although assessing shoulder strength using an HHD in a field-based setting is reliable, the results should be treated with caution due to high threshold for reliable measures, especially in adolescents (Møller et al., 2018). Furthermore, no external fixation was used during the assessments due to practical and clinical relevance, this might have influenced our results. However, external fixation in the field is not very practical due to the extra time needed to set-up the assessment procedure, therefore, our protocol was developed to be more clinically relevant. The end range in the ROM measurements was determined by subjective criteria, based on clinical skills, but was not objectively controlled. Therefore, the results may be affected by the skills of the examiner. Finally, although this is a large cohort ($n = 301$), future studies should be focused on international multicenter studies due to the differences in training volume between countries. However, all things considered this normative database may help all stakeholders involved in the adolescent tennis player to make better decisions regarding rehabilitation, return to play and high-performance.

CONCLUSION

This is the first paper to present specific isometric and eccER shoulder strength values measured with a HHD and shoulder rotational ROM data based on a large ($n = 301$) cohort of adolescent male and female competitive tennis players. Our most important findings of the study were age and sex differences in the isometric as well as in the eccER shoulder strength. In view of performance the study highlights the gain in shoulder ER ROM and the need for developing strength throughout puberty especially in female players. Finally, the potential risk factor reported as ER weakness is evident also in our cohort.

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 study was in accordance with the declaration of Helsinki and preapproved by the Regional Ethical Review Board, Stockholm, Sweden (approval no. 2012/1731/2). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

FJ, MA, JF-F, and AC designed the study. FJ, AM, and MA were part of the data collection. FJ, AW, and AC analyzed the data and prepared the manuscript. All authors read and approved the final manuscript, contributed to the article, and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2022.798255/full#supplementary-material

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BRIEF RESEARCH REPORT
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Toward Detecting the Zone of Elite Tennis Players Through Wearable Technology

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Wearable devices fall short in providing information other than physiological metrics despite athletes' demand for psychological feedback. To address this, we introduce a preliminary exploration to track psychological states of athletes based on commercial wearable devices, coach observations and machine learning. Our system collects Inertial Measuring Unit data from tennis players, while their coaches provide labels on their psychological states. A recurrent neural network is then trained to predict coach labels from sensor data. We test our approach by predicting being in the zone, a psychological state of optimal performance. We conduct two experimental games with two elite coaches and four professional players for evaluation. Our learned models achieve above 85% test accuracy, implying that our approach could be utilized to predict the zone at relatively low cost. Based on these findings, we discuss design implications and feasibility of this approach by contextualizing it in a real-life scenario.

Keywords: sports, psychological states, deep learning, flow state, machine learning

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1. INTRODUCTION

Research on sports wearable technologies suggest that athletes are not satisfied by raw physical data and demand feedback on their psychological states (Havlucu et al., 2017). However, the state of the art methods fall short in tracking the psychological states to provide feedback in realistic environments (Reinecke et al., 2011). Existing wearable devices offer affordability and convenience, but are limited to providing physiological information, such as heart rate (Aroganam et al., 2019). Considering both limitations, our motivation is to create affordable and convenient methods to track and give feedback on psychological states. We approach this motivation by correlating the physiological data collected from conventional wearable devices such as Apple Watch with labels from expert coaches, who are shown to observe psychological states in their players (Bakker et al., 2011; Havlucu et al., 2018), and training models to detect these states through machine learning (**Figure 1**).

We introduce a preliminary exploration to this approach by tracking what the coaches call being-in-the-zone (Young and Pain, 1999) in tennis. We picked tennis, since it is physically intense and mentally challenging (Fernandez et al., 2006). Based on the interview findings of previous research with tennis coaches, we focused on being in the zone as a psychological state (Havlucu et al., 2018). We conducted an experimental study involving two tennis games, with two elite coaches and four professional players. Our goal was to predict if tennis players are in the zone, by utilizing the Inertial Measuring Unit (IMU) data from Apple Watch Series 2 and coaches comments

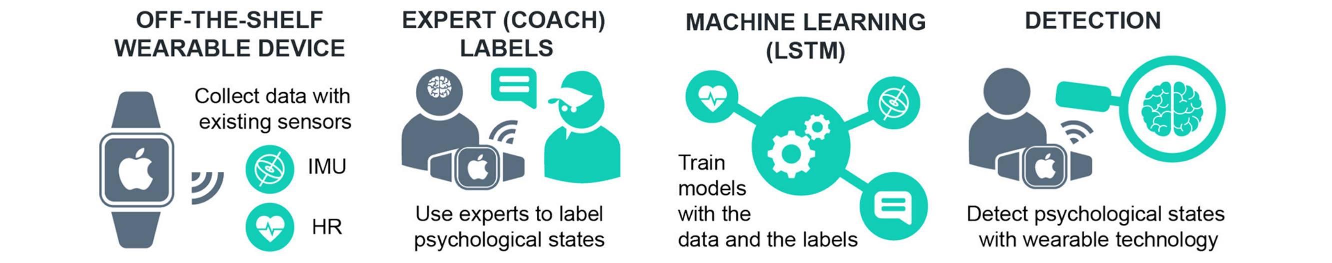

FIGURE 1 | Summary of our approach to detect psychological states with wearable technology, expert labels and machine learning.

on their players zone. We used a deep recurrent neural network (LSTM) model to learn and was able to predict whether a tennis player is in the zone with around 85% test accuracy. Based on these results, we discuss the design implications and the feasibility of our approach. We also contextualize our approach in a real-life scenario.

The main contribution of this work is two-fold; (1) a novel step toward detecting psychological states through off-the-shelf wearable technology, machine learning and expert labels, and (2) design implications and the feasibility of such technology for HCI. Note that this work is a preliminary exploration for tackling our broad motivation, due to the extremely challenging nature of detecting psychological states and conducting longitudinal studies. We believe our findings can guide sports researchers and interaction designers on how to detect psychological states, as well as present particular directions for future of wearable technology.

2. BACKGROUND

Tennis is among a few individual sports, which has both self-paced (serve) and externally-paced (ground strokes) performances with continuous switches (Koehn et al., 2013). Tennis players try to counteract their opponents' actions, pay attention to their own performance and get distracted by repetitive breaks, while exerting intense physical effort, all of which trigger shifts in their mental states (Fernandez et al., 2006). Therefore, tennis players wish to get feedback on the mental aspects of their performance, rather than feedback on their physical performance (Havlucu et al., 2017). These mentally challenging features make tennis a great case for exploring the psychological measures of a sports performance.

Flow state, commonly known as 'the zone' for sports (Young and Pain, 1999), is a psychological state the state of optimal experience and performance (Jackson and Csikszentmihalyi, 1999). In the zone, athletes describe being immersed in and in total control of their performance effortlessly, which leads to their ideal performance (Kimiecik and Stein, 1992). Therefore, it is the state every athlete aspires get into. Research on the zone presents characteristics and dimensions to experience the zone (Jackson and Csikszentmihalyi, 1999). However, experiencing the zone consistently has been shown to be extremely challenging. Researchers have investigated the relationship between tennis performance and the zone (Koehn et al., 2013). Their findings indicate that the zone is a valuable psychological state to assess tennis performance. Studies on other sports such as football revealed coaches rating of players' performance included a significant correlation to their self-rated zone experience (Bakker et al., 2011). Specifically for tennis, these results were in line with the findings of Havlucu et al. that coaches could observe the zone of their players while rating their performance (Havlucu et al., 2018). They further elaborate that coaches track the body language, posture, activity and rituals of the players as the tennis specific cues of the zone.

3. RELATED WORK

Current state-of-the-art fall short in tracking psychological states of athletes since measuring these states rely on invasive methods and can not be applied in real sports settings (Reinecke et al., 2011). The conventional method to measure psychological states is subjective scales (Jackson and Eklund, 2002), which include items rated by the participants and are administered through the Experience Sampling Method (ESM) (Csikszentmihalyi and Larson, 2014). ESM, Researchers probe participants at various intervals to fill out the scales. However, ESM intrudes into participants performance. In a sports setting, this intrusion can trigger unwelcome shifts in psychological states. Unlike ESM, our approach does not interfere with the participants activities during data collection.

Another approach is to correlate psychological states with psychophysiological measures. For example, researchers argue that heart rate variability (HRV) and respiratory rate are reliable indicators for different psychological states and use bulky and expensive equipment like electrocardiography and electroencephalography (EEG) to detect these states (Nacke and Lindley, 2008). Yet, we should note that the technology is advancing and these devices have become cheaper since the last decade. Thus, we see chest straps being utilized to measure HRV during matches in tennis (Fuentes-García et al., 2022) and racket sports (Parraca et al., 2022). Although, the same is true for measuring EEG with textile head ware (Pineda-Hernández, 2022), it still very challenging for athletes to perform a sports activity, especially professionally. These methods are still far from having the convenience and affordability of using current wearable technologies. In contrast, we use a machine learning approach to successfully predict the psychological state of 'zone' with wearables.

Human Activity Recognition (HAR) employs sensors from wearable devices and machine learning to predict and recognize diverse physical activities (Wang et al., 2019). In sports cases, multiple studies use IMU data to effectively recognize sports actions (e.g., forehand) (Connaghan et al., 2011). Although this approach is only used for detecting physical activity, the affordability and convenience proposed overcomes the limitations of the aforementioned methods. Therefore, we were inspired by HAR to create our approach to detect psychological states.

Psychological states manifest in behavioral responses along with physiological responses, which could be detected by HAR. Previous research illustrates with music, participants' walking style and rhythm change reflecting changing stress levels (psychological states), which is sensed and analyzed by IMUs attached to their heads (Tateyama et al., 2019). Tennis players also show behavioral responses while experiencing 'the zone'. Elite tennis coaches can observe the zone from their players' body language, posture, activity and rituals (Havlucu et al., 2018). They argue these cues are relevant to the movement and behavior of the players, which suggests IMUs could be used to detect these states.

4. METHOD

Our goal is to track the zone by utilizing data from off-the-shelf wearable technologies. We decided to limit the data to IMU for two reasons. First, tennis coaches observe the zone from their players movement and behavior, which can be quantified by IMUs (Havlucu et al., 2018). We were also inspired by research on other fields, for instance music, that report behavioral responses of psychological states such as distress levels could be successfully detected with IMUs (Tateyama et al., 2019). Second, IMU sensors are present in many off-the shelf wearable devices, unlike heart rate or EMG sensors. In our case, IMU offered affordability and convenience compared to other sensors, while providing high accuracy for our trained models (see Results).

4.1. Machine Learning Tasks

There are several questions of interest that we want to address with multiple machine learning tasks. The answers have design implications on the use cases of our approach:

1) Can we detect the psychological state of being in the zone of a single or multiple tennis player(s) with a model learned from physical IMU data? This question deals with the core idea of the paper; whether the movement information contained in the IMU data can be used to detect 'the zone'. For this, we define two machine learning tasks: (a) Use the data of each player separately and learn personalized models for each player. (b) Use the data of all the players which involves learning a single aggregate model from all the player data. We look at the test accuracies of both tasks to decide on the answer.

2) Can a learned model generalize to new players? This question deals with whether a learned model can predict the zone labels of a previously unseen player. If the answer is positive, a generalized model can be produced to detect 'the zone' of every player. If it is negative, we need to collect data for each player, i.e., the models need to be personalized. The associated machine learning task: (a) Use the data of 3 players for training and the data of the remaining for testing, and rotating the tested player. We look at the test accuracies to decide on the answer.

3) If a learned model cannot generalize, can it be re-trained to speed up learning for a new player? This question deals with if it is beneficial to re-use a learned model, if the answer to the previous question is negative or if the resulting performance is low. If the answer is positive, the data collection and training duration can be shortened. The associated machine learning task: (a) Re-train the models from the task 2a using the remaining players data. We compare the number of training epochs to reach an average test accuracy threshold (80%) between the models trained from scratch (in the task 1a) and the re-trained models, and testing accuracies to decide on the answer.

4.2. Machine Learning Formulation

We formulate the zone state detection as a binary classification problem where the windows of 12-dimensional IMU time series as the input and the latest coach label as the target. We use a Long Short Term Memory (LSTM) recurrent neural network model for all the ML tasks with a windows size of 50 (5 s). The structure of neural network includes two stacked LSTM layers with hidden unit sizes of 64 and 32 respectively, followed by a fully connected layer with 8 ReLU neurons and a single sigmoid output. We apply a dropout rate of 0.5 after the first LSTM layer. We use cross entropy loss, Adam optimizer with learning rate of 0.0025 and batch size of 128. Each model is trained for 100 epochs. The exact machine learning approach is of limited importance for our purposes. LSTM based models are widely used and well-established in activity recognition that are shown to be successful (Wang et al., 2019). LSTMs can successfully model the temporal nature of the data. Our model produced sufficient results for the sake of this study. However, we do not claim that it is the *best possible model*.

4.2.1. Train-Test Splitting

The coach labels are not distributed uniformly in time (see **Figure 2** in Results). This makes it difficult to perform standard time-series data splitting such as only taking the last 20% for testing. However, the label ratios are more or less 50%. Thus, we randomly pick parts from the data of at least 50 points and remove them as the test set. We then use the remaining data as the training set. This makes sure that the train and test sets have roughly the same ratio of labels and that no point in the test set is ever in any of the windows of the training set. The amount of data for the test set is picked to roughly give a 1/4 ratio of test data to train data. We perform this random splitting 5 times and report the average results.

4.3. Participants, Procedure, Setting, and the Data

Two elite level tennis coaches and four professional players participated in the experiment. The coaches had 25–28 years of tennis experience, with 9–11 years of professional coaching.

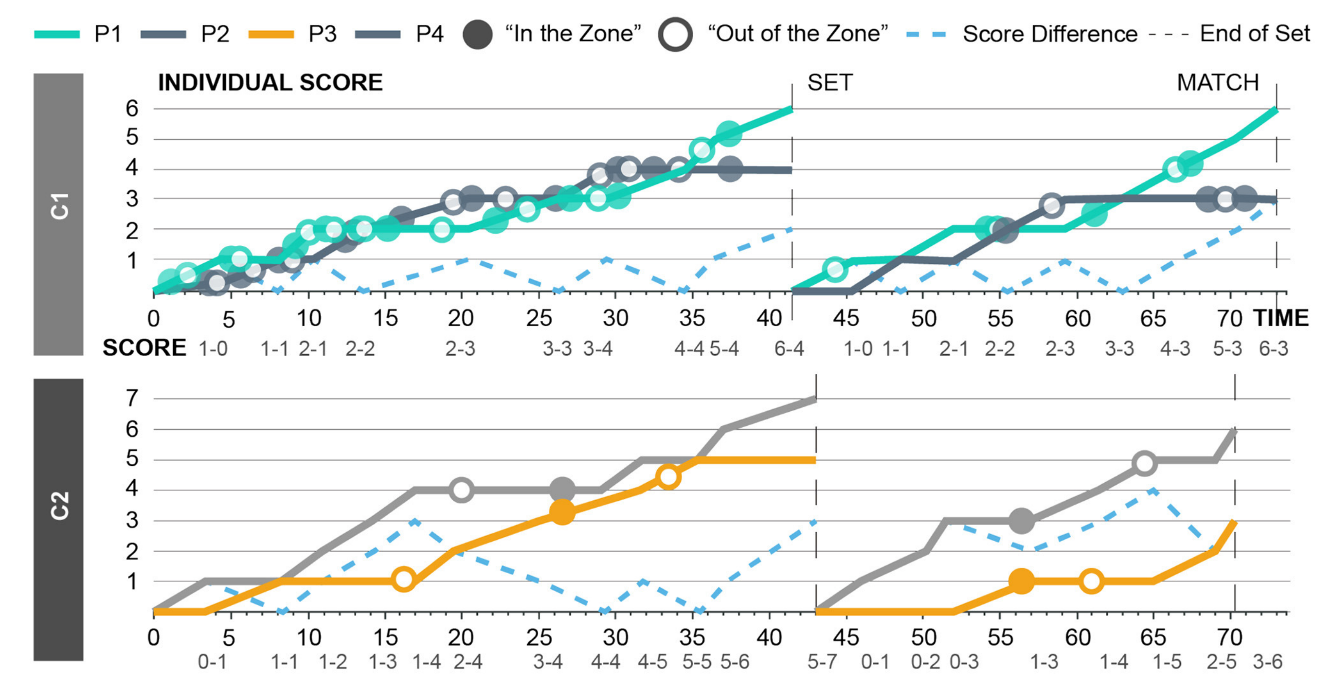

FIGURE 2 | Labels of coaches, C1 (top) and C2 (bottom), for their respective players (P1 and P2, P3 and P4) according to individual scores and score differences.

They were both male, 35–38 years old, respectively. We described our aims to the coaches prior to conducting the experiment. Both coaches were knowledgeable of the zone from their own and their player's experience and shared they could observe the zone of their players. Accordingly, each coach was asked to select two of their professional players. All players were male, because the coaches only trained male players. Previous research demonstrated that gender has no significant effect on the zone in tennis (Koehn and Morris, 2012). The players were aged between 18 and 20 (M = 19.0, SD = 0.7), and all have participated in and won international tournaments.

We conducted the experiments on the coaches registered tennis club indoor hard courts. In each experiment, one coach's two players played a game, while their coach observed the players simultaneously. The coaches and the players were different in both games (Coach 1 with Player 1 and 2, Coach 2 with Player 3 and 4). The games were in best-of-three format and each lasted around 75 min. During the games, each player was asked to wear Apple Watch Series 2 on their dominant wrists, which was decided according to the arm players used for the racket. We collected 10 Hz IMU data from these devices. The IMU data, measured at each time step, is a 12 dimensional vector consisting of acceleration (3-dim), gravity vector (3-dim), orientation (3-dim) and rotation-rate (3-dim). Simultaneously, the coaches were instructed to label their players getting in and out of the zone according to their own observations of the players' movement and behavior. Due to their experience of the zone, the coaches were free to share and label any observation they have found relevant. These labels were used as binary data. The exact timing of these labels were stamped by the coaches. The content of the labels were written down by the experimenter and then matched with the timestamps. The total number of IMU measurements were about 193,000 with 47 labels by the first coach and 9 labels by the second. The duplicates were removed and the missing time stamps were filled with linear interpolation before learning.

5. RESULTS

5.1. The Games and the Labels

Both games ended with two consecutively won sets. The first game was more intense and contained many comebacks. The coach from the first game (C1) labeled more instances for both players (P1 and P2, 47 vs. 7) (**Figure 2**) and the content of these labels were more elaborative (i.e., C1 - "[P1] is doing his rituals. His gaze is sharpened. He is controlling his breath."). On the other hand, the coach from the second game (C2) only labeled the entrance to and exit from the zone. However, the LSTM model was only trained with binary labels ("In the Zone" and "Out of the Zone").

5.2. The Machine Learning Tasks

To summarize, our evaluations answered the 1*st* and the 3*rd* questions positively, and the 2*nd* question negatively. All of our results are presented in **Table 1**. In this section, we elaborate on the results and explain the findings.

1) Coaches zone labels can be detected from IMU data in tennis with high accuracy.

The 1a and 1b columns of **Table 1** show that the testing accuracy of the models learned from individual player data and from the aggregated data are above or close to 85% other

TABLE 1 | The testing results of tasks explained in the Section 4.1 using 5 train-test splits and 100 epochs.

ML task	1a Individual models	1b Aggregate model	2a Generalization	3a 80% threshold	3a Accuracy
C1 P1	85.69% (1.14%)	N/A	50.52% (1.38%)	19 vs. 14	88.31% (0.73%)
C1 P2	78.49% (1.20%)	N/A	51.81% (0.57%)	N/A vs. 24	85.64% (1.59%)
C2 P3	87.22% (1.59%)	N/A	49.74% (1.90%)	23 vs. 5	88.44% (0.79%)
C2 P4	85.79% (1.28%)	N/A	52.00% (1.66%)	17 vs. 4	88.64% (1.79%)
All/Avg.	84.30% (2.63%)	83.24% (0.55%)	51.02% (2.93%)	N/A	87.75% (2.62%)

"C" represents the coaches and "P" represents the players. The last row provides the average of the average accuracies of individual models for tasks 1a, 2a, and 3a. The 3a Threshold column shows the training epoch when the average accuracy is consistently better than 85% (random start vs. transferred). The values in parenthesis show the standard deviations.

than the second player of the first coach. Previous studies in HAR present accuracies between 80 and 90% to yield in successful detection (Connaghan et al., 2011). Given the challenging nature of detecting psychological states, these results show that our approach can be utilized to detect the zone state of a player. We conclude that the answer to the first question is positive.

2) The models cannot be generalized between players.

The 2a column of **Table 1** shows that the testing accuracy of the learned models are the same as random guess. This suggests that, at least with our data, the learned models can not generalize to a previously unseen player and individual training is needed for our approach to work. As such, we conclude that the answer to the second question is negative. This result may be due to the highly personalized nature of the zone and psychological states as discussed in Section 6.1.

3) Learning can be sped up by utilizing a previously learned model.

The 3a Threshold column of **Table 1** shows that the models converge faster if we retrain a previous model as compared to training from random initialization. Furthermore, the re-trained models obtained better performance with the same number of epochs, with all models surpassing 85%. This suggests that previously collected data has some use even if the models are not generalizable between players. This also suggests that there could be a weak shared representation among the players. We conclude the answer to the third question is positive. This positive answer has implications on how a model should learn from data. The results suggest that the more data is collected and more models are learned, the faster the learning will be. Another point is that the existing models may decrease the amount of data needed to learn.

6. DISCUSSION

Our goal is to track the zone by utilizing data from off-the-shelf wearable technologies. The results suggest that our approach could be utilized to predict the zone of a tennis player with above 85% accuracy. In this section, we discuss the feasibility of our approach through design implications of the results, contextualize it in a real life scenario to illustrate the potential, present the limitations of the current study and point out future research directions.

6.1. Personalized Psychological States

We can train machine learning models to detect what coaches call 'the zone' for individual players with high accuracy. Additionally, we can train a single model for multiple players. Yet, these models do not generalize to new players. Thus, players must be observed and labeled before predicting psychological state. This may not be a shortcoming of our approach, but simply the nature of psychological states (Young and Pain, 1999). Previous research discusses the zone as a highly personal state. Athletes have their own individual experience in the zone and some aspects of this experience may not be observed in others. According to coaches, unique player behaviors provide cues about their state (Havlucu et al., 2018). They need to know the player well to perceive these states. We could argue that user's model cannot be used to predict another user due to the highly personal nature of 'the zone'. Nonetheless, our results suggest that previously learned models can partially be used. The personal nature of these states is an open area for future research.

6.2. Labeling "The Zone"

Each coachs labeling of the zone was different. Although the data trained in the model was binary (In the Zoneİ and Out of the Zone), the number of instances were significantly higher in the first experiment (47 vs. 9). We emphasized that the coaches should be experts and need to know the players well to properly assess the zone (Havlucu et al., 2018). This means each player should be labeled only by their own coach. These coaches could label the zone differently. Thus, the labels they produce is subjective. This challenges the reproducibility of the labels and generalizability of the models. On the other hand, it proposes a system that produces personalized models for each user and illustrates the possibility of predicting the zone of individual players. Therefore, we believe subjectivity of the labels is not a major issue for this work. In fact, subjectivity could be a strength of the approach, as the players might need a subjective assessment of their psychological states, which is not provided by current wearable devices (Havlucu et al., 2018). Additionally, the first game was more competitive, which may have resulted in more switches between the psychological states of the players and more coach labels. However, more labels do not necessarily mean more robust measurement. We do not yet know the optimal amount or time (i.e., after, during or before points) of the labels to reliably measure these states. In any case, we need to investigate the quantity and temporal dimensions by recruiting more coaches

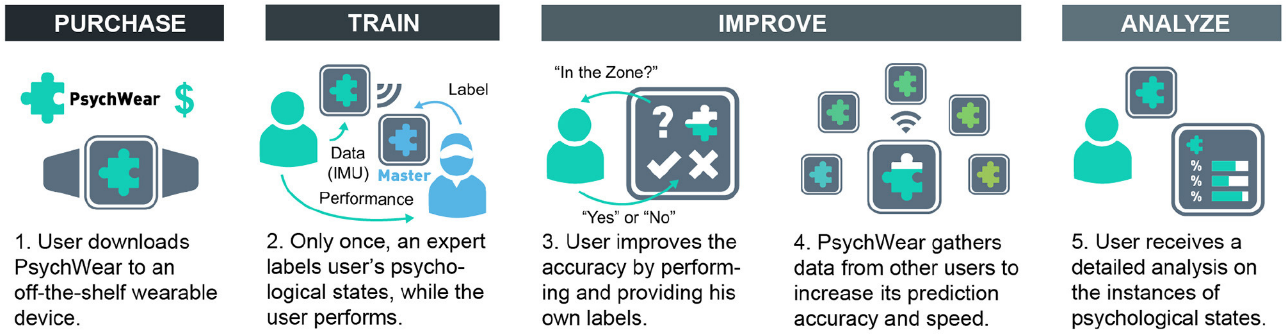

FIGURE 3 | Contextualization of the approach: PsychWear's usage scenario and workflow.

and comparing their labels with the trained models. We believe this will allow a more coherent and reliable way of measuring psychological states and possibly present a guideline on how to effectively label these instances, which could be addressed by future studies.

6.3. Contextualization of the Approach

Based on our findings, we envision that our approach can translate into a future wearable device application, PsychWear. Note that PsychWear does not aim to replace the coaches, but aims to supplement them. **Figure 3** illustrates how PsychWear works. Tennis clubs buy affordable wearable devices and PsychWear for a small fee. Then the coaches provide labels for each player in training sessions. These sessions are required for each new player, because PsychWear can predict the zone specifically for each player (Section 6.1 and 2a column of **Table 1**). However, PsychWear can work with only one training session per player with high accuracy (1a and 1b columns of **Table 1**). During training, the players wear the devices and run PsychWear. They play a tennis game competing against other players, while PsychWear extracts the IMU data from the devices. Meanwhile, the coaches provide zone labels for each player (Section 6.2) using the master PsychWear application. PsychWear sends these data to the cloud, where the learning occurs, and then downloads the resulting model on the devices. This lets PsychWear increase its learning speed for new players (3a column of **Table 1**). Additionally, PsychWear can improve itself over every game. Players can choose to provide their own labels. This mode asks the players if they are in the zone upon prediction. The players provide a yes/no answer, which iterates PsychWears current data. Although this feature is not tested since the experiment is not repeated with the same participants, activity recognition literatur exhibits that improving the data set increases prediction accuracy (Wang et al., 2019). Moreover, PsychWear can be used in other physical activities in which the mental states of the performer has a significant effect on the performance outcome, and that have experts who can perceive the psychological states. Dancing, where the performance reflects the mental state, or yoga, where the mental processes are integrated to the physical activity are some examples. Exertion games, digital games that require physical effort, can also benefit from this tool.

6.4. Limitations

Although our results are promising to track the zone in tennis, the experiments were conducted with only two coaches and four players and were not repeated with the same players. The demanding nature of this experiment and its target group hindered rapid and repetitive measurement. We recognize our relatively small number of participants do not produce a generalizable and validated large-scale user study even with experts. Nonetheless, our aim in this study is to explore the novel concept of detecting psychological states through off-the shelf-wearable devices and machine learning, rather than validating the results. There are examples recently published in ACM conferences with similar number of participants. Khan et al. (2017) explored the feasibility of a novel and inexpensive activity recognition system in cricket with only 6 participants, who were mostly amateur players. Hölzemann and Van Laerhoven (2018) included only 3 participants for recognizing basketball activities with IMUs. We argue that our study contributes in exploring the feasibility of detecting psychological states with wearable technology. Note that, we have around 193,000 IMU measurements which by itself constitutes a large data set even with few participants. We plan to conduct more experiments and increase the participant pool. Moreover, we were not able to longitudinally evaluate the model. We need to know how well the model responds to previously trained players on different occasions. This will inform how many labeling instances are needed before accurately predicting the zone. Toward this end, we intend to repeat the experiments with the same players.

Additionally, we should mention limitations regarding our data collection. In each game, one coach was tasked to observe two players simultaneously, which may have challenged their concentration. Although, they are elite coaches, this may have resulted in data loss for observing both players. Moreover, the players were asked to wear the watches on their dominant wrists to collect more precise data on their movement with the racket. However, they were not used to wearing watches, thus their movement and the data collected might be hindered.

7. CONCLUSION

In this paper, we showed that wearable devices could help to detect psychological states. We introduced a novel approach that is utilized to predict 'the zone' of a tennis player with above 85% accuracy, by using Inertial Measuring Unit (IMU) data and elite coaches' labels on player performances. Primarily, we believe our exploration casts light upon how the future of wearable sports technology can detect psychological states of users. In broader terms, we argue this work presents novel directions for future wearable technology in HCI, and informs future studies aiming deeper understanding of the concept. However, the results should be treated within the discussed limitations, especially concerning the relatively small sample size. The nature of this work was to test the feasibility of the introduced approach. With this regard, we presented its limitations and pointed out design implications, rather than validating the results of the presented study. To this end, we contextualized this technical approach to a real life scenario that illustrates its potential. We believe that our contribution has thus become accessible for readers of non-technical backgrounds, namely interaction design and psychology researchers.

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 human participants were reviewed and approved by Koc University Ethical Committee. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Self-assessed tactical skills in tennis players: Psychometric evaluation of the Tactical Skills Questionnaire in Tennis

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To our knowledge, no feasible, valid and reliable instrument exists to examine tactical skills over the course of multiple training and game situations in tennis yet. Therefore, the aim of this study was to develop and evaluate the psychometric properties of the Tactical Skills Questionnaire in Tennis (TSQT). The TSQT is a new instrument with closed-ended questions designed to examine tactical skills in tennis players. Participants were 233 competitive tennis players (age: 17.06 ± 4.74 years) competing on national or regional levels. With a principal component analysis (PCA) we identified four theoretically meaningful subscales for the 31-item TSQT: "Anticipation and positioning," "Game intelligence and adaptability," "Decision-making," and "Recognizing game situations" and confirmed them with a confirmatory factor analysis (CFA) ($\chi^2 = 527.02$, df = 426, $p < 0.001$, CFI = 0.93, RMSEA = 0.045, SRMR = 0.079). Internal consistency was good, with Cronbach's alpha of 0.89 for the entire scale and McDonald's omega ranging from 0.69 to 0.78 for the separate subscales. A subsample of 57 players completed the TSQT twice to assess test-retest reliability. Absolute test-retest reliability of the subscales was good with no significant differences in mean scores between test and retest ($p > 0.05$). Relative test-retest reliability was moderate with ICC values ranging from 0.65 to 0.71. National players outperformed regional players on the subscales "Game intelligence and adaptability," "Decision-making," and "Recognizing game situations" ($p < 0.05$), and there was a trend toward significance for "Anticipation and positioning" ($p = 0.07$). This study supported the psychometric properties of the TSQT. Evaluating tactical skills with the TSQT provides players, coaches and other professionals with insight in players' self-assessed tactical skills over the course of multiple training and game situations. It creates the opportunity for players to reflect on their skills and detect personal development areas with their coach. We advise to use this information as input for tailor-made training programs.

KEYWORDS

racket sports, tennis, Tactical Skills Questionnaire in Tennis (TSQT), principal component analysis, talent development, performance

Introduction

Outstanding tactical skills are requisite for elite performance in many sports (1–4). At the highest performance level in dynamic open-ended sports like tennis, players must often make quick and accurate tactical decisions (5). In temporally constrained situations, they must detect and use contextual and kinematic information to anticipate the opponent's intentions. Specific sources of contextual information, including shot sequence and the position of the players on the court, facilitate player anticipation (6). Some have suggested that these contextual sources include the minimal required information needed for successful anticipation, and that the later emergence of kinematic information from the opponent's actions around ball-racket contact may be confirmatory (7, 8). In other words, as postural cues from the opponent become available, the number of options for responding appropriately may decrease to permit the emergence of an option with high success likelihood. Elite tennis players have been found to be better at detecting and using contextual and kinematic information than less skilled players, resulting in their superior anticipation and decision-making skills compared to players with lower performance levels (9). For example, they have a greater ability to put pressure on their opponents by choosing responses that are more likely to compromise the opponent's actions (e.g., force the opponent to move or play to their weaker side) (10). Players' positions on the court are crucial, as an optimal position enhances court coverage and enables an effective response to the opponent's most likely stroke direction. Not surprisingly, game intelligence has been considered essential for tennis performance, and it is often defined as the ability to "read the game" and act accordingly (11). As all these tactical skills (e.g., anticipation, decision-making, positioning, and game intelligence) must be well developed to meet the game's competitive demands, monitoring them is important to assist player development. This is particularly relevant for talented youth players aiming to reach the elite level. Still, no instrument is available to assess these skills over the course of multiple tennis training and game situations.

A feasible instrument to gather information on players' tactical skills is the Tactical Skills Inventory for Sports (12). This self-report questionnaire measures invasive game player's accumulated know-how on their tactical skills over a prolonged period of time, independent of their shape of the day or their opponent. It contains scales for declarative knowledge describing "knowing what to do" and procedural knowledge relating to "doing it". Research in field hockey players revealed that elite players scored higher than amateur players on both self-assessed declarative and procedural knowledge (13). However, within a group of elite players the selection of an appropriate action within the context of the game, i.e., procedural knowledge, seems to differentiate more between performance levels than knowledge of the rules and goals of the game, i.e., declarative knowledge. This finding is confirmed in a study with soccer players, however, less is known regarding the game of tennis. For studying tactical skills, it is important to consider both the "quality" and "quantity" of players' tactical skills. Quality is inferred from the players' excellence in the demonstrated tactical skills and quantity refers to how often players display their tactical skills. Both factors may determine match outcome. For instance, the performance depends on players' ability to make the right decision about the next stroke. Thus, the *quality* of this action affects match performance. In addition, players who make the right decision about their next stroke more often will ultimately outperform players who occasionally make the right decision. This means that the outcome of a match also hinges on the *quantity* of a players' ability to make the right decision at the right time.

To our knowledge, no feasible, valid and reliable instrument exists to examine procedural knowledge (e.g., decision-making, anticipation, positioning, and game intelligence) over the course of multiple training and game situations in tennis yet. Such instrument provides players, coaches and other professionals with insight in players' self-assessed tactical skills. It creates the opportunity for players to reflect on their skills and together with the coach to detect personal development areas. As such, it can provide relevant input for the content of training programs. Considering the relevance of assessing these skills in tennis, the aim of this study is to develop and evaluate the psychometric properties of the Tactical Skills Questionnaire in Tennis (TSQT) with a sample of competitive tennis players. Specifically, the purpose is to assess its content validity, construct validity, internal consistency, test-retest reliability and discriminative validity.

Materials and methods

We conducted this study in seven phases: (a) questionnaire design and construction, (b) exploration of the readability and comprehension of questionnaire items, (c) identification of components with principal component analysis (PCA), (d) verification of the component model with confirmatory factor analysis (CFA), (e) examination of internal consistency, (f) evaluation of test-retest reliability, and (g) assessment of discriminative validity. We used the COSMIN Study Design Checklist for Patient-Reported Outcome Measurement Instruments for reporting on these procedures (14).

Ethical considerations

We obtained ethical approval for this research protocol (PSY-1819-S-0262) from the Psychology Department of the University of Groningen (Groningen, Netherlands, September

19th, 2019), and we obtained advanced written informed consent or assent from all players and advanced written informed consent from parents or legal guardians of all players under 16 years of age (the legal age for giving consent in the Netherlands).

Participants

The study's inclusion criteria required participants to be healthy volunteers, between 10 and 35 years of age, who had both competitive tennis experience and sufficient proficiency in speaking, reading and writing Dutch to take this questionnaire. Based on common sample size recommendations for conducting factor analysis, our aim was to recruit at least 200 participants (15). We recruited participants from different tennis clubs in the Netherlands and the Royal Dutch Lawn Tennis Association (KNLTB). Our total participant sample included 233 competitive tennis players (160 males, 73 females; *M* age = 17.06, *SD* = 4.74 years). The average number of training hours per week (including both tennis training and strength and conditioning training) ranged between 0 and 3 h per week for 26.7% of the sample. For 18.1% of the sample, the average training per week was at least 3 h. For 19.4, 17.2, and 18.5% of the sample, the average training per week was at least 6, 9, and 12 h, respectively.

Development of the Tactical Skills Questionnaire in Tennis

The aim of the first two phases of this research was to ensure acceptable content validity of the TSQT. In other words, we first sought to confirm that the questionnaire adequately covered all relevant tactical skills to be measured (16). Following advice from Artino et al. (17), we began with a literature review that helped to operationalize the construct of tactical skills and determined whether other similar measures of tactical skills in tennis already existed. Finding no evidence of any similar instrument we designed the TSQT by using the TACSIS as an example model, reformulating various TACSIS items to be tennis-specific (12). For example, we changed an item of the TACSIS "*My positioning during a match is generally*" into "*My position on the court is*". We adapted another item from the TACSIS "*My anticipation (thinking about proceeding actions) is*" to "*In looking ahead (thinking about my next stroke), I am*". Next, we relied on a group of four scientists with extensive experience in research on tactical skills in sports (experience on this topic ranging from 7 to 20 years) to formulate new items for the domains of anticipation, positioning, decision-making and game intelligence. A distinction was made between the quality and quantity of these skills. The quality of tactical skills was inferred from the players' self-assessed excellence in the demonstrated tactical skills and the quantity of tactical skills was inferred from the players' self-assessed frequency of displaying the tactical skills.

In the next step we discussed the new items with an expert panel consisting of an embedded scientist, a performance manager and two highly experienced international tennis coaches of the Royal Dutch Lawn Tennis Association (KNLTB). The expert panel offered suggestions for improving the questionnaire, including adding items to assess the ability to read game situations before acting and performing. We then formulated or reformulated items to meet this need (e.g., "*I quickly see when my opponent changes the direction of the ball*"). The expert panel also indicated a need to distinguish between tactical skills when a player has a lot of response time (offensive situation), enough time (neutral situation) or not enough time (defensive situation). Again, we formulated and reformulated items to address this domain in different situations (e.g., "*In making the right decisions when my opponent is under pressure, I am:*" was developed for a situation in which players have a lot of time, the item "*In a cross rally I choose the right moment to open down the line*" was developed for a neutral situation in which players have enough time, and "*My position when I am under pressure from my opponent is:*" was developed for a defensive situation in which players do not have enough time).

In the second phase we examined the readability and comprehension of each item. We piloted a preliminary version of the questionnaire for 13 youth tennis players aged 12–14 years to check the understanding of items within the youngest age groups who would be completing the questionnaire. Players completed the questionnaire individually during tennis practice and were allowed to give comments and suggestions. We confirmed that these young participants understood all items, except two, and we reformulated these two items. Thus, the first and second phase of test development resulted in an initial 38-item TSQT, with content validity supported by the results of the literature review, expert item evaluation and pilot testing. We developed the questionnaire in Dutch and then translated it into English according to the back-translation procedure whereby one researcher with a proficiency in both languages translated the items from Dutch to English and these English items were translated back to Dutch by another bilingual translator. We compared the new translations with the original items and made several minor linguistic modifications to maintain the intended item meanings. The final questionnaire can be found in Supplementary material 1.

TSQT structure

The TSQT consisted of 38 items on a 5-point Likert scale. We chose an uneven-point scale with a neutral middle option to avoid forcing respondents to answer positively or negatively. To minimize response bias, we placed negative options on the left side of the scale and positive options on the right side of the scale (18). As such, the questionnaire provided two semi-negative choices: "almost never" and "sometimes" relating to questions about the quantity of skills and "very mediocre" and "mediocre" relating to questions about the quality of skills. There was one neutral option ("regularly" or "reasonable") and two semi-positive choices ("often" and "almost always" or "good" and "very good"). To improve the reliability, we labeled all options (18). The questionnaire ended with some demographic questions about the respondent's age, gender, tennis level and training hours.

Procedures

We administered the questionnaire to our 233 participants at different tennis clubs and the Royal Dutch Lawn Tennis Association (KNLTB) in the Netherlands. Participants completed the questionnaire individually with a researcher present. A subsample (n = 57) completed the questionnaire twice within 2–4 weeks. The time interval between test and retest was considered long enough to reduce the chance of participants recalling their first answers, and short enough to reduce the chance for a true change of the construct to occur (19).

Statistical analysis

For most statistical analyses, we used the Statistical Package for the Social Sciences for Windows (SPSS, version 26; IBM Corp., Armonk, N.Y., USA). For the confirmatory factor analysis (CFA), we used LISREL for Windows, version 8.80 (20). For all significance tests, we used an α-level of 0.05. We checked normality of the data distribution for items by exploring normality plots and z-scores for skewness and kurtosis. The percentage of missing values across the 38 items varied between 0 and 2.6%. We imputed missing values with regression estimates obtained by predicting missing values with a regression of observed scores on other items. After stratification on age, gender and tennis level, we randomly allocated subjects to the group for PCA (n = 117) and CFA (n = 116).

Principal component analysis

In the third phase, we assessed the adequacy of sampling by Kaiser Meyer Olkin (KMO). We interpreted the KMO using the guidelines of Hutcheson and Sofroniou (21) (0.40 = minimum; 0.50–0.70 = mediocre; 0.70–0.80 = good; 0.80–0.90 = great; >0.90 superb). To determine if correlations between items were sufficiently large to perform a PCA, we used Bartlett's Test of Sphericity. We performed a PCA to examine the component structure of the 38-item questionnaire (i.e., the construct validity). Construct validity refers to whether the items of a questionnaire represent the underlying conceptual structure (22). Due to conceptual considerations, we extracted four components in the analysis. We used an oblique rotation, because all items were intended to measure the same concept and components were assumed to correlate. We deleted items with low communalities (<0.30) and/or items with low component loadings on each component (<0.30). A low communality suggests that the item has little in common with the other items and a low component loading means that the component has a weak association with the principal component score.

Confirmatory factor analysis

In the fourth phase, we used a CFA to verify the four-component model identified by the PCA. We estimated the relationships between the four components and between each item and the corresponding component. We also estimated the explained variance and error variance for each item. We judged the adequacy of model fit by the following fit statistics: comparative fit index (CFI), root mean square error of approximation (RMSEA), and standardized root-mean square residual (SRMR). For the CFI, we considered values of ≥0.90 as acceptable and values of ≥0.95 as good (23, 24). For the RMSEA, we interpreted values of ≤0.06 as good (24). For the SRMR, we considered values of ≤0.08 as acceptable and values of ≤0.06 as good (24–26). We also examined the chi-square value; however, the statistic is highly sensitive to sample size (27). We used modification indices and theoretical arguments to improve the model fit.

Internal consistency

In the fifth phase, we calculated mean item scores for each subscale of the TSQT. To assess the internal consistency of the TSQT, we determined the average inter-item correlation and McDonald's omega for each subscale and Cronbach's alpha for the total scale. In contrast to the commonly reported Cronbach's alpha, McDonald's omega makes fewer and more realistic assumptions and problems associated with inflation and attenuation of internal consistency estimations are far less likely (28). We considered an average inter-item correlation between 0.15 and 0.50 as good (29). In agreement with the guidelines of Nunnally (30) for Cronbach's alpha, we considered McDonald's omega of ≥ 0.7 as acceptable. To determine the relationships between subscales, we calculated Pearson's correlation coefficients based on mean item scores. We interpreted the strength of the relationship as weak (0.10–0.30), moderate (0.30–0.50), or strong (>0.50) (31).

TABLE 1 Items and pattern loadings of the TSQT.

	1	2	3	4
Quantity of tactical skills (1 = almost never and 5 = almost always)				
1. I use the weak spot of my opponent		**0.542**		0.325
2. I quickly see where my opponent is serving to	**0.692**			
3. When I am under pressure from my opponent, I make the right decisions		0.359	**0.614**	
4. In a cross rally I choose the right moment to open down the line			**0.613**	
5. Before my opponent hits the ball, I move toward the right spot	**0.622**			
6. I choose the right moment to change the direction of the ball			**0.309**	0.405
7. When my opponent serves, I quickly move to the right spot	**0.449**			0.306
8. When I want to disrupt my opponent, I change the (top) spin of my balls		**0.507**	0.421	
9. I quickly see where my opponent is standing with my service				**0.755**
10. I incorporate the experiences of earlier points in my decisions		**0.400**		0.468
11. When I want to disrupt my opponent, I change the height of my balls		**0.744**		
12. Before my opponent hits a drop shot, I move forward	**0.656**			
13. When I notice that my tactical plan is not working, I quickly adjust my game		**0.316**	0.344	
14. I quickly see when my opponent changes the direction of the ball	0.420			**0.423**
15. When I am in an attacking position, I see where the open space is				**0.738**
16. When I'm at the net, I quickly see where my opponent is hitting the ball				**0.398**
Quality of tactical skills (1 = very mediocre and 5 = very good)				
17. The decisions I make about my next stroke are generally:			**0.652**	
18. In moving to the spot where my opponent serves, I am:	**0.350**			
19. In making the right decisions at the right time, I am:			**0.680**	
20. My choice from various options to score a point is generally:			**0.568**	
21. In varying my strokes at the right time, I am:			**0.654**	
22. In being at the right spot at the right time, I am:	**0.720**			
23. My game intelligence is:	**0.421**		0.327	
24. In making the right decisions when my opponent is under pressure, I am:				**0.407**
25. My position on the court is:	**0.516**			
26. In determining the depth of an incoming ball, I am:	**0.597**			
27. My position when I am under pressure from my opponent is:	**0.499**			
28. In recognizing game situations, I am:	0.382	**0.407**		
29. In quickly recognizing my opponent's weak spot, I am:		0.467		**0.547**
30. My position when I put pressure on my opponent is:				**0.613**
31. In responding to a defensive ball of my opponent, I am:			**0.592**	

Extraction method: Principal component analysis; Rotation Method: Oblimin with Kaiser Normalization.
Pattern loadings <0.30 are not displayed, pattern loadings on the allocated component for the CFA are presented in bold.
Component 1 (Anticipation and positioning) = items 2, 5, 7, 12, 18, 22, 23, 25, 26, 27.
Component 2 (Game intelligence and adaptability) = items 1, 8, 10, 11, 13, 28.
Component 3 (Decision-making) = items 3, 4, 6, 17, 19, 20, 21, 31.
Component 4 (Recognizing game situations) = items 9, 14, 15, 16, 24, 29, 30.

Test-retest reliability

In the sixth phase, we assessed test-retest reliability with a subsample of 57 tennis players (34 males, 23 females; age: 18.78 ± 4.60 years). The size of the subsample corresponds with the recommended sample size of at least 50 participants for test-retest reliability (32, 33). We determined the absolute and relative reliability of the TSQT. Absolute reliability refers to the degree to which repeated measurements vary for individuals. Relative reliability refers to the ability of individuals to maintain their rank in a sample with repeated measurements (34). To estimate the absolute test-retest reliability of the TSQT, we calculated mean differences between test and retest, with 95% confidence intervals. We assessed the relative test-retest reliability by intraclass correlation coefficients (ICC) with 95% confidence intervals based on single ratings, consistency and two-way mixed-effects model. We interpreted the ICC values using the guidelines of Koo and Li (35) (<0.5 = poor; 0.5–0.75 = moderate; 0.75–0.90 = good; >0.90 = excellent).

Discriminative validity

In the last phase, we evaluated discriminative validity within a sample of 218 players since the competitive level of 15 players was unknown. Players were classified as national or regional according to their competitive level of performance. National players competed nationally (usually throughout the Netherlands) or internationally (usually in other countries), while regional players usually competed in their own region in the Netherlands. The sample consisted of 88 national players (54 males, 34 females; age: 15.61 ± 4.35 years) and 130 regional players (97 males, 33 females; age: 18.07 ± 4.70 years). We assessed the discriminative validity by a one-way multivariate analysis of covariance (MANCOVA) with performance level as between-subjects factor (national vs. regional) and four subscales as dependent variables, whilst controlling for age and sex as covariates. We hypothesized that national players would outperform regional tennis players on the different subscales of the TSQT.

Results

Principal component analysis

The KMO measure of sampling adequacy was 0.82, which was considered great, and Bartlett's test of sphericity was significant [$\chi^2_{(703)} = 1{,}790.28$, $p < 0.001$] indicating that there was a certain redundancy between the items that could be summarized with a few components. The initial PCA yielded a four-component model that explained 42.1% of the variance. Six items with communalities of <0.30 and one item with a pattern coefficient of <0.30 were removed from the questionnaire for subsequent analysis. A second PCA was performed on the retained 31 items. Items and pattern loadings are presented in Table 1. In total, the four components accounted for 47.0% of the variance (27.6, 7.4, 6.5, and 5.5%, respectively, before rotation). The components were labeled "Anticipation and positioning" (Component 1, 10 items), "Game intelligence and adaptability" (Component 2, 6 items), "Decision-making" (Component 3, 8 items), and "Recognizing game situations" (Component 4, 7 items).

Confirmatory factor analysis

The initial CFA indicated acceptable model fit for the 31-item, four-component model identified by EFA ($\chi^2 = 569.94$, df = 428, $p < 0.001$, CFI = 0.91, RMSEA = 0.054, SRMR = 0.083). Modification indices suggested to add a path from the item "My game intelligence is" to "Game intelligence and adaptability" to improve model fit. The item corresponds with the content of the component; therefore, this path was added. After that, the non-significant loading of the item to "Anticipation and positioning" was deleted. Furthermore, modification indices suggested to add covariances between error terms. Therefore, the covariance between three pairs of error terms was added. The final CFA resulted in an acceptable to good model fit ($\chi^2 = 527.02$, df = 426, $p < 0.001$, CFI = 0.93, RMSEA = 0.045, SRMR = 0.079). The TSQT includes four subscales "Anticipation and positioning" (9 items), "Game intelligence and adaptability", (7 items), "Decision-making" (8 items), and "Recognizing game situations" (7 items).

Internal consistency

Descriptive statistics and internal consistency of the four subscales are displayed in Table 2. Overall, the TSQT was found to be highly reliable ($\alpha = 0.89$).

The relationship between subscales is shown in Table 3. The largest positive correlation was found between the subscales "Decision-making" and "Recognizing game situations" ($r = 0.62$).

Test-retest reliability

Descriptive statistics of the absolute and relative reliability of the TSQT are shown in Table 4. A value of 0 was within the 95% confidence interval of the mean differences between test (T1) and retest (T2), supporting the absolute reliability of the TSQT. Moderate relative reliability was observed for the subscales "Anticipation and positioning" (ICC = 0.66), "Game intelligence and adaptability" (ICC = 0.65), "Decision-making" (ICC = 0.71), and "Recognizing game situations" (ICC = 0.69).

Discriminative validity

Table 5 shows descriptive statistics of national and regional players for each subscale. One-way MANCOVA showed a difference between national and regional players on the combined dependent variables after controlling for age and sex, $F_{(4,211)} = 5.245$, $p < 0.001$; Wilk's $\Lambda = 0.910$, partial $\eta^2 = 0.090$. Follow-up analyses showed that national players scored higher than regional players on the subscales "Game intelligence and adaptability" ($p < 0.001$), "Decision-making" ($p < 0.001$) and "Recognizing game situations" ($p < 0.01$), and there was a trend toward significance for "Anticipation and positioning" ($p = 0.07$).

Discussion

Our aim in the present study was to develop and evaluate the psychometric properties of the TSQT with a sample of competitive tennis players. Findings of this study supported its

TABLE 2 Descriptive statistics, McDonald's omega, and average inter-item correlation coefficients of subscales of the TSQT ($n = 233$).

	M	*SD*	McDonald's omega	Inter-item correlation
Anticipation and positioning (9 items)	3.47	0.54	0.78	0.29
Game intelligence and adaptability (7 items)	3.55	0.57	0.69	0.25
Decision-making (8 items)	3.46	0.51	0.77	0.30
Recognizing game situations (7 items)	3.68	0.55	0.73	0.29

TABLE 3 Pearson correlations between subscales of the TSQT.

	Anticipation and positioning	Game intelligence and adaptability	Decision-making	Recognizing game situations
Anticipation and positioning	1			
Game intelligence and adaptability	0.51*	1		
Decision-making	0.48*	0.51*	1	
Recognizing game situations	0.55*	0.50*	0.62*	1

*$p < 0.01$.

content validity, construct validity, internal consistency, test-retest reliability and discriminative validity.

We affirmed content validity by the results of the literature review and item evaluation by the expert panel. Previous studies have shown the relevance of tactical skills for elite tennis players (6, 9, 36). In the common categorization of tactical skills based on declarative or procedural knowledge, it appeared that procedural knowledge discriminated best between the more and the less successful field hockey and soccer players (13, 37). To avoid a ceiling effect in the answers for tennis players at the highest level, we specifically developed items about procedural knowledge, i.e., "doing it" in tennis. We adapted numerous items for procedural knowledge from the TACSIS and applied them to tennis. We formulated novel items around the construct of tactical skills. All items were checked by the expert panel and four authors of this study who confirmed that they represent tactical skills in tennis.

With the PCA and CFA, we omitted seven items from the original 38-item questionnaire because they made insufficient contribution to the component (i.e., the pattern loading was too low) or they loaded on the non-hypothesized component. For example, we deleted the item "*My choice to lob or pass when my opponent is at the net is:*" due to a low pattern loading. The item touches on more than one issue (i.e., choice to lob and choice to pass), but leaves room for only one response. Respondents might have understood this double-barreled item differently, resulting in a weak influence on the component. Final analyses resulted in a 31-item TSQT, composed of four subscales: "Anticipation and positioning" (9 items), "Game intelligence and adaptability" (7 items), "Decision-making" (8 items), and "Recognizing game situations" (7 items). The four subscales of the TSQT are considered to represent important domains of tactical skills in tennis, supporting the construct validity of the TSQT. Nevertheless, the four-component model structure explained merely 47% of variance in the instrument, suggesting that tactical skills may be affected by a broader range of factors than are assessed within this scale.

We confirmed the internal consistency of the TSQT by average inter-items correlations from 0.25 to 0.30, Cronbach's α of 0.89 and McDonald's ω ranging between 0.69 and 0.78 for the separate subscales. These coefficients were similar to those reported for the TACSIS (12). The high internal consistency found in the present study clearly demonstrates that the items of the TSQT measure the same concept. This is supported by the positive correlations between the subscales. Moreover, the subscales of the TSQT were absolutely and relatively stable over time, indicating that the TSQT is a reliable questionnaire for examining these skills in competitive tennis players. The time interval of 2–4 weeks between test and retest was considered long enough to make the players forget their answers from the first test, and short enough for players to improve their tactical skills. The ICC values for the subscales were between 0.65 and 0.71, indicating that the TSQT meets moderate to acceptable levels of reliability for application in a group of competitive tennis players (35). The ICC values were similar to those reported in youth hockey players for the subscales of the TACSIS (ICC 0.60–0.88) (12).

We largely confirmed the discriminative validity of the TSQT by differences between national and regional players on the TSQT and the subscales "Game intelligence and adaptability," "Decision-making," and "Recognizing game

TABLE 4 Test-retest reliability for each subscale of the TSQT ($n = 57$).

	$M \pm SD$ T1	$M \pm SD$ T2	$M \pm SD$ T1–T2	SE T1–T2	95% CI T1–T2	ICC	95% CI ICC
Anticipation and positioning	3.42 ± 0.52	3.49 ± 0.51	−0.06 ± 0.43	0.06	−0.180–0.050	0.658	0.483–0.783
Game intelligence and adaptability	3.52 ± 0.54	3.51 ± 0.58	0.02 ± 0.48	0.06	−0.112–0.143	0.652	0.473–0.780
Decision-making	3.33 ± 0.48	3.38 ± 0.49	−0.09 ± 0.37	0.05	−0.185–0.012	0.703	0.544–0.814
Recognizing game situations	3.60 ± 0.60	3.51 ± 0.60	0.11 ± 0.47	0.06	−0.014–0.238	0.685	0.519–0.802

M ± SD of T1–T2 = mean difference between the score for the first and second measurement; SE of T1–T2 = standard error of the mean difference; 95% CI T1–T2 = 95% confidence interval for the mean difference; ICC, intraclass correlation coefficient; 95% CI for ICC = 95% confidence interval for intraclass correlation coefficient.

TABLE 5 Descriptive statistics of national and regional players for each subscale of the TSQT ($n = 218$).

	National ($n = 88$)		Regional ($n = 130$)					
	M	*SD*	*M*	*SD*	*F*	*df*	*p*	ηp2
Anticipation and positioning	3.53	0.57	3.42	0.53	3.309	1, 214	0.070	0.015
Game intelligence and adaptability	3.69	0.56	3.42	0.57	13.155	1, 214	<0.001	0.058
Decision-making	3.64	0.51	3.32	0.48	16.139	1, 214	<0.001	0.070
Recognizing game situations	3.83	0.53	3.56	0.54	9.975	1, 214	0.002	0.045

situations". These results are in line with the results of a systematic review showing that players with higher performance levels display superior tactical skills than players whose performance levels are lower (9). However, national players did not outperform regional players on the subscale "Anticipation and positioning", although this finding almost reached statistical significance ($p = 0.07$), but the effect size was small at 0.015, measured by partial-eta squared. One possible explanation for the non-significant finding could be that the sample size was too small, and the study might have been underpowered to detect differences between performance levels for each subscale of the TSQT. It could also be possible that differences in performance level between the national and regional youth players might have been too small to discriminate performance levels for all subscales. An alternative explanation might be that the items underlying the subscale "Anticipation and positioning" were not precise enough to detect differences at the group level.

There are several practical applications of the TSQT. Evaluating self-assessed tactical skills in tennis players provides players, coaches and other professionals with insight in players' tactical skills. They can use the TSQT to reflect on player's self-assessed strengths and weaknesses. This can open the discussion about the content of the training programs and designing tailor-made exercises to optimize performance development. With the TSQT, one can specifically target areas for development such as working on, for example, "choosing the right moment to open down the line in a cross rally". If it becomes clear that a player assesses him- or herself low on this item from the subscale "Decision-making", the coach can create a training environment in which the player is challenged in this situation specifically. Focusing on a player's strengths is crucial as well, so that players can learn to use their strengths in order to win matches. The TSQT can also assist in making players aware of their development areas and stimulate their self-regulated learning. By having them self-assess their tactical skills, they are stimulated to share and take responsibility for their own developmental process. Various studies among talented athletes have shown the value of well-developed self-regulatory skills, such as reflection, for performance and performance development (38–40). It is essential to realize that due to the characteristics of the TSQT, being a self-report measure, it is not suitable for selection purposes. Players may give socially desirable answers if they feel that reporting less-developed domains of tactical skills may have adverse effects for them, such as decreasing their chances for selection. This makes the comparison between individual players based on their responses on the TSQT questionable.

The advantage of a self-report measure such as the TSQT lies not only in its value for creating moments of reflection of players. The questionnaire also opens up the opportunity to assess large groups in a relatively easy way and derive rich contextual information. In addition, since it taps into the accumulated know-how of players and covers multiple training and game situations, it is less influenced by a player's shape of the day or opponent compared to so called "objective" measures of tactical skills. Objective methods of assessing tactical skills include measures that directly assess observed performance in one or more tactical domains. These methods may use a variety of metrics, such as number of eye fixations and correct responses for anticipating groundstroke type and direction [see for a review (9)]. Although no gold standard for objective tactical skills assessment has emerged, popular measures include temporal occlusion paradigms, stick-figure stimulations and observational instruments (5, 41, 42). Despite it can be argued that objective measures have the advantage for obtaining unbiased, reliable data, these measures merely focus on one or a limited number of aspects of tactical performance which are observed during a limited number of training sessions or games. This may be one of the reasons why in a study on soccer players no statistically significant relationship between self-assessed tactical skills as measured by the TACSIS and objective tactical performance during small sided games has been found (43). In addition, not seldom, objective measures of tactical skills are expensive and time-consuming. This makes them less suitable if one aims to assess tactical skills over the course of multiple training and game situations in large groups.

Several strengths and weaknesses of this study are acknowledged. One strength of the current study was that it focused on both the quantity and quality of tactical skills. By gaining insight in both factors, an appropriate picture can be obtained from player's tactical skills. The importance of both factors seems to be confirmed by the fact that the ratio of the remaining items in terms of quantity and quality is similar after the PCA and CFA as in the initial 38-items questionnaire. A weakness of the study was related to the relatively small sample size for PCA and CFA. The literature about factor analysis provides a wide range of rough guidelines regarding an adequate sample size. Most of these guidelines consistently advocate for an absolute minimum sample size to obtain decent factor solutions, ranging from an ideal sample size of at least 50–1,000 participants (15, 44, 45). Other studies recommend a minimum sample size from 3 to 20 times the number of items (15). The sample size of this study is within these recommended ranges, but near the required minimum (15, 44, 45). However, for most of these recommendations there is little empirical evidence. In addition, the adequacy of sampling was supported with the KMO above 0.8. Moreover, Barlett's test of sphericity was significant ($p < 0.001$), indicating that it was reasonable to proceed with PCA even considering the small sample size. The application of the TSQT in other countries, cultures, performance groups, age categories and racquet sports require the verification of the conclusions in the current sample, consisting of competitive tennis players from the Netherlands. To improve feasibility, it should be examined if the psychometric properties of the TSQT are maintained if the scale consists of fewer items measuring the same construct. Future research should focus on assessing tactical skills with the TSQT longitudinally to detect any improvements in tactical skills over time due to a training program. Moreover, it would be interesting for further studies to assess tactical skills in large groups to define benchmarks per age category and males and females separately.

In conclusion, findings from this study provide coaches and other professionals with a valid and reliable questionnaire for assessing tactical skills in competitive tennis players. Evaluating tactical skills with the TSQT provides players, coaches and other professionals with insight in players' self-assessed tactical skills over the course of multiple training and game situations. It creates the opportunity for players to reflect on their tactical skills and detect personal development areas with their coach. It is advised to use this information as input for tailor-made training programs.

Data availability statement

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

Ethics statement

The studies involving human participants were reviewed and approved by Psychology Department of the University of Groningen. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

NK, ME-G, BH, and CV contributed to the study conception and design. NK collected the data and wrote the first draft of the manuscript. NK and MH analyzed the data. NK, MH, ME-G, BH, and CV reviewed and edited previous versions of the manuscript, read, and approved the final version of the manuscript. All authors contributed to the article and approved the submitted version.

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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

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2022.988595/full#supplementary-material

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Effects of athletic training on physical fitness and stroke velocity in healthy youth and adult tennis players: A systematic review and meta-analysis

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Better physical fitness and stroke velocity in healthy elite compared to sub-elite tennis players have been shown in previous studies. However, evidence-based knowledge regarding the effectiveness of athletic training on physical fitness and stroke velocity is currently lacking. Thus, the objective of this systematic review with meta-analysis was to characterize, aggregate, and quantify athletic training effects on measures of physical fitness and stroke velocity in healthy youth and adult tennis players. A computerized systematic literature search was performed in the databases PubMed, Web of Science, and SportDiscus from their inception date to August 2022. Studies were included, among others, if the intervention period lasted a minimum of four weeks and if at least one parameter of physical fitness (i.e., speed, agility, lower-extremity muscle power, upper-extremity muscle power/strength, endurance, balance, flexibility) or stroke performance (i.e., stroke velocity) was tested. Initially, 11,511 articles were identified, after removing duplicates and assessing abstracts and full texts, 24 articles were used to calculate weighted standardized mean differences (*SMD*). For measures of physical fitness, athletic training resulted in small (speed: *SMD* = 0.44), moderate (endurance: *SMD* = 0.61, upper-extremity muscle power: *SMD* = 0.72; flexibility: *SMD* = 0.63), and large (agility: *SMD* = 0.93, lower-extremity muscle power: *SMD* = 0.88; upper-extremity muscle strength: *SMD* = 0.90; balance: *SMD* = 0.88) effects. Further, a large effect (*SMD* = 0.90) on stroke velocity was detected. The additionally performed sub-analyses showed differences in the effectiveness of athletic training on variables of physical fitness and stroke speed when considering players' age (i.e., youth players: $<$18 years; adult players: $\geq$18 years). Precisely, there was a high potential for training-related adaptations in adult players with respect to lower-extremity muscle power, upper-extremity muscle strength, and stroke velocity and in youth players with respect to endurance. Interventions to promote physical fitness and stroke velocity in healthy tennis players revealed varying levels of effectiveness ranging from small to large and these were additionally affected by players' age. Therefore, future studies should investigate modalities to increase training efficacy in youth and adult tennis players, especially for fitness components that showed small- to moderate-sized changes.

KEYWORDS

intervention, muscle power/strength, agility, speed, balance, flexibility, endurance, stroke speed

1. Introduction

Tennis is a popular sport and is characterized by high demands on both physical fitness (e.g., strength, power, agility, speed etc.) and technical (i.e., serve/stroke technique) factors. Both factors are used to distinguish successful from less successful players, which makes them particularly relevant for training purposes. In this regard, several cross-sectional studies (1–8) and a systematic review with meta-analysis (9) showed significant differences for both stroke velocity and the underlying physical fitness components (e.g., agility, muscle power, endurance, speed) in tennis players depending on their competition level. For example, Kramer et al. (1) detected shorter 10 m sprint times, better agility scores in the Spider test, and higher jump values in elite compared to sub-elite youth male and female players. Further, Ulbricht et al. (2) determined higher stroke velocities for the tennis serve in elite vs. sub-elite youth male and female players. Therefore, the question arises about the effectiveness of athletic training to increase variables of physical fitness and stroke performance in healthy tennis players. With regard to physical fitness, intervention studies with adult players showed beneficial effects on speed, muscle strength, and endurance (10, 11). However, a recent systematic review by Xiao et al. (12) reported a differentiated picture describing (a) significant performance improvements for speed and agility, (b) conflicting evidence regarding muscle power, and (c) no evidence with respect to muscle strength, flexibility, and endurance as a result of athletic training. These discrepancies between findings are most likely due to the fact that Xiao and colleagues only included studies with 12- to 18-year-olds, in whom processes of growth, maturation, and development are still ongoing compared to adults (13). Regarding stroke velocity, positive effects of athletic training were also reported in male youth and adult players (14, 15). Consistent with these findings from original studies, a recent review also reported training-related improvements in tennis serve velocity for the majority of included studies (16).

Although the aforementioned studies have increased the knowledge about the effects of athletic training programs on variables of physical fitness and stroke velocity in healthy youth tennis players, a systematic characterization, aggregation and, most importantly, quantification of the reported intervention effects especially for adult players is still lacking. Therefore, the purpose of the present systematic review with meta-analysis was to characterize, aggregate, and quantify the effects of athletic training on measures of physical fitness and stroke velocity in healthy youth (<18 years) and adult (≥18 years) tennis players. We assumed that athletic training leads to improvements in variables of physical fitness and stroke velocity, but effectiveness will differ with respect to of players' age (i.e., youth vs. adult tennis players).

2. Methods

2.1. Search strategy

A systematic literature search of the PubMed, Web of Science, and SportDiscus databases was performed to identify eligible articles. The following Boolean expression was used:

Tennis AND ((training OR practice OR exercise OR intervention OR program OR drill) AND (functional OR performance OR agility OR flexibility OR athletic OR strength OR power OR speed OR fitness OR physical OR stroke OR balance OR resistance)) NOT table.

The search covered the period between their inception date and August 2022. Only articles written in English with full-text access were included. In addition, the reference lists of included studies and relevant reviews were screened for relevant studies. After all duplicates were removed, both authors screened the title and abstract of all articles for eligibility according to the inclusion and exclusion criteria (**Table 1**). The full texts of all potentially eligible records were independently assessed by both authors and disagreements resolved through discussion and consents. The process of literature search, study selection, and exclusion criteria is presented in **Figure 1** using the PRISMA flow chart (17).

2.2. Study selection criteria

The inclusion and exclusion criteria are presented in **Table 1**. Studies were eligible for this review if they (a) examined healthy tennis players, (b) conducted an athletic or sport-specific intervention, (c) had a control condition, (d) reported at least one parameter of physical fitness or stroke velocity, and (e) performed an intervention that lasted at least four weeks as suggested by Farrell and Turgeon (18). Studies were excluded if (a) injured tennis players or no tennis players were studied, (b)

TABLE 1 Overview of the inclusion and exclusion criteria.

Category	Inclusion criteria	Exclusion criteria
Population	Healthy female and male tennis players	Injured tennis players; no tennis players; beginner tennis players
Intervention	Athletic training; physical exercise; sport-specific intervention	Motor imagery; electromyostimulation
Comparison	Control group	No control condition
Outcome	At least one parameter of physical fitness or stroke velocity	Data did not allow to calculate effect size
Study design	Intervention studies with ≥4 weeks of training	Intervention studies with <4 weeks of training; no English full text

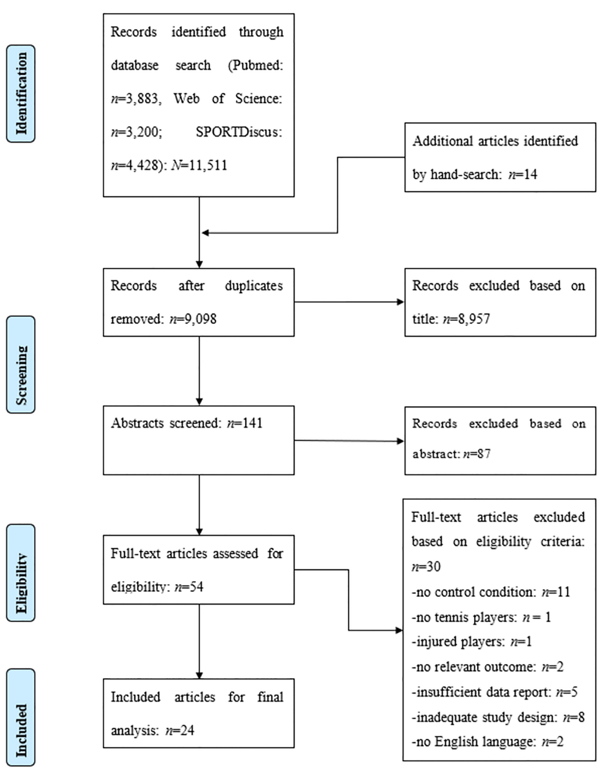

FIGURE 1
PRISMA flow chart illustrating the different phases of literature search, study selection, and reasons for exclusion of records.

the intervention consisted of non-physical exercises (e.g., motor imagery) or electromyostimulation was performed, (c) no control condition was present, (d) results did not allow the calculation of effect size, (e) acute effects (i.e., <4 weeks) of an intervention were studied, and (f) they were not published in English language.

2.3. Study coding

Included studies were coded using the following variables: author and year of publication, number of participants, sex, age, and study group with type of intervention. Interventions were coded based on the number of weeks of training, frequency and duration of a training session, and the number of sets and repetitions. If there were increases in volume during the intervention period, ranges were reported.

The following categories of physical fitness were differentiated: speed, agility, lower-extremity muscle power, upper-extremity muscle power/strength, endurance, balance, and flexibility. Further, stroke velocity was characterized *via* sport-specific assessments (i.e., serve test, forehand test). Because studies reported different parameters for each category, the most frequently reported measure was used to reduce heterogeneity between studies (**Table 2**).

2.4. Assessment of methodological quality

To assess the methodological quality of the included studies, the Physiotherapy Evidence Database (PEDro) scale was used (19). The PEDro scale rates study validity and statistical replicability of studies on a scale of 0 to 10, with ≥6 representing a cut-off score for high-quality studies (19). The predefined cut-off score of ≥6 points was not an inclusion or exclusion criterion. Quality assessment of the included studies was performed independently by both authors, and disagreements were resolved through discussion and consensus.

2.5. Statistical analyses

To quantify the effectiveness of athletic training programs on measures of physical fitness and stroke velocity, the within-subject standardized mean difference was calculated as SMD_W = (pretest mean value – posttest mean value)/pretest standard deviation and the between-subject standardized mean difference as SMD_b = (posttest mean value in the experimental group – posttest mean value in the control group)/pooled standard deviation (20) using Review Manager version 5.4.1. SMD_W and SMD_b can be positive or negative. Positive SMD_W values indicate an improvement in performance (i.e., increase in stroke velocity) from pretest to posttest, while negative SMD_W values indicate a decrease in performance (i.e., decrease in stroke velocity). Positive SMD_b values indicate an improvement in performance in favor of the experimental group (EG), while negative values indicate an improvement in favor of the control group (CG). The *SMD* values were reported for all players (6–42 years) as well as for youth (<18 years) and adult (≥18 years) players, separately.

SMD_W and SMD_b values can be classified and interpreted according to Cohen (21) into the following ranges: $0 \leq 0.49$ representing small effects, $0.50 \leq 0.79$ representing moderate effects, and ≥0.80 representing large effects. Further, heterogeneity (I^2) was computed by using the formula provided by Deeks et al. (22): $I^2 = (Q - df/Q) * 100\%$ where Q is the chi-squared statistics and df represents the degrees of freedom (23). This measure describes the percentage of the variability in effect estimates that is due to heterogeneity rather than sampling error (chance). Deeks et al. (22) postulate that heterogeneity can be interpreted as trivial ($0 \leq 40\%$), moderate ($30 \leq 60\%$), substantial ($50 \leq 90\%$), or considerable ($75 \leq 100\%$).

TABLE 2 Overview of the preferred and alternative outcome by category.

Category	Preferred outcome	Alternative outcome
Speed	20 m sprint time in seconds ($n = 5$)	10 m sprint time seconds ($n = 4$)
Agility	5-0-5 agility test time in seconds ($n = 4$)	T-agility test in seconds ($n = 2$) Spider test in seconds ($n = 2$) Lateral agility test in seconds ($n = 1$) Illinois agility test in seconds ($n = 1$) Foran test in seconds ($n = 1$)
Lower-extremity muscle power	Countermovement jump height in cm ($n = 6$)	Vertical jump height in cm ($n = 3$)
Upper-extremity muscle power	Medicine ball throw in cm ($n = 1$)	seated medicine ball throw in cm ($n = 1$) Overhead medicine ball throw in km/h ($n = 1$)
Upper-extremity muscle strength	Handgrip strength ($n = 3$)	10-RM chest press in kg ($n = 1$) 1-RM bench press in kg ($n = 1$)
Endurance	VO_2max in ml/min/kg ($n = 2$)	VIFT in km/h ($n = 1$) Wingate anaerobic power test in no. ($n = 1$) Ergometer test in Watt ($n = 1$)
Balance	Y-balance test in cm ($n = 2$)	N/A
Flexibility	Sit-and-reach test in cm ($n = 2$)	N/A
Stroke performance	Maximal stroke velocity in km/h ($n = 14$)	Mean stroke velocity in km/h ($n = 1$)

The figure in brackets indicates the number of studies that made use of the test. N/A, not available; RM, repetition maximum; VIFT, velocity of the intermittent fitness test.

3. Results

3.1. Study selection

Figure 1 illustrates the different stages of the systematic literature search and the process of study selection. The search term resulted in 11,511 articles to be reviewed. In addition, 14 studies from other sources (i.e., reference lists, review articles) were added. After removing duplicates and screening titles and abstracts, 54 studies were screened for eligibility. Of these, 30 were excluded for the following reasons: eleven studies did not include a control group, one study did not examine tennis players, one study examined injured tennis players, two studies did not report relevant parameters (e.g., physical fitness, stroke velocity), five studies did not provide sufficient information on outcome measures, eight studies did not use an adequate study design, and two studies were not written in English language.

3.2. Study characteristics

Table 3 shows the characteristics of the 24 included studies. A total of 509 subjects aged between 6 and 42 years were investigated. Fifteen studies (14, 26, 28, 30, 31, 33–37, 39–43) examined youth tennis players under 18 years and nine reports (10, 11, 15, 24, 25, 27, 29, 32, 38) were conducted with adult tennis players aged between 18 and 42 years. Thirteen studies (14, 15, 24, 27–29, 31, 33, 34, 36, 39, 42, 43) investigated male tennis players, three studies (10, 11, 41) tested female players, five studies (25, 26, 30, 35, 40) examined both sexes while three studies (32, 34, 37) did not specify players' sex. Regarding performance level, four studies (10, 11, 25, 27) analyzed college players, three studies (28, 33, 34) examined national ranked players, two papers (24, 29) analyzed tournament players, one report each investigated competitive players (42), international ranked players (34), and ITN Level 3 (15). Twelve studies did not specify the players' performance level.

3.3. Outcome measures

Fourteen studies (10, 11, 27, 30, 31, 33, 34, 36–38, 40–43) investigated the influence of athletic training on measures of physical fitness and 15 studies (10, 11, 14, 15, 24–26, 28, 29, 32, 33, 35, 37, 39, 40) on parameters of stroke velocity. In terms of physical fitness, nine studies (10, 11, 31, 33, 34, 36, 40–42) examined lower-extremity muscle power and three studies (11, 33, 40) assessed upper-extremity muscle power. Five articles (10, 11, 31, 34, 41) analyzed tennis-specific endurance, eleven articles (11, 27, 30, 33, 34, 36–38, 41–43) investigated agility, nine studies (11, 30, 31, 33, 34, 36, 40–42) evaluated speed, two papers (11, 36) explored balance, three articles (36, 40, 41) studied flexibility, and five studies (10, 11, 14, 40, 41) quantified upper-extremity muscle strength.

TABLE 3 Studies examining the effects of athletic training programs on measures of physical fitness and stroke velocity in healthy tennis players.

Reference	No. of subjects (sex); age [years (range or mean ± SD)]; performance level	Groups/training devices	Trainings modality No. of training weeks/frequency/sessions, single session duration, total duration per week No. of sets, reps, duration per exercise	Exercises	Test modality	Results
Mont et al. (24)	30, M; 18–42 years; tournament level	EG1 ($n = 8$): eccentric internal and external shoulder training EG2 ($n = 9$): concentric internal and external shoulder training CG ($n = 13$): no training	6 wk, 3 d, 18 sessions, N/A, N/A 8 sets of 10 reps	Isokinetic shoulder rotation	*Stroke performance:* Maximal serve velocity [km/h]	EG1-pp: $SMD_W = 0.77$ EG2-pp: $SMD_W = 1.86$ CG-pp: $SMD_W = 0.13$ EG1-CG: $SMD_b = 0.93$ (0.01, 1.86) EG2-CG: $SMD_b = 0.66$ (−0.22, 1.53)
Treiber et al. (25)	22, F (11), M (11); 21,2 years; college level	EG ($n = 11$): shoulder resistance training CG ($n = 11$): regular tennis training	4 wk, 3 d, 12 sessions, N/A, N/A 2–4 sets of 20 reps	TheraBand exercises (slow and quick); "Empty can" exercises with light dumbbell	*Stroke performance:* Maximal serve velocity [km/h]	EG-pp: $SMD_W = 0.38$ CG-pp:$SMD_W = -0.12$ EG-CG: $SMD_b = 0.25$ (−0.58, 1.09)
Kraemer et al. (10)	24, F; 17–21 years; college level	EG1 ($n = 8$): periodized training EG2 ($n = 8$): single-set circuit resistance training program CG ($n = 8$): regular tennis training	9 mo, 2–3 d, 100 sessions, 90 min; 180–270 min 14 exercises EG1: 2–4 sets of 4–6, 8–10 or 12-15 reps EG2: 1 set of 8–10 reps	Leg press, bench press, single curls, bent over rows, dumbbell lunge, split squat, military press, single knee, front pull downs, back extensions, internal/external rotations, sit-ups/crunches, hip tucks, wrist extensions/curls	*Lower-extremity muscle power:* Vertical jump height [cm]	EG1-pp: $SMD_W = 1.02$ EG2-pp: $SMD_W = 0.19$ CG-pp: $SMD_W = 0.05$ EG1-CG: $SMD_b = 0.54$ (0.14, 2.27) EG2-CG: $SMD_b = 0.07$ (−0.91, 1.05)
					Upper-extremity muscle strength: 1-RM bench press [kg]	EG1-pp: $SMD_W = 1.42$ EG2-pp: $SMD_W = 1.64$ CG-pp: $SMD_W = 0.26$ EG1-CG: $SMD_b = 2.13$ (0.90, 3.36) EG2-CG: $SMD_b = 1.78$ (0.62, 2.94)
					Endurance: Ergometer test [Watt]	EG1-pp: $SMD_W = 0.80$ EG2-pp: $SMD_W = 0.16$ CG-pp: $SMD_W = 0.05$ EG1-CG: $SMD_b = 1.37$ (0.28, 2.46) EG2-CG: $SMD_b = 0.26$ (−0.72, 1.25)
					Stroke performance: Maximal serve velocity [m/s]	EG1-pp: $SMD_W = -0.84$ EG2-pp: $SMD_W = -1.84$ CG-pp: $SMD_W = -0.41$ EG1-CG: $SMD_b = 0.17$ (−0.79, 1.12) EG2-CG: $SMD_b = 0.06$ (−0.87, 0.99)

(*continued*)

TABLE 3 Continued

Reference	No. of subjects (sex); age [years (range or mean ± SD)]; performance level	Groups/training devices	Trainings modality No. of training weeks/frequency/sessions, single session duration, total duration per week No. of sets, reps, duration per exercise	Exercises	Test modality	Results
Kraemer et al. (11)	27, F; 19 ± 1 years; college level	EG1 ($n = 9$): non-linear periodized resistance training EG2 ($n = 10$): non-periodized resistance training CG ($n = 8$): regular tennis practice	9 mo, 2–3 d, 100 sessions, 90 min; 180–270 min 12 exercises EG1: 2–3 sets of 4–6, 8–10 or 12–15 reps EG2: 2–3 sets of 8–10 reps	Leg press, bench press, single curls, bent over rows, dumbbell lunge, split squat, military press, single knee extensions, internal/external rotations, sit-ups/crunches, hip tucks, wrist extensions/curls	*Endurance:* VO2max [ml/kg/min]	EG1-pp: $SMD_W = 1.97$ EG2-pp: $SMD_W = 0.14$ CG-pp: $SMD_W = -0.32$ EG1-CG: $SMD_b = 2.51$ (1.20, 3.82) EG2-CG: $SMD_b = 0.68$ (−0.33, 1.68)
					Speed: 20 m sprint [s]	EG1-pp: $SMD_W = 0.38$ EG2-pp: $SMD_W = 0$ CG-pp: $SMD_W = 0.41$ EG1-CG: $SMD_b = 0.39$ (−0.58, 1.35) EG2-CG: $SMD_b = 0.29$ (−0.64, 1.23)
					Agility: Lateral agility test [s]	EG1-pp: $SMD_W = -0.38$ EG2-pp: $SMD_W = -0.14$ CG-pp: $SMD_W = 0.16$ EG1-CG: $SMD_b = 0.47$ (−0.50, 1.43) EG2-CG: $SMD_b = 0.25$ (−0.69, 1.18)
					Upper-extremity muscle strength: Handgrip strength [kg]	EG1-pp: SMD_W 0.64 EG2-pp: SMD_W 0.74 CG-pp: $SMD_W - 0.34$ EG1-CG: SMD_b 1.12 (0.09, 2.14) EG2-CG: SMD_b 0.87 (−0.10, 1.84)
					Lower-extremity muscle power: Vertical jump height [cm]	EG1-pp: $SMD_W = 3.01$ EG2-pp: $SMD_W = 2.17$ CG-pp: $SMD_W = 0.51$ EG1-CG: $SMD_b = 2.64$ (1.34, 3.94) EG2-CG: $SMD_b = 1.89$ (0.77, 3.01)
					Stroke performance: Maximal serve velocity [m/s]	EG1-pp: $SMD_W = 1.95$ EG2-pp: $SMD_W = 1.03$ CG-pp: $SMD_W = -0.41$ EG1-CG: $SMD_b = 2.79$ (1.46, 4.13) EG2-CG: $SMD_b = 2.29$ (1.10, 3.49)

(*continued*)

TABLE 3 Continued

Reference	No. of subjects (sex); age [years (range or mean ± SD)]; performance level	Groups/training devices	Trainings modality No. of training weeks/frequency/sessions, single session duration, total duration per week No. of sets, reps, duration per exercise	Exercises	Test modality	Results
Malliou et al. (26)	40, both genders; 13–14 years; N/A	EG1 ($n = 20$): strength training CG ($n = 20$): regular tennis training	7 wk, 3 d, 21 sessions, 15 min; 45 min EG: 2–3 sets of 10–15 reps	EG1: 6 exercises	*Stroke performance:* Maximal serve velocity [km/h]	EG-pp: $SMD_W = 0.53$ CG-pp: $SMD_W = 0.09$ EG1-CG: $SMD_b = 0.26\ (-0.36,\ 0.88)$
Paul et al. (27)	20, M; 18–24 years; college level	EG1 ($n = 10$): agility training CG ($n = 10$): regular tennis training	EG: 7 wk, 4 d, 28 sessions, 30 min, 120 min 10 exercises	Ladder agility drill, lateral cone slalom, forward and backward cone slalom, spider run, cross cone, medicine ball mini-tennis	*Agility:* Illinois agility test [s]	EG1-pp: $SMD_W = 0.79$ CG-pp: $SMD_W = 0.12$ EG1-CG: $SMD_b = 1.24\ (0.29,\ 2.20)$
Fernandez-Fernandez et al. (28)	30, M; 14.2 ± 0.5 years; national ranked	EG ($n = 15$): strength training CG ($n = 15$): regular tennis training	6 wk, 3 d; 18 sessions, 60–70 min; 180–210 min 2 sets of 20 reps	EG: medicine ball exercises, core training, elbow extension, rowing, external rotation, shoulder abduction, diagonal pattern flexion, reverse throw, forward throw, wrist flexion/extension	*Stroke performance:* Maximal serve velocity [km/h]	EG-pp: $SMD_W = 0.62$ CG-pp: $SMD_W = 0.05$ EG-CG: $SMD_b = 0.98\ (0.23, 1.74)$
Behringer et al. (14)	36, M; 15.03 ± 1.64 years, N/A	EG1 ($n = 12$): resistance training EG2 ($n = 12$): plyometric training CG ($n = 12$): regular tennis training	8 wk, 2 d, 16 sessions, 90 min, 180 min EG1: 8 exercises, 2 sets of 15 reps EG2: 6–8 exercises, 3–4 sets of 10–15 reps	EG1: low pulley dead lifts, flexion abdominal machine, seated back-extension machine, lateral flexion machine, leg-press, chest-press, lat-pull-down machine EG2: rope skipping, lateral barrier hop, box hopping, CMJ, SJ, push-ups, medicine ball chest pass	*Stroke performance:* Mean serve velocity [km/h]	EG1-pp: $SMD_W = 0.02$ EG2-pp: $SMD_W = 0.30$ CG-pp: $SMD_W = -0.32$ EG1-CG: $SMD_b = 0.04\ (-0.76,\ 0.84)$ EG2-CG: $SMD_b = 1.44\ (0.54,\ 2.34)$
					Upper-extremity muscle strength: 10-RM chest press [kg]	EG1-pp: $SMD_W = 0.80$ EG2-pp: $SMD_W = 0.78$ CG-pp: $SMD_W = 0.12$ EG1-CG: $SMD_b = 0.56\ (-0.26,\ 1.37)$ EG2-CG: $SMD_b = 0.51\ (-0.30,\ 1.33)$
Genevois et al. (15)	44, M; 26.9 ± 7.5 years; ITN 3	EG1 ($n = 12$): handled medicine ball training EG2 ($n = 20$): overweight racket training CG ($n = 12$): regular tennis training	6 wk, 2 d, 90 min, 180 min EG1: 6 sets of 6 exercises EG2: 7–10 sets	EG1: medicine ball exercises EG2: 10 crosscourt forehand drives with overweight racket	*Stroke performance:* Maximal forehand velocity [m/s]	EG1-pp: $SMD_W = 0.57$ EG2-pp: $SMD_W = 0.91$ CG-pp: $SMD_W = -0.48$ EG1-CG: $SMD_b = 1.75\ (0.81,\ 2.69)$ EG2-CG: $SMD_b = 0.62\ (-0.20,\ 1.44)$
Ölcücü et al. (29)	40, M, 20-25 years; tournament level	EG1 ($n = 20$): plyometric training CG ($n = 20$): regular tennis training	8wk, 3d, 35 min, 105 min 2 sets of 12 reps	N/A	*Stroke performance:* Maximal serve velocity [m/s]	EG-pp: $SMD_W = 1.94$ CG-pp: $SMD_W = 1.11$ EG-CG: $SMD_b = 1.60\ (0.98,\ 2.31)$
Sannicandro et al. (30)	23, F (8), M (15); 12–14 years, N/A	EG ($n = 11$): balance training CG ($n = 12$): tennis-specific drills	6 wk, 2 d, 12 sessions, 30 min, 60 min EG: 3–4 sets of 5–10 reps, 6 exercises	EG: high skipping, diagonal 1-legged bounds, maintaining equilibrium before the last bound for 3 s, forwards bounds equilibrium before the last bound for 3 s, low rows using an elastic exercises	*Speed:* 20 m sprint [s]	EG-pp: $SMD_W = 0$ CG-pp: $SMD_W = 0$ EG-CG: $SMD_b = 0.39\ (-0.58,\ 1.35)$

(*continued*)

TABLE 3 Continued

Reference	No. of subjects (sex); age [years (range or mean ± SD)]; performance level	Groups/training devices	Trainings modality No. of training weeks/frequency/sessions, single session duration, total duration per week No. of sets, reps, duration per exercise	Exercises	Test modality	Results
				band bound to a support performed against bipodalic inflatable disk, medicine ball chest passes with balancing on a bipodalic inflatable disk or standing on one leg, exercises with unstable surface	*Agility:* Foran test [s]	EG-pp: $SMD_W = 0.33$ CG-pp: $SMD_W = 0$ EG-CG: $SMD_b = 1.42$ (0.46, 2.38)
Fernandez-Fernandez et al. (31)	16, M, 16.9 ± 0.5 years; international ranked	EG ($n = 8$): combined explosive strength and repeated sprint training CG ($n = 8$): regular tennis training	8 wk, 3 d, 50–80 min, 150–240 min EG: sprint training: 3–4 sets of 5–6 reps explosive strength: 4–6 exercises with 3–4 sets of 12–15 reps	15-20 m sprint, CMJ, multilateral hops, plyometric jumps, step multilateral calf jumps, agility drills, resisted standing start sprints	*Speed:* 20 m sprint [s]	EG-pp: $SMD_W = 0.50$ CG-pp: $SMD_W = -0.20$ EG-CG: $SMD_b = 0.90$ (−0.13, 1.93)
					Lower-extremity muscle power: CMJ height [cm]	EG-pp: $SMD_W = 0.43$ CG-pp: $SMD_W = -0.11$ EG-CG: $SMD_b = 1.73$ (0.58, 2.88)
					Endurance: VIFT [km/h]	EG-pp: $SMD_W = 0$ CG-pp: $SMD_W = 0.33$ EG-CG: $SMD_b = 0$ (−0.98, 0.98)
Kara et al. (32)	20, N/A; 18-24 years; N/A	EG ($n = 10$): tennis specific strength training CG ($n = 10$): regular tennis training	6 wk; 3 d; 18 sessions; 45–60 min; 135–180 min 11 exercises, 3–4 sets of 8–12 reps/30 s	Squat, single arm, rotational service pull, isometric quarter squat, tennis serves shot throw, 2 arm 90/90 external rotation, reverse 90/90 throw, plyometric 90/90 internal rotation in service position, jump into single-leg Romanian dead lift, crunch, throwing medicine ball, jump at squat position and static stance	*Stroke performance:* Maximal serve velocity [km/h]	EG-pp: $SMD_W = 1.85$ CG-pp: $SMD_W = 0.54$ EG-CG: $SMD_b = -0.56$ (−1.46, 0.33)
Fernandez-Fernandez et al (33)	60, M; 12.5 ± 0.3 years; national ranked	EG ($n = 30$): plyometric training for the upper and lower body CG ($n = 30$): regular tennis training	8 wk, 2 d, 16 sessions, 30–60 min, 60–120 min 4–8 exercises, 2–4 sets of 10–15 reps	Medicine ball throws, CMJ, 2/1-leg zigzag over lines, 2-leg multidirectional hurdle jumps, lateral bounds and stabilization, 1-foot ankle hop forward, 1-leg box jump	*Lower-extremity muscle power:* CMJ height [cm]	EG-pp: $SMD_W = 0.44$ CG-pp: $SMD_W = 0.14$ EG-CG: $SMD_b = 0.27$ (−0.24, 0.78)
					Speed: 20 m sprint [s]	EG-pp: $SMD_W = 0.65$ CG-pp: $SMD_W = 0.05$ EG-CG: $SMD_b = 0.76$ (0.23, 1.28)
					Agility: 505 agility test [s]	EG-pp: $SMD_W = 0.45$ CG-pp: $SMD_W = 0.10$ EG-CG: $SMD_b = -0.38$ (−0.13, 0.89)
					Upper-extremity muscle power: MBT [cm]	EG-pp: $SMD_W = 0.59$ CG-pp: $SMD_W = 0.03$ EG-CG: $SMD_b = 0.70$ (0.17, 1.22)

(continued)

TABLE 3 Continued

Reference	No. of subjects (sex); age [years (range or mean ± SD)]; performance level	Groups/training devices	Trainings modality No. of training weeks/frequency/sessions, single session duration, total duration per week No. of sets, reps, duration per exercise	Exercises	Test modality	Results
					Stroke performance: Maximal serve velocity [km/h]	EG-pp: $SMD_W = 1.06$ CG-pp: $SMD_W = 0.10$ EG-CG: $SMD_b = 0.56$ (0.04, 1.07)
Fernandez-Fernandez et al. (34)	20, N/A; 14.8 ± 0.1 years; national ranked	EG ($n = 10$): mixed high intensity intermittent runs and tennis specific training CG ($n = 10$): tennis-specific drills	8 wk; 2 d; 16 sessions; 16-22 min, 32–44 min 2 sets of 8–11 min runs	Big x, suicide, recovery/defense, open pattern	*Speed:* 20 m sprint	EG-pp: $SMD_W = -0.42$ CG-pp: $SMD_W = -0.32$ EG-CG: $SMD_b = -0.08$ (−0.96, 0.80)
					Agility: 505-agility test [s]	EG-pp: $SMD_W = 1.00$ CG-pp: $SMD_W = 0.12$ EG-CG: $SMD_b = -0.63$ (−0.27, 1.53)
					Lower-extremity muscle power: CMJ height [cm]	EG-pp: $SMD_W = 0.25$ CG-pp: $SMD_W = 0.50$ EG-CG: $SMD_b = 0.10$ (−0.78, 0.97)
					Endurance: VO_2max [ml/kg/min]	EG-pp: $SMD_W = 1.13$ CG-pp: $SMD_W = 0.55$ EG-CG: $SMD_b = 0.87$ (−0.05, 1.78)
Terrazo-Rebollo et al. (35)	20, F (5), M (15); 15.5 ± 0.9 years, N/A	EG1 ($n = 7$): regular tennis training and training with overloads EG2 ($n = 7$): regular tennis training and medicine ball throws and elastic bands CG ($n = 6$): regular tennis training	8 wk, 3 d, 60 min, 180 min per session (120 min tennis and 60 min additional training) EG1: 9 exercises, 3 sets with 6-14 reps EG2: 8 exercises, 3 sets of 6 reps	EG1: bench press, trunk curl, leg press, forehand/backhand barbell, trunk extension, dumbbell lying shoulder external rotation, one arm dumbbell row to waist, standing high pulley internal rotation, barbell throw, squat EG2: forehand/backhand side throws, chest throws, two-arm overhand forward/backhand throws, one-arm overhead forward throws, side floor throws, two-arm trunk rotation, one-arm diagonal trunk flexion	*Stroke performance:* Maximal serve velocity [km/h]	EG1-pp: $SMD_W = 0.42$ EG2-pp: $SMD_W = 0.14$ CG-pp: $SMD_W = -0.11$ EG1-CG: $SMD_b = 0.24$ (−0.86, 1.33) EG2-CG: $SMD_b = 0.18$ (−0.91, 1.27)
Yildiz et al. (36)	28, M; 9.6 ± 0.7 years; N/A	EG1 ($n = 10$): traditional training EG2 ($n = 10$): functional training CG ($n = 8$): regular tennis training	8 wk, 3 d; 24 sessions; 70 min; 210 min 10 exercises, 3 sets of 10–12 reps	EG1: chest press, shoulder press, lateral pull-down, biceps curls, triceps push-down, seated leg extensions, leg curl, standing calf rise, modified push-up, sit-up EG2: squat, dead bug, plank, bridge, chop, lift, push up, pull up, medicine ball throw	*Lower-extremity muscle power:* CMJ height [cm]	EG1-pp: $SMD_W = 0.24$ EG2-pp: $SMD_W = 1.81$ CG-pp: $SMD_W = 0.23$ EG1-CG: $SMD_b = 1.21$ (0.20, 2.22) EG2-CG: $SMD_b = 2.66$ (1.38, 3.93)
					Speed: 10 m sprint [s]	EG1-pp: $SMD_W = -0.18$ EG2-pp: $SMD_W = 1.55$ CG-pp: $SMD_W = 0.23$ EG1-CG:

(*continued*)

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TABLE 3 Continued

Reference	No. of subjects (sex); age [years (range or mean ± SD)]; performance level	Groups/training devices	Trainings modality No. of training weeks/frequency/sessions, single session duration, total duration per week No. of sets, reps, duration per exercise	Exercises	Test modality	Results
						$SMD_b = 1.75$ (0.81, 2.69) EG2-CG: $SMD_b = 0.62$ (−0.20, 1.44)
					Agility: T-agility test [s]	EG1-pp: $SMD_W = -0.08$ EG2-pp: $SMD_W = 1.11$ CG-pp: $SMD_W = 0$ EG1-CG: $SMD_b = 0.64$ (−1.60, 0.31) EG2-CG: $SMD_b = 1.41$ (−2.45, −0.38)
					Balance: Y-balance test [cm]	EG1-pp: $SMD_W = 0.25$ EG2-pp: $SMD_W = 3.06$ CG-pp: $SMD_W = -0.12$ EG1-CG: $SMD_b = 0.53$ (−0.41, 1.48) EG2-CG: $SMD_b = 3.06$ (1.70, 4.43)
					Flexibility: Sit-and-reach test [cm]	EG1-pp: $SMD_W = 0$ EG2-pp: $SMD_W = 1.71$ CG-pp: $SMD_W = 0$ EG1-CG: $SMD_b = 0.57$ (−0.38, 1.52) EG2-CG: $SMD_b = 2.78$ (1.48, 4.08)
Bashir et al. (37)	30, N/A; 15.3 ± 0.8; N/A	EG ($n = 15$): core training CG ($n = 15$): control group	5 wk, 3 d, 15 sessions, N/A, N/A 3–5 exercises, 1–3 sets of 15–20 reps	Supine and quadruped abdominal muscle contraction, side bridge, dead bug supine, medicine ball rotation, squat, superman, oblique pulley with side shuffles, standing wall cross toss, diagonal curl, twist on a Swiss ball, single leg standing on unstable surface	*Agility:* T-agility test [s]	EG-pp: $SMD_W = 0.59$ CG-pp: $SMD_W = -0.19$ EG-CG: $SMD_b = 1.31$ (0.52, 2.10)
Ziagkas et al. (38)	24, M, 20.9 ± 0.7years	EG ($n = 12$): plyometric training CG ($n = 12$): watching tennis matches	8 wk, 2d, 16 sessions, 30 min, 60 min N/A, 2-4 sets of 10-15 reps	N/A	*Agility:* Spider-Test [s]	EG-pp: $SMD_W = 2.06$ CG-pp: $SMD_W = 0.64$ EG-CG: $SMD_b = 2.27$ (0.63, 2.45)
Kocyigit et al. (39)	24, M; 12–14 years, N/A	EG ($n = 12$): combined training CG ($n = 12$): regular tennis training	3 mo, 3 d, 36 sessions, 90 min, 270 min	EG: strength, speed, agility, endurance training; rope skipping, rally exercises	*Stroke performance:* Maximal serve velocity [km/h]	EG-pp: $SMD_W = 2.06$ CG-pp: $SMD_W = 0.77$ EG-CG: $SMD_b = 2.89$ (1.74, 4.03)

(*continued*)

TABLE 3 Continued

Reference	No. of subjects (sex); age [years (range or mean ± SD)]; performance level	Groups/training devices	Trainings modality No. of training weeks/frequency/sessions, single session duration, total duration per week No. of sets, reps, duration per exercise	Exercises	Test modality	Results
Egesoy et al. (40)	36, F (15), M (21); 10–14 years, N/A	EG1 ($n = 12$): static core training EG2 ($n = 12$): dynamic core training CG ($n = 12$): regular tennis training	8 wk, 2d, 16 sessions, 25–30 min, 50–60 min 9 exercises, 2 sets of 20–40 s	EG1: front plank, side plank, leg raise hold, dead bug, bird and dogs, banana, superman, posterior plank, glute bridge hold EG2: plank climbers, supine plank leg lift, Russian twist, dead bug. Bird and dogs, leg raise, side plank, leg lift, plank leg extensions, reverse crunch	*Lower-extremity muscle power:* CMJ height [cm]	EG1-pp: $SMD_W = 0.33$ EG2-pp: $SMD_W = 0.58$ CG-pp: $SMD_W = 0.09$ EG1-CG: $SMD_b = 0.11$ (−0.70, 0.91) EG2-CG: $SMD_b = -0.17$ (−0.98, 0.63)
					Flexibility: Sit-and-reach test [cm]	EG1-pp: $SMD_W = 0.09$ EG2-pp: $SMD_W = 0.06$ CG-pp: $SMD_W = 0.24$ EG1-CG: $SMD_b = -0.14$ (−0.94, 0.66) EG2-CG: $SMD_b = -0.42$ (−1.23, 0.39)
					Upper-extremity muscle strength: Handgrip strength [kg]	EG1-pp: $SMD_W = 0.71$ EG2-pp: $SMD_W = 0.78$ CG-pp: $SMD_W = 0.10$ EG1-CG: $SMD_b = 0.48$ (−0.33, 1.29) EG2-CG: $SMD_b = 0.30$ (−0.51, 1.10)
					Speed: 10 m sprint [s]	EG1-pp: $SMD_W = 0.08$ EG2-pp: $SMD_W = 0.06$ CG-pp: $SMD_W = 0$ EG1-CG: $SMD_b = 0.47$ (−0.34, 1.28) EG2-CG: $SMD_b = 0.29$ (−0.52, 1.09)
					Balance: Y-balance test [cm]	EG1-pp: $SMD_W = 0.31$ EG2-pp: $SMD_W = 0.37$ CG-pp: $SMD_W = 0.12$ EG1-CG: $SMD_b = 0.38$ (−0.43, 1.19) EG2-CG: $SMD_b = 0.04$ (−0.76, 0.84)
					Upper-extremity muscle power: Seated medicine ball throw test [cm]	EG1-pp: $SMD_W = 0.20$ EG2-pp: $SMD_W = 0.31$ CG-pp: $SMD_W = 0.07$ EG1-CG: $SMD_b = 0.46$ (−0.35, 1.27) EG2-CG: $SMD_b = 0.37$ (−0.44, 1.18)

(*continued*)

TABLE 3 Continued

Reference	No. of subjects (sex); age [years (range or mean ± SD)]; performance level	Groups/training devices	Trainings modality No. of training weeks/frequency/sessions, single session duration, total duration per week No. of sets, reps, duration per exercise	Exercises	Test modality	Results
					Stroke performance: Maximal serve velocity [km/h]	EG1-pp: $SMD_W = 0.19$ EG2-pp: $SMD_W = 0.19$ CG-pp: $SMD_W = 0.03$ EG1-CG: $SMD_b = 0.24\ (-0.56,\ 1.05)$ EG2-CG: $SMD_b = 0.16\ (-0.64,\ 0.96)$
Zirhli et al. (41)	20, F; 10–12 years; N/A	EG ($n = 10$): 2 d tennis training, 2 d functional training CG ($n = 10$): 4 d tennis training	8 wk, 4 d, 90 min, 360 min EG: 9 exercises, 3 sets of 7–10 reps	EG: burpees, bungee run, forward jump squat, plank, torso rotation, side to side run, agility run, side to side crash, reverse walking	*Speed:* 10 m sprint [s]	EG-pp: $SMD_W = 0.71$ CG-pp: $SMD_W = -0.13$ EG-CG: $SMD_b = 1.81\ (0.77,\ 2.85)$
					Lower-extremity muscle power: Vertical jump height [cm]	EG-pp: $SMD_W = 0.52$ CG-pp: $SMD_W = 0.03$ EG-CG: $SMD_b = 1.01\ (0.08,\ 1.94)$
					Agility: T-agility test [s]	EG-pp: $SMD_W = 2.52$ CG-pp: $SMD_W = 0.07$ EG-CG: $SMD_b = 1.81\ (0.77,\ 2.85)$
					Upper-extremity muscle strength: Handgrip strength [kg]	EG-pp: $SMD_W = 0.96$ CG-pp: $SMD_W = 0.02$ EG-CG: $SMD_b = 1.43\ (0.45,\ 2.41)$
					Endurance: Wingate anaerobic power test [no.]	EG-pp: $SMD_W = 2.01$ CG-pp: $SMD_W = -0.11$ EG-CG: $SMD_b = 1.74\ (0.71,\ 2.77)$
					Flexibility: Sit-and-reach test [cm]	EG-pp: $SMD_W = 0.57$ CG-pp: $SMD_W = 0.13$ EG-CG: $SMD_b = 0.83\ (-0.09,\ 1.74)$
Canos et al. (42)	24, M; 14–16 years; competitive	EG1 ($n = 8$): machine-based training EG2 ($n = 8$): flywheel training CG ($n = 8$): regular tennis training	8 wk, 2 d, 16 sessions, N/A, N/A EG1 and EG2:5–6 exercises 3 sets of 6–8 reps followed by a block of 2–3 sets of 5–6 specific exercises	EG1: shoulder press, lateral pulldown, complete leg press, bench press, half squat, forward lunge, dumbbell power EG2: low row 90°, forehand closed stance, backhand stance, one handed chest crossover, one handed low row with one step, global chest press, one handed shoulder press	*Lower-extremity muscle power:* CMJ height [cm]	EG1-pp: $SMD_W = 0.79$ EG2-pp: $SMD_W = 1.00$ CG-pp: $SMD_W = -0.13$ EG1-CG: $SMD_b = -0.12\ (-1.10,\ 0.86)$ EG2-CG: $SMD_b = 1.01\ (-0.03,\ 2.06)$

(*continued*)

TABLE 3 Continued

Reference	No. of subjects (sex); age [years (range or mean ± SD)]; performance level	Groups/training devices	Trainings modality No. of training weeks/frequency/sessions, single session duration, total duration per week No. of sets, reps, duration per exercise	Exercises	Test modality	Results
					Upper-extremity muscle power: Overhead medicine ball throw test [km/h]	EG1-pp: $SMD_W = 2.15$ EG2-pp: $SMD_W = 2.64$ CG-pp: $SMD_W = 0.43$ EG1-CG: $SMD_b = 1.32\ (0.24,\ 2.40)$ EG2-CG: $SMD_b = 1.37\ (0.28,\ 2.45)$
					Speed: 10 m sprint [s]	EG1-pp: $SMD_W = 1.00$ EG2-pp: $SMD_W = -0.057$ CG-pp: $SMD_W = -0.017$ EG1-CG: $SMD_b = -0.15\ (-1.13,\ 0.83)$ EG2-CG: $SMD_b = -1.00\ (-2.04,\ 0.04)$
					Agility: 505-agility test [s]	EG1-pp: $SMD_W = 0.80$ EG2-pp: $SMD_W = -0.11$ CG-pp: $SMD_W = -0.53$ EG1-CG: $SMD_b = 2.82\ (1.44,\ 4.20)$ EG2-CG: $SMD_b = 2.23\ (0.98,\ 3.48)$
Mengyao et al. (43)	30, M; 16–18 years; N/A	EG ($n = 15$): core strength training CG ($n = 15$): regular tennis training	8 wk, 3 d, 24 sessions, 60 min, 180 min 11 exercises, 3 sets of 15 reps	Bird dog and side bridges, back extension, raised upper body and lower body, abdominal crunch and Swiss ball, crunch, plank, lunge, squat, Russian twist on the Swiss ball, bicycle crunch, medicine ball throws	*Agility:* Spider-test [s]	EG-pp: $SMD_W = 1.27$ CG-pp: $SMD_W = 0.46$ EG-CG: $SMD_b = -0.82\ (-1.56,\ -0.07)$

CG, control group; CMJ, countermovement jump; d, days; EG, experimental group; F, female; ITN, international tennis number; M, male; mo, month; NA/, not available; RM, repetition maximum; SJ, squat jump; SMD_b, between-subject standardized mean differences; *SMDw*, within-subject standardized mean difference; VIFT, velocity of the intermittent fitness test; wk, weeks.

3.4. Intervention characteristics

In total, 33 different interventions were performed. Athletic training duration ranged from four weeks to nine months with a period of 6–8 weeks being used most frequently ($n = 18$ studies). The players completed two to three sessions of additional athletic training per week. Each training session lasted between 16 and 90 min, although in some studies ($n = 4$) session duration was not specified. On average, nine exercises were performed during each training session, although the respective number ranged from a minimum of three (34) to a maximum of 14 (10) different exercises per session. However, seven studies (15, 24, 25, 28, 29, 38, 39) did not report the number of exercises which were executed during the intervention. In eleven studies (10, 11, 14, 24–26, 28, 32, 35, 36, 42), various strength training programs (e.g., shoulder resistance training, periodized or non-periodized resistance training, single set circuit training, non-linear periodized resistance training) were conducted, six papers (14, 15, 29, 33, 35, 38) investigated the influence of plyometric training (e.g., CMJ, SJ, medicine ball chest pass), three studies (37, 40, 43) analyzed the effectiveness of core training (e.g., plank, dead bug, climbers), and two studies (36, 41) conducted functional training (e.g., burpees, jump squat, agility run, plank, squat, medicine ball throw). In addition, several other interventions were carried out: overweight racket training (15), balance training (e.g., training on unstable underground, unipedal balance exercises) (30), combined explosive strength and repeated sprint training (e.g., plyometric jumps, agility drills, CMJ, 15–20 m sprints) (31), mixed high intensity intermittent runs (34), combined training (e.g., agility, strength, endurance) (39), and agility training (27).

3.5. Methodological quality of the included trials

The included studies achieved a PEDro score between 4 and 7 points. Eighteen out of 24 studies achieved the cut-off score of ≥ 6 points, while six studies did not achieve this score. Three studies of these examined young players (36, 39, 43), and three studies explored adult players (11, 32, 38).

3.6. Effects of athletic training on measures of physical fitness

3.6.1. Speed

Figure 2 shows the effects of athletic training on measures of speed in healthy tennis players. Eight studies (30, 31, 33, 34, 36, 40–42) investigated youth players and one study (11) dealt with adult players. For all players, the weighted mean SMD_b amounted to 0.44 (9 studies, $I^2 = 51\%$, $Chi^2 = 24.2$, $df = 12$, $p = .02$), which is indicative of a small effect favoring the EG. Further, the age-specific sub-analysis revealed a moderate effect in youth ($SMD_b = 0.50$) and a small effect in adult ($SMD_b = 0.11$) players, both in favor of the EG.

3.6.2. Agility

The effects of athletic training on variables of agility in healthy tennis players are displayed in **Figure 3**. Eight studies (30, 33, 34, 36, 37, 41–43) investigated youth players and three studies (11, 27, 38) analyzed adult players. When considering all players, the weighted mean SMD_b yielded 0.93 (11 studies, $I^2 = 77\%$, $Chi^2 = 56.73$, $df = 13$, $p < 0.00001$), indicating a large effect in favor of the EG. In addition, the age-specific sub-analysis showed a large effect in youth ($SMD_b = 0.98$) and in adult ($SMD_b = 0.88$) players, both in favor of the EG.

3.6.3. Lower-extremity muscle power

Figure 4 illustrates the effects of athletic training on parameters of lower-extremity muscle power in healthy tennis players. Six studies (31, 33, 34, 36, 40, 41) examined youth players and two studies (10, 11) assessed adult players. In general, the weighted mean SMD_b was 0.88 (8 studies, $I^2 = 70\%$, $Chi^2 = 43.14$, $df = 13$, $p < 0.0001$), which indicates a large effect in favor of the EG. The additionally performed age-specific sub-analysis revealed a moderate effect in youth ($SMD_b = 0.68$) and a large effect in adult ($SMD_b = 1.40$) players, both in favor of the EG.

3.6.4. Upper-extremity muscle power

Figure 5 shows the effects of athletic training on parameters of upper-extremity muscle power in healthy youth tennis players (33, 40, 42). The weighted mean SMD_b amounted to 0.72 (3 studies, $I^2 = 0\%$, $\mathrm{Chi}^2 = 3.67$, $df = 4$, $p = 0.45$) indicating a moderate effect in favor of the EG.

3.6.5. Upper-extremity muscle strength

Figure 6 displays the effect of athletic training on variables of upper-extremity muscle strength in healthy tennis players. Three studies (14, 40, 41) evaluated youth players and two studies (10, 11) analyzed adult players. For all players, the weighted mean SMD_b of 0.90 (5 studies, $I^2 = 33\%$, $Chi^2 = 12.01$, $df = 8$, $p = 0.15$) indicates a large effect in favor of the EG. Further, the age-specific sub-analysis revealed a moderate effect in youth ($SMD_b = 0.60$) and a large effect in adult ($SMD_b = 1.39$) players, both in favor of the EG.

3.6.6. Endurance

The effects of athletic training on measures of endurance in tennis athletes are shown in **Figure 7**. Three studies (31, 34, 41) examined youth players and two studies (10, 11) dealt with adult players. Overall, the weighted mean SMD_b

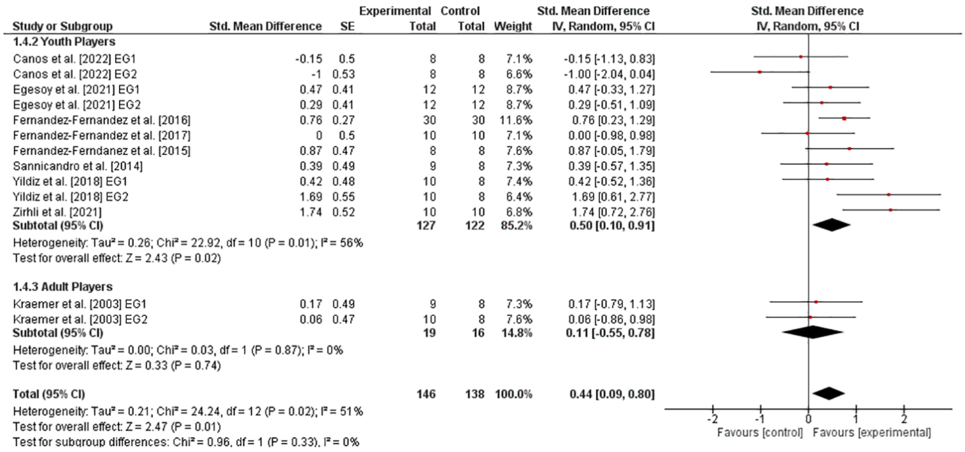

FIGURE 2
Effects of athletic training on measures of speed (e.g., 20 m sprint time) in healthy youth and adult tennis players. *CI* = confidence interval, *df* = degrees of freedom, *SE* = standard error, *IV* = inverse variance.

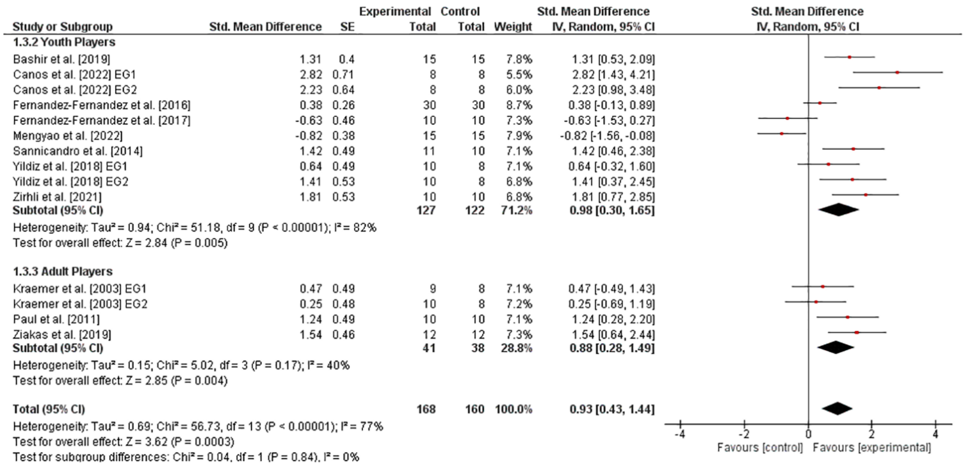

FIGURE 3
Effects of athletic training on measures of agility (e.g., 5-0-5 test time) in healthy youth and adult tennis players. *CI* = confidence interval, *df* = degrees of freedom, *SE* = standard error, *IV* = inverse variance.

amounted to 0.61 (4 studies, $I^2 = 46\%$, $Chi^2 = 11.02$, $df = 6$, $p = 0.09$), indicating a moderate effect favoring the EG. Moreover, a large effect was detected in youth ($SMD_b = 0.86$) and a small effect in adult ($SMD_b = 0.41$) players, both in favor of the EG.

3.6.7. Balance

Two studies (36, 40) investigated the effects of athletic training on measures of balance performance in healthy youth tennis players (**Figure 8**). Our analysis revealed a weighted mean SMD_b of 0.88 (2 studies, $I^2 = 79\%$, $Chi^2 = 14.52$, $df = 3$, $p = 0.002$) indicating a large effect in favor of the EG.

3.6.8. Flexibility

Three studies (36, 40, 41) examined the effects of athletic training on parameters of flexibility in healthy youth tennis players (**Figure 9**). The weighted mean SMD_b amounted to 0.63 (3 studies, $I^2 = 80\%$, $Chi^2 = 19.70$, $df = 4$, $p = 0.0006$), which indicates a moderate effect in favor of the EG.

3.7. Effects of athletic training on measures of stroke velocity

The effects of athletic training on parameters of stroke velocity) in healthy tennis players are shown in **Figure 10**.

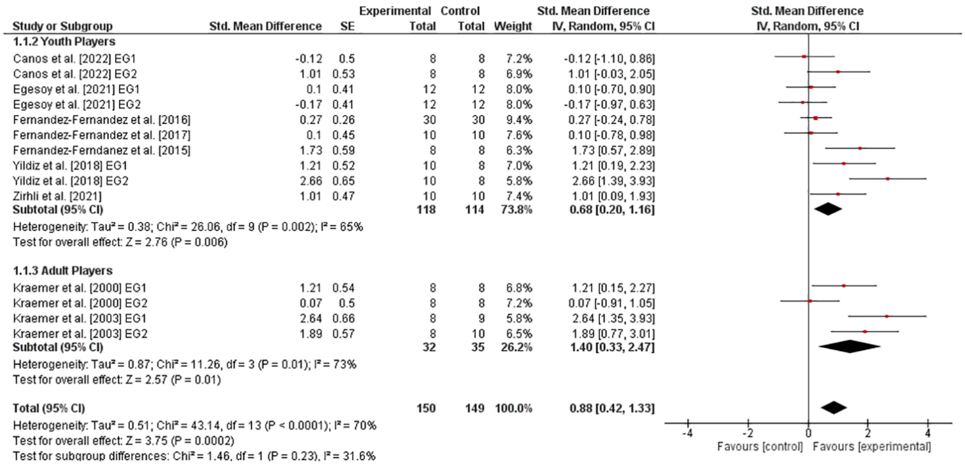

FIGURE 4
Effects of athletic training on measures of lower-extremity muscle power (e.g., counter movement jump height) in healthy youth and adult tennis players. *CI* = confidence interval, *df* = degrees of freedom, *SE* = standard error, *IV* = inverse variance.

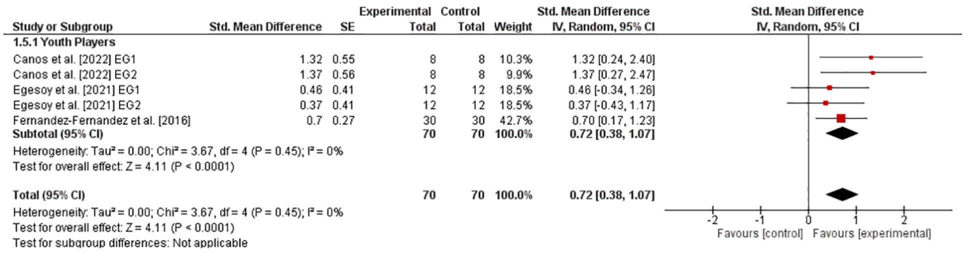

FIGURE 5
Effects of athletic training on measures of upper-extremity muscle power (e.g., medicine ball throw) in healthy youth tennis players. *CI* = confidence interval, *df* = degrees of freedom, *SE* = standard error, *IV* = inverse variance.

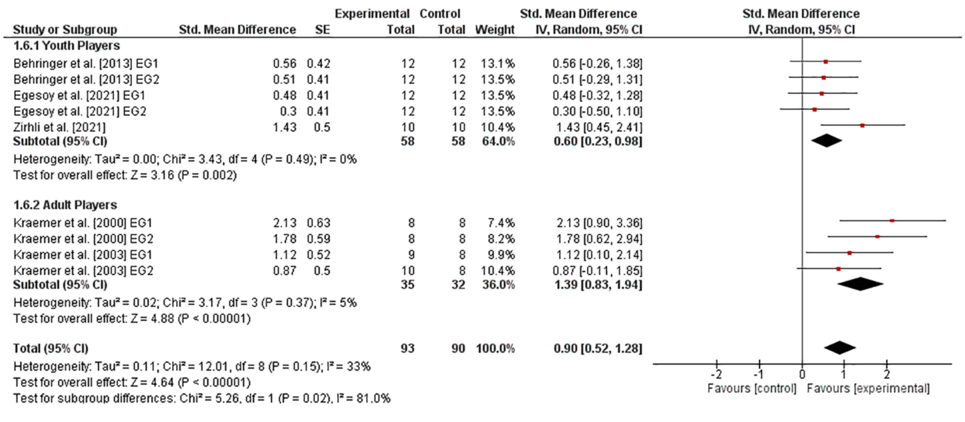

FIGURE 6
Effects of athletic training on measures of upper-extremity muscle strength (e.g., handgrip strength) in healthy youth and adult tennis players. *CI* = confidence interval, *df* = degrees of freedom, *SE* = standard error, *IV* = inverse variance.

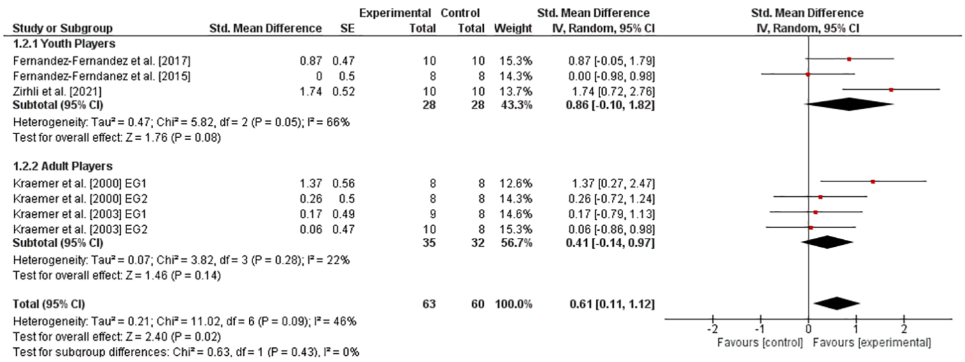

FIGURE 7
Effects of athletic training on measures of endurance (e.g., VO_2max) in healthy youth and adult tennis players. *CI* = confidence interval, *df* = degrees of freedom, *SE* = standard error, *IV* = inverse variance.

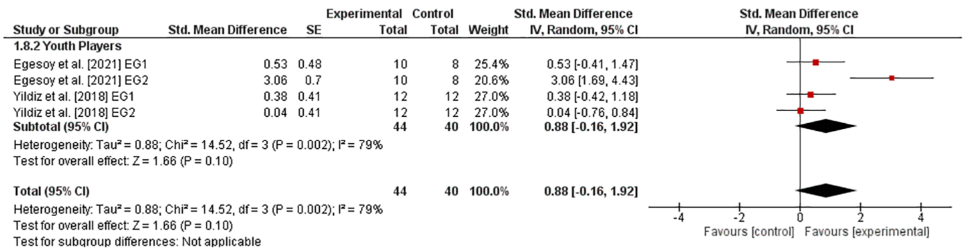

FIGURE 8
Effects of athletic training on measures of balance (e.g., Y balance test) in healthy youth tennis players. *CI* = confidence interval, *df* = degrees of freedom, *SE* = standard error, *IV* = inverse variance.

Eight studies (14, 26, 28, 33, 35, 36, 39, 40) analyzed youth players and six studies (10, 11, 15, 24, 25, 32) examined adult players. Overall, the analyses yielded a weighted mean SMD_b of 0.90 ($I^2 = 69\%$, $Chi^2 = 70.92$ $df = 22$, $p < 0.00001$) indicating a large effect favoring the EG. Furthermore, large effects in youth ($SMD_b = 0.70$) as well as in adult ($SMD_b = 1.15$) players were detected.

4. Discussion

To the best of our knowledge, the present systematic review with meta-analysis is the first to characterize, aggregate, and quantify the effects of athletic training programs on measures of physical fitness and stroke velocity in healthy youth and adult tennis players. Overall, the analysis of the data of 24 studies that met the criteria selection revealed for measures of physical fitness small (speed: $SMD = 0.44$), moderate (endurance: $SMD = 0.61$, upper-extremity muscle power: $SMD = 0.72$, flexibility: $SMD = 0.63$), and large (agility: $SMD = 0.83$, lower-extremity muscle power: $SMD = 0.88$, upper-extremity muscle strength: $SMD = 0.90$, balance: $SMD = 0.88$) effects, all in favor of the EG. For stroke velocity (e.g., maximal and mean stroke velocity), the analyses yielded a large effect of physical training ($SMD = 0.90$) also favoring the EG. Furthermore, the additionally performed sub-analyses showed differences in the effectiveness of athletic training programs on variables of physical fitness and stroke velocity when considering players' age (i.e., youth players: < 18 years vs. adult players: ≥ 18 years).

4.1. Effectiveness of athletic training on measures of physical fitness

In line with our hypothesis stating that athletic training will lead to improvements in variables of physical fitness, but the effectiveness will differ with respect to of players' age (i.e., youth vs. adult tennis players), this present systematic review with meta-analysis showed beneficial effects of athletic training on measures of physical fitness in healthy tennis players in favor of the EG, which can be classified as small to large. Specifically, large effects were detected for agility ($SMD = 0.93$), balance ($SMD = 0.88$), lower-extremity muscle power

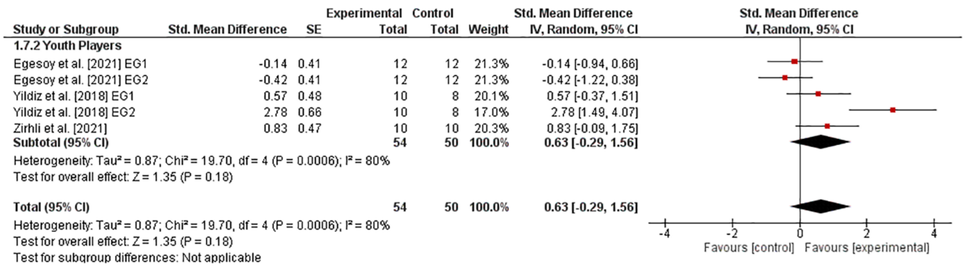

FIGURE 9
Effects of athletic training on measures of flexibility (e.g., sit-and-reach test) in healthy youth tennis players. *CI* = confidence interval, *df* = degrees of freedom, *SE* = standard error, *IV* = inverse variance.

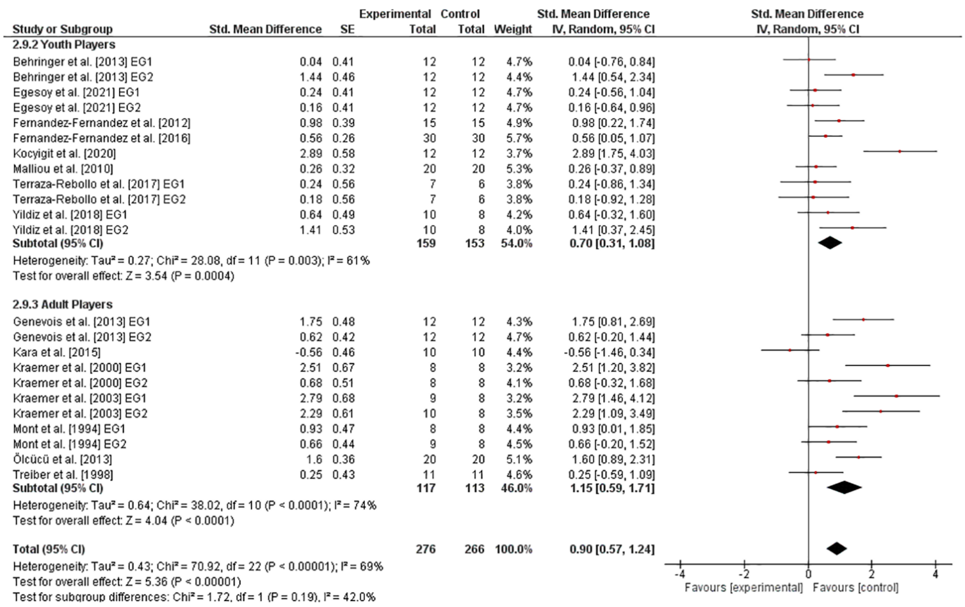

FIGURE 10
Effects of athletic training on measures of stroke performance (e.g., maximal stroke velocity) in healthy youth and adult tennis players. *CI* = confidence interval, *df* = degrees of freedom, *SE* = standard error, *IV* = inverse variance.

(*SMD* = 0.88), and upper-extremity muscle strength (*SMD* = 0.90), indicating a high trainability (large adaptive reserve) in these physical fitness components.

In terms of agility, the sub-analysis showed a large effect in youth (*SMD* = 0.98) as well as in adult (*SMD* = 0.88) players, suggesting a high adaptive reserve in both age groups. Precisely, agility is mainly composed of two components: (i) change of direction speed (i.e., technique, straight sprinting speed, leg muscle qualities, and anthropometry) and (ii) perceptual and decision-making factors (visual scanning, knowledge of situations, pattern recognition, and anticipation) (44). Due to their complex composition, both components require several years of training to achieve maximum performance (27), which means that training-related adaptations progress can be achieved regardless of age and with the use of different interventions. Precisely, functional training (41), plyometric training (38), and flywheel training (42) were applied and all of them resulted in positive effects on measures of agility. Furthermore, Meckel et al. (45) showed that agility accounted for almost 40% of the players' ranking (i.e., country's youth tennis players listing). Therefore, from this and the previously reported findings of the present study, it can be deduced that the promotion of agility seems particularly important for success in tennis.

Regarding balance, the large effect (*SMD* = 0.88) refers exclusively to the youth tennis players, since no study was found for adult players. There seems to be a particularly high adaptive reserve due to ongoing growth, maturation, and developmental processes in children and adolescents. Particularly, the neural system is not yet fully matured and thus offers a prominent potential for the promotion of informationally determined physical fitness components like balance (46). In this regard, several original studies (47–49) as well as review articles and meta-analyses (50, 51) have shown significant improvements following balance training on measures of balance and sport-related performance in youth.

With respect to lower-extremity muscle power, the sub-analysis revealed a moderate effect (*SMD* = 0.68) in youth and a large effect (*SMD* = 1.40) in adult players. This indicates that there is a high potential for muscular adaptations at a later stage. In fact, factors favorably influencing the development and training of muscular strength, such as an increase in circulating androgens (e.g., testosterone), are reported for the transition from youth to adulthood (52, 53). In this context, Vrijens (54) showed larger improvements (i.e., isometric strength of the elbow flexors/extensors and knee flexors/extensors) in pubertal (i.e., 16-year-olds) compared to prepubertal participants (i.e., 10-year-olds) following eight weeks (3 times per week) of resistance training. Concerning upper-extremity muscle strength, the sub-analysis yielded similar results, namely a moderate effect (*SMD* = 0.60) in youth and a large effect (*SMD* = 1.39) in adult players. Thus, as for lower-extremity muscle power the same line of argumentation can be applied.

Moderate effects were obtained for upper-extremity muscle power (*SMD* = 0.72), flexibility (*SMD* = 0.63), and endurance (*SMD* = 0.61). Regarding upper-extremity muscle power and flexibility, the moderate effects refer solely to the youth tennis players, as no studies were found for adult players. Thus, both physical fitness components seem to be well trainable in youth tennis players. In this context, using a regression analysis Ulbricht et al. (2) showed that upper-extremity muscle power was the most correlated predictor of tennis performance (i.e., national youth ranking) in female and male elite junior tennis players. Therefore, promoting upper-extremity muscle power seems particularly worthwhile for enhancing tennis performance.

In terms of endurance, the sub-analysis showed a large effect (*SMD* = 0.86) in youth and a small effect (*SMD* = 0.41) in adult players, indicating that the former one seems to have a higher adaptive reserve. Again, it can be argued that processes such as growth, maturation, and development are not yet complete in youth compared to adult players, and the cardiovascular as well as pulmonary system offers a particular potential for the promotion of energetically determined physical fitness components such as endurance (55). In this regard, a recent systematic and meta-analysis (56) revealed beneficial effects of endurance training (i.e., high-intensity interval training) on oxygen consumption, heart rate, repeated sprint ability etc. in young athletes (mean age: 15.5 ± 2.2 years).

A small effect was found for speed (*SMD* = 0.44). However, the sub-analysis showed a small effect (*SMD* = 0.11) only in adult players but a moderate effect (*SMD* = 0.50) in youth players. Most likely, this is because speed is a component that is largely genetically determined (55). Thus, the potential for training-induced adaptations is relatively low. Since the neuronal system, which is responsible for speed-related processes such as the perception, processing, and transmission of information is not yet fully mature in children and adolescents compared to adults, youth players seem to have more possibilities for training-related adaptation, which may explain their moderate effect (57).

4.2. Effectiveness of athletic training on measures of stroke velocity

In accordance with our hypothesis stating that athletic training will result in enhancements in stroke velocity, but the effectiveness will differ depending on players' age (i.e., youth vs. adult tennis players), we identified large effects (*SMD* = 0.90) of athletic training on stroke velocity in healthy tennis players in favor of the EG. However, the sub-analysis showed a large effect (*SMD* = 1.15) only in adult players but a moderate effect (*SMD* = 0.70) in youth players. Thus, both age groups seem to have a good adaptive potential for the promotion of stroke velocity, which is even higher in adult players. In terms of adult players, the interventions used ranged from plyometric training (29) over medicine ball training (14) to periodized strength training (10, 11) (e.g., crunches, back extensions, split squats), with non-linear periodized resistance being particularly effective. In accordance to this, the German Tennis Confederation (58) recommends to improve stroke velocity by using athletic exercises such as multi-directional jumps, medicine ball throws, and core strengthening. For youth players, the German Tennis Confederation (58) recommends improving stroke velocity especially by practicing stroke techniques, as evidence exists that technical demands and the underlying motor skills and cognitive processes are acquired through several years of practice (59). In addition, athletic exercises should be performed. In the present systematic review and meta-analysis the intervention used ranged from plyometric training (14) over functional training (36) (e.g., squat, plank, dead bug) to combined training (39) (including strength, speed, agility, and endurance exercises) with combined training being particularly effective.

4.3. Limitations

This systematic review with meta-analysis has a few limitations. The used methodology varied between the included studies in terms of players' characteristics (age, sex, performance level), assessments (tests, outcomes), and interventions (modalities like duration, frequency, volume of training etc.) which is reflected in a trivial to considerable heterogeneity between studies. Thus, future studies should apply instrumented assessment methods (i.e., biomechanical tests using force plates, plantar pressure devices etc.) in addition to the frequently used field-based tests to reduce the variability in effect estimates. Further, the included studies represent healthy tennis players in the age range of 6–42 years, thus no statement can be made especially about master athletes. Moreover, of the 24 included studies, three and eleven studies examined only women and men, respectively. Therefore, no sex-specific analyses could be performed.

5. Conclusions

The systematic review and meta-analysis characterized, aggregated, and quantified the effects of athletic training programs on measures of physical fitness and stroke velocity in healthy tennis players. For measures of physical fitness, we detected small (speed), moderate (endurance, upper-extremity muscle power, flexibility), and large (agility, lower-extremity muscle power, upper-extremity muscle strength, balance) effects, all in favor of the EG. In addition, a large effect also favoring the EG was found for parameters of stroke velocity. This indicates that athletic training is effective to varying degrees and this is further influenced by players' age (i.e., youth players: < 18 years vs. adult players: ≥ 18 years). For both age groups, we therefore conclude that further research is needed to investigate optimal training regimes in order to enlarge the effectiveness especially for those fitness components that showed small- to moderate-sized changes.

6. Practical applications

The results of the present systematic review with meta-analysis reveal implications for practitioners. In terms of physical fitness outcomes, large effects and thus a high potential for training-induced adaptations were found in youth players with respect to agility, balance and endurance, and in adult players with respect to agility, lower-extremity muscle power and upper-extremity muscle strength. This age specificity in trainability should therefore be considered when designing programs for long-term athlete development. In terms of stroke velocity, large effects were detected in adult and moderate effects in youth players. This suggests similar trainability in both age categories, according to which programs to train stroke techniques should start in adolescence and continue throughout adulthood.

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/s.

Author contributions

Conceptualization: JL, TM. Data curation: JL, TM. Formal analysis: JL. Methodology: JL. Writing – original draft: JL. Writing – review & editing: JL, TM. All authors contributed to the article and approved the submitted version.

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

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2022.1061087/full#supplementary-material.

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Physiological demands in simulated tennis matches and hitting tests take account of the translational and rotational kinetic energy ratio of the ball

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Assessment of fatigue effect on hitting ability in tennis has been controversial in previous studies. The purpose of this study was to determine the relationship between player fatigue and groundstroke type in tennis. We hypothesized that subjects with higher blood lactate concentration during play would apply heavier spin to the ball. We divided players into two groups based on their blood lactate concentration during a pre-measured hitting test (HIGH and LOW). Each group performed a simulated match-play protocol consisting of repeated running and hitting tests, which simulated a three-set match. Heart rate, percent of heart rate reserve, oxygen uptake, pulmonary ventilation, and respiratory exchange were measured. The distance between the ball's landing point and the target, and the ball's kinematics, were recorded during the hitting test between sets. We found no significant difference in ball kinetic energy between groups, but the HIGH group hit the ball with a greater ratio of rotational kinetic energy to total kinetic energy. However, the progression of the simulation protocol did not affect physiological responses (including blood lactate concentration) or hitting ability. Therefore, it is suggested that the type of groundstrokes used by players is one of the factors that should be considered when discussing fatigue in tennis.

KEYWORDS
physiological demands, simulated match-play tennis, mechanical energy, forehand groundstroke, fatigue, blood lactate

Introduction

Tennis is a world-class competitive and recreational sport attracting millions of players and fans worldwide (1). Tennis has been the subject of many physiology, biomechanics, and game analysis studies, both in the laboratory and in actual competition situations. In laboratory studies, treadmill-based simulated match-play tennis protocols and ball feeder-based hitting tests are often employed. Such studies tend to focus on physiological responses related to fatigue (2, 3) and tennis-specific performance such as stroke velocity or accuracy (4, 5). It is recognized that tennis performance substantially depends on a complex interaction of physical fitness (aerobic and anaerobic) and tennis-specific skills (6). However, these factors have been considered separately in most previous studies; the simulated match-play tennis protocol did not include hitting motions (2, 3), and a hitting test did not evaluate increase in fatigue as the game progressed (4). In an actual match, tennis is characterized by explosive actions, including sprints and hitting motions such as service or stroke, and players' physiological responses constantly change throughout the match (7). We concluded that for examining fatigue during both the sprint and hitting phases, it would be more appropriate to combine both simulated match-play tennis protocol (contributing the sprint phase) and hitting test.

Previous studies concluded that intensive rallies mainly demand energy provision for bouts of high-intensity work *via* intramuscular phosphates and glycolysis (8). Lack of anaerobic capability in tennis players causes early fatigue, leading in turn to impairment of ground stroke accuracy (9). Fatigue in tennis has been investigated using measurements of blood lactate concentration (BLa) and discussed in review articles (1, 10). These authors had mentioned that the BLa during tennis play had indicated varying results in the literature (11, 12), and no consensus has been reached. These inconsistent results suggest that BLa is associated with various factors, including match time, individual techniques, play-style and emotional stress. When focusing on the hitting technique in an actual game, players hit the ball in various forms and often use the drive and flat shots in groundstroke. However, the effect of these shots on BLa has not been reported.

On the other hand, the mechanical energy required for each shot will depend on the energy acquired by the racket as a result of body movements and the efficiency of energy transfer between the racket and the ball. Cross and Lindsey (13) propose a method to estimate the speed and spin of the ball after impact with the racket. Calculating the mechanical energy of the ball based on this method (assuming the ball speed and spin to be zero before impact) indicates that the ball's kinetic energy decreases more when the ball impacts the string bed tangentially than under a normal impact. This can also be observed from the motion data of the ball and racket when players hit serves. Based on the ball speed and spin rate reported in a previous study (14), the estimated kinetic energy of the ball in the flat, slice, and kick serves of male professional players was 79.2 J, 66.0 J, and 56.1 J, respectively [the ball's mass and moment of inertia assumed to be 57.7 g and the 0.55 mr^2 $kg \cdot m^2$ (15), where m and r are the ball's mass and radius]. However, no difference in the racket speed at impact was reported for these three types of serves (16). In groundstrokes, players hit the ball at various angles of impact (17), and the energy required for each shot may differ depending on whether the player applies greater or lesser spin to the ball. Since more rotation elicits a higher physical strain, it is thus possible that there might be a trend in the number of rotations when grouping by high and low values of BLa.

The mean duration of work periods during a match has been reported as approximately 4–7 s (18) and that of rest periods as 10–20 s (1). Average oxygen uptake values were above 80% maximum oxygen uptake (VO_2max) during intensive rallies, but at approximately 50–60% VO_2max (23–29 mL/kg/min) during match-play tennis including both sprint and hitting motions (1, 4), which is in the moderate intensity range. We speculated that the simulated match-play tennis protocol without hitting motion results in a lower exercise intensity than that found in previous studies. It is thus possible that the lesser physical strain from only running may not elicit any difference in physiological responses even if grouped by BLa values, due to alternate replenishing of energy sources and restoration of homeostasis (by oxidative metabolism) in the intervals (19).

Therefore, the purpose of this study was to compare the effect of high and low BLa groups on (1) the kinetic energy of the ball during a hitting test and (2) physiological responses during a simulated match-play tennis protocol. It was hypothesized that the high BLa group would show higher rotational kinetic energy in the hitting test compared to the low BLa group. We also hypothesized that running simulations would show no difference in physiological responses between groups.

Methods

Participants

Fourteen tennis players were recruited [ten males; age: 21 ± 1 year, height: 1.72 ± 0.06 m, body mass (BM): 63.6 ± 5.4 kg, and four females; age: 19 ± 1 year, height: 1.69 ± 0.04 m, BM: 62.2 ± 3.8 kg]. Participants were classified into two groups of seven participants each based on the median BLa in the first hitting test, HIGH (age: 20 ± 1 year, height: 1.73 ± 0.07 m, BM: 63.6 ± 6.8 kg, BLa: 2.58 ± 0.38 mmol/L) and LOW (age: 19 ± 1 year, height: 1.70 ± 0.03 m, BM: 62.2 ± 3.2 kg, BLa: 1.78 ± 0.25 mmol/L). Two women were included in each group (HIGH: 3.08 ± 0.11 mmol/L, LOW: 1.93 ± 0.25 mmol/L). All participants belonged to a national-level college tennis club, and their weekly training volume was approximately 15 h/week. One participant was a left-handed tennis player. The study protocol was approved by the National Institute of Fitness and Sports in Kanoya Ethics Committee (Permission number: 11–58), and participants provided their informed consent to participate prior to commencing the study. The study complied with the latest version of the Declaration of Helsinki, and was conducted according to international standards.

Procedures

On arrival at an indoor hard court, players performed approximately 15 min of warm-up by running and hitting groundstrokes fed by a ball machine. After the warm-up, a finger prick BLa (Lactate Pro 2, Arkray Global Business Inc, Japan) measurement was taken. This measurement was also taken both immediately before and after the hitting test. Players were equipped with a portable metabolic system, which allowed the measurement of oxygen uptake (VO_2), pulmonary ventilation (VE) and respiratory exchange ratio (RER) (MetaMax-3B, Cortex, Germany) and heart rate (HR) (RS-800, Polar, United States). Once the equipment was attached, players performed the hitting test and simulated match-play tennis. The total duration of the simulated match-play tennis was 6,108 s (1 h 41 min 48 s).

Simulated match-play tennis protocol

The simulated match-play tennis protocol employed was a modified running protocol designed by Lynch et al. (2). It was designed to simulate the temporal profile and volume of metabolic heat production of a professional tennis match, including the exact timing duration of rest breaks mandated by the Rules of Tennis.

The protocol consisted of a series of 16 km/h sprints lasting an average of 6 s. To this end, players were asked to run 26.6 m in 6 s (16 km/h). This was followed by periods of recovery of 20 s. One 26 s cycle of exercise and recovery was recognized as one simulated "point". Each simulated "game" consisted of six "points", and each simulated "set" consisted of eight "games". Each session comprised three simulated "sets". Each mandated break of 90 s between odd games was implemented in accordance with International Tennis Federation rules (**Figure 1A**).

Hitting test

The hitting test was performed before and after the simulated match-play tennis protocol and between sets. This test aimed to have the player perform groundstrokes with the same intensity as normally employed in an actual match. It consisted of returning a forehand down-the-line groundstroke to the opposite end of the court in a standing position behind the ball's bounce point (**Figure 1B**). A ball feeder (TQ-2000H II, Tanaka Electric Co., Japan) fed 50 balls at a frequency of one ball every 3.5 s, with a velocity of 60 km/h, 85 cm over the net, and landing 60 cm from the opposite baseline on the deuce side, in front of the player. Players were instructed to hit the balls at a submaximal velocity, returning the balls toward standard square landing zones (2.05 × 5.49 m) at the opposite end of the court. The ball trajectory was filmed by a digital video camera (FASTCAM Mini UX100, Photron Ltd., Japan). At the same time, the speed and spin rate of the ball just after hitting were measured by a laser Doppler ball kinematics analyzer (TrackMan tennis radar, TrackMan, Denmark). For left-handed players, the same hitting test was conducted on the opposite (left) side.

The two-dimensional coordinates of the ball landing points in digitized space were obtained from the video images using a custom program and converted to horizontal position in real space by the two-dimensional direct linear transformation method (20). Mean error of the landing point was defined as a relative position from the center of the target zone. The first and last 10 data points of each hitting test were excluded from the analysis. The kinetic energy of the ball was calculated by the following equations:

$$E_t = \frac{1}{2} m v^2$$

$$E_r = \frac{1}{2} I \omega^2$$

where E_t is translational kinetic energy, m is the ball's mass, and v is the ball's speed; and E_r is rotational kinetic energy, I is the moment of inertia, and ω is the angular speed. Total kinetic energy (E_k) was then calculated as the sum of E_t and E_r, and the ratio of rotational kinetic energy to total kinetic energy ($\%E_r = E_r/E_k$) was also obtained.

Calculation and statistical analysis

The HR, percentage of HR reserve (%HRR), VO_2, VE and RER were averaged over the last min of the first and last game (i.e., games 1 and 8) in each set, and the hitting test. %HRR was calculated using the Karvonen formula: %HRR = (HR − rest HR)/(maximum HR − rest HR) × 100. Since maximum HR was not measured in the present study, a predicted value based on previously published results (220 - age) was adopted (21). All statistical computations were performed using the IBM SPSS Statistics 28 software package (SPSS Inc., USA). The distribution of the data was analyzed by a Shapiro–Wilk test, and Mauchly's test was used to examine sphericity. Physiological measurements except blood lactate concentration were analyzed by a three-way repeated measures analysis of variance (ANOVA) to compare data from different experimental groups, using group (2 levels: HIGH, LOW), set (3 levels: set 1, 2, 3) and time point in the set (3 levels: game 1, game 8, hitting test) as independent variables. The same ANOVA was performed for blood lactate concentration (2 levels: HIGH, LOW), set (4 levels: initial test before starting the simulated match-play tennis protocol and set 1, 2, 3) and timing of measurement

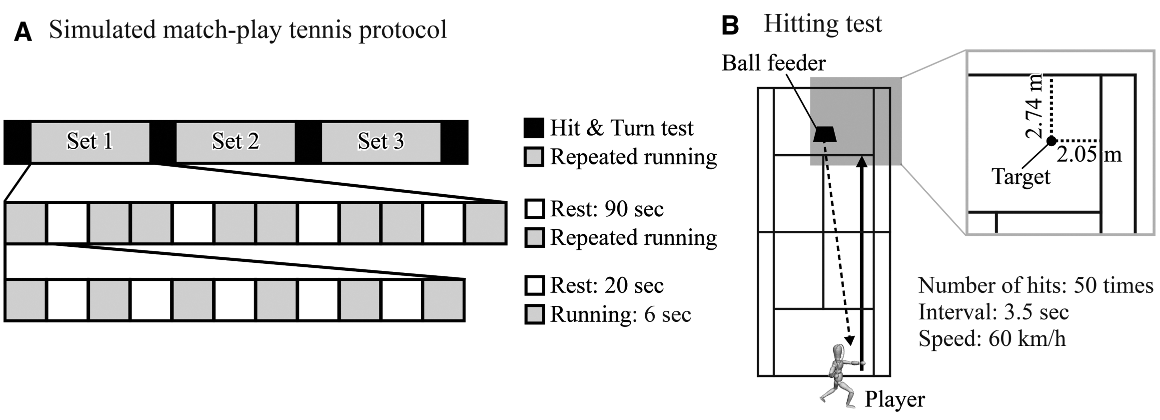

FIGURE 1
Overview of simulated match-play tennis protocol and hitting test. (A) Time structure of exercise and rest in the simulated match-play tennis protocol. From top to bottom, the structure of a match (3 sets), a set (8 games), and a game (5 points) are shown. The hitting test is shown in black, running in gray, and rest in white. (B) Overview of the hitting test. The target was set at 2.74 m from the baseline and 2.05 m from the singles line on the advantage side.

(pre and post hitting test). The variables of the hitting test were similarly compared by two-way repeated measures ANOVA using group (2 levels: HIGH, LOW) and set as the independent variables. In the analysis of repeated measures, a Greenhouse–Geisser correction was used in the case of violations of the sphericity assumption. When a significant main effect or interaction effect was identified, a Holm's step-down procedure was performed for pairwise comparisons. The level of significance was set at $p < 0.05$. Cohen's d (d) was used as a measure of effect size for paired samples, with 0.2 to <0.6, ≥0.6 to <1.2, ≥1.2 to <2.0, ≥2.0 to <4.0, and ≥4.0 representing small, moderate, large, very large and extremely large treatment effects, respectively (22).

Results

Physiological measurements

The analysis of blood lactate concentration showed a main effect of group [$F(1, 12) = 6.281$; $p = 0.028$; $\eta_p^2 = 0.344$] and pre/post [$F(1, 12) = 69.409$; $p < 0.001$; $\eta_p^2 = 0.853$] and an interaction between group and pre/post [$F(1, 12) = 4.778$; $p = 0.049$; $\eta_p^2 = 0.285$] (**Table 1**). Confirming the results of the post test (**Figure 2A**), BLa was higher in post than pre in both HIGH ($t = 7.437$; $p < 0.001$; $d = 2.446$; very large effect) and LOW ($t = 4.345$; $p = 0.004$; $d = 1.429$), and HIGH was higher than LOW in post ($t = 3.291$; $p = 0.011$; $d = 1.413$; large effect).

The main effects of HR and %HRR were detected for game (HR: $F(1.121, 13.455) = 58.046$; $p < 0.001$; $\eta_p^2 = 0.829$, %HRR: $F(1.142, 13.706) = 64.515$; $p < 0.001$; $\eta_p^2 = 0.843$), but not for group (HR: $F(1, 12) = 3.230$; $p = 0.097$; $\eta_p^2 = 0.212$, %HRR: $F(1, 12) = 3.406$; $p = 0.090$; $\eta_p^2 = 0.221$) or set (HR: $F(2, 24) = 0.463$; $p = 0.635$; $\eta_p^2 = 0.037$, %HRR: $F(2, 24) = 0.877$; $p = 0.429$; $\eta_p^2 = 0.068$), and no interaction effects were observed (**Table 1**). In addition, HR (game 1 < hitting: $t = 8.811$; $p < 0.001$; $d = 1.749$; large effect, game 8 < hitting: $t = 7.233$; $p < 0.001$; $d = 1.494$; large effect) and %HRR (game 1 < hitting: $t = 9.646$; $p < 0.001$; $d = 1.996$; large effect, game 8 < hitting: $t = 7.443$; $p < 0.001$; $d = 1.751$; large effect) were significantly higher in the hitting test than in the simulated match-play tennis protocol (**Figures 2B,C**).

The main effects of VO_2 and VE were detected for game (VO_2: $F(1.078, 12.941) = 42.644$; $p < 0.001$; $\eta_p^2 = 0.780$, VE: $F(1.070, 12.845) = 42.773$; $p < 0.001$; $\eta_p^2 = 0.781$) but not for group in VO_2 (VO_2: $F(1, 12) = 0.592$; $p = 0.457$; $\eta_p^2 = 0.047$, VE: $F(1, 12) = 5.152$; $p = 0.042$; $\eta_p^2 = 0.300$). Moreover, VO_2 showed an interaction effect between set and game [$F(4, 48) = 5.815$; $p < 0.001$; $\eta_p^2 = 0.326$] (**Table 1**). The hitting test was higher than in both VO_2 (game 1 < hitting: $t = 7.033$; $p < 0.001$; $d = 1.952$; large effect, game 8 < hitting: $t = 6.326$; $p < 0.001$; $d = 1.936$; large effect) and VE (game 1 < hitting: $t = 6.923$; $p < 0.001$; $d = 2.190$; very large effect, game 8 < hitting: $t = 6.813$; $p < 0.001$; $d = 2.166$; very large effect) than the simulated match-play tennis protocol (**Figures 2D,E**). RER showed a main effect for set [$F(2, 24) = 30.182$; $p < 0.001$; $\eta_p^2 = 0.716$], and an interaction between set and game was also observed [$F(4, 48) = 4.870$; $p = 0.002$; $\eta_p^2 = 0.289$] (**Table 1**). The RER measured in game 8 decreased as the set progressed (set 1 > set 2: $t = 3.857$; $p = 0.008$; $d = 0.692$; moderate effect, set 1 > set 3: $t = 8.016$; $p < 0.001$; $d = 1.438$; large effect, set 2 > set 3: $t = 4.159$; $p = 0.003$; $d = 0.746$; moderate effect), and similarly the RER measured in the hitting test was lower in set 3 than in the other sets (set 1 > set 3: $t = 6.579$; $p < 0.001$; $d = 1.181$; moderate effect, set 2 > set 3: $t = 4.159$; $p = 0.003$; $d = 0.746$; moderate effect) (**Figure 2F**).

Mechanical measurements

There was no main effect of group [$F(1, 12) = 0.594$; $p = 0.456$; $\eta_p^2 = 0.047$] or set [$F(3, 36) = 0.146$; $p = 0.931$; $\eta_p^2 = 0.012$] on Ek of the ball, nor was there any interaction effect [$F(3, 36) = 0.268$; $p = 0.848$; $\eta_p^2 = 0.022$] (**Figure 3A**). Similarly, there was no main effect of group [$F(1, 12) = 0.031$; $p = 0.862$; $\eta_p^2 = 0.003$] or set [$F(3, 36) = 0.130$; $p = 0.942$; $\eta_p^2 = 0.011$] on Et of the ball, nor was there any interaction effect [$F(3, 36) = 0.338$; $p = 0.798$; $\eta_p^2 = 0.027$] (**Figure 3B**).

On the other hand, a between-group main effect of Er was observed [$F(1, 12) = 11.401$; $p = 0.006$; $\eta_p^2 = 0.487$]. However, there was no main effect of the set [$F(3, 36) = 0.754$; $p = 0.527$; $\eta_p^2 = 0.059$], and no group-set interaction [$F(3, 36) = 1.246$; $p = 0.307$; $\eta_p^2 = 0.094$] was observed (**Figure 3C**). Similarly, a between-group main effect of %Er was observed [$F(1, 12) = 7.766$; $p = 0.016$; $\eta_p^2 = 0.393$]. However, there was no main effect of the set [$F(3, 36) = 1.108$; $p = 0.359$; $\eta_p^2 = 0.085$], and no group-set interaction [$F(3, 36) = 1.121$; $p = 0.353$; $\eta_p^2 = 0.085$] was observed (**Figure 3D**).

Finally, no main effect of group [$F(1, 12) = 0.594$; $p = 0.456$; $\eta_p^2 = 0.049$] or set [$F(1.748, 20.979) = 0.475$; $p = 0.603$; $\eta_p^2 = 0.038$] on distance between the target and ball landing point and no interaction effect [$F(1.748, 20.979) = 0.852$; $p = 0.427$; $\eta_p^2 = 0.066$] were observed (**Figure 3F**).

Discussion

This study aimed to compare the effect of high vs. low BLa concentration in players (HIGH and LOW) (based on the initial hitting test) on the ball's kinetic energy during a hitting test and physiological responses during a simulated match-play tennis protocol. We hypothesized that players in the HIGH group would show a higher %E_r in the hitting test than those in the LOW group, and that running simulations would show no difference in physiological responses between groups. Supporting these hypotheses, we found that HIGH always showed higher BLa after the hitting test than LOW, E_k was not significantly different between HIGH and LOW, %E_r was higher in HIGH, and physiological responses in both HIGH and LOW were associated with activity types such as running or hitting but did not depend on match progression (set progress) or differences between groups.

This study is the first to show that the rotational kinetic energy of the groundstroke is a relevant factor influencing the value of BLa in tennis. E_r was higher in HIGH than in LOW and E_k was comparable between groups, possibly because E_r has much smaller magnitude than E_t. In other words, the reason for the difference in physiological responses between the two groups may have been a decrease in energy transfer efficiency between the ball and racket when applying spin to the ball, rather than an increase in the ball's

TABLE 1 Main effects and interactions of physiological measures.

		Main effect			Interaction			
		Group	Set	Game/Pre Post	Group × Set	Group × Game/ Pre Post	Set × Game/ Pre Post	Group × Set × Game/Pre Post
Blood lactate concentration	ndf	1	3	1	3	1	3	3
	ddf	12	36	12	36	12	36	36
	F	6.281	1.102	69.409	0.279	4.778	1.362	0.564
	p	0.028	0.361	<0.001	0.840	0.049	0.270	0.642
	η_p^2	0.344	0.084	0.853	0.023	0.285	0.102	0.045
Heart Rate	ndf	1	2	1.121	2	1.121	4	4
	ddf	12	24	13.455	24	13.455	48	48
	F	3.230	0.463	58.046	1.241	0.048	2.158	0.158
	p	0.097	0.635	<0.001	0.307	0.856	0.088	0.959
	η_p^2	0.212	0.037	0.829	0.094	0.004	0.152	0.013
% Hear rate reserve	ndf	1	2	1.142	2	1.142	4	4
	ddf	12	24	13.706	24	13.706	48	48
	F	3.406	0.877	64.515	0.643	0.285	2.068	0.414
	p	0.090	0.429	<0.001	0.535	0.632	0.100	0.798
	η_p^2	0.221	0.068	0.843	0.051	0.023	0.147	0.033
Oxygen uptake	ndf	1	2	1.078	2	1.078	4	4
	ddf	12	24	12.941	24	12.941	48	48
	F	0.592	4.433	42.644	1.052	0.889	5.815	1.415
	p	0.457	0.023	<0.001	0.365	0.371	<0.001	0.243
	η_p^2	0.047	0.270	0.780	0.081	0.069	0.326	0.105
Pulmonary ventilation	ndf	1	2	1.070	2	1.070	4	4
	ddf	12	24	12.845	24	12.845	48	48
	F	5.152	1.007	42.773	0.561	0.069	1.341	2.145
	p	0.042	0.380	<0.001	0.578	0.814	0.269	0.090
	η_p^2	0.300	0.077	0.781	0.045	0.006	0.100	0.152
Respiratory exchange ratio	ndf	12	2	2	2	2	4	4
	ddf	1	24	24	24	24	48	48
	F	1.466	30.182	3.115	1.339	0.478	4.870	1.015
	p	0.249	<0.001	0.063	0.281	0.626	0.002	0.409
	η_p^2	0.109	0.716	0.206	0.100	0.038	0.289	0.078

The factors are group, set, and game, but only lactate is considered as a Pre/Post instead of Game. Significant differences are highlighted. The ndf and ddf are numerator and denominator degrees of freedom, respectively.

rotational kinetic energy. As noted, ball-racket impact phenomena have been the subject of many studies, and the speed and spin of the ball after ball-racket impact can be estimated (13). When the kinetic energy of the ball is simulated by varying the angle of impact on the racket, mechanical energy transfer efficiency decreases as more spin is applied, as can be observationally inferred from the kinematics of the ball (14) and racket (16) when the player hits a serve. Therefore, even if the same amount of mechanical energy was applied to the ball, a player with a higher $\%E_r$ (HIGH) would have had to apply more mechanical energy to their racket. To obtain more mechanical energy, the glycolytic system is more rapidly utilized by mobilization of upper-body muscles required for the ball hitting action, and as a result, one would expect differences in BLa (elevation).

The accuracy and mechanical energy of the ball were not affected by the progression of the protocol (**Figure 3**). Therefore, it is not possible to conclude that fatigue affected the results of the hitting tests conducted in this study. Focusing on the relationship between the intensity of the hitting test and the performance of the groundstrokes, a previous study reported that the groundstroke

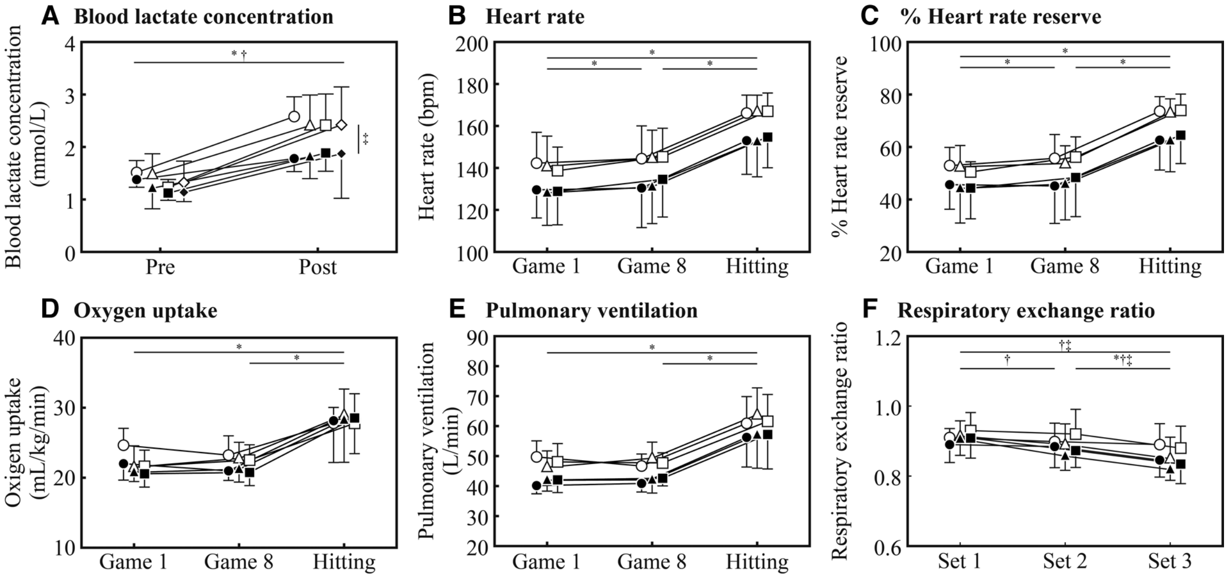

FIGURE 2
Physiological measurements at each time point. The HIGH group is indicated by a white symbol and the LOW group by a black symbol. (A) Blood lactate concentration pre and post hitting test before the simulated match-play tennis protocol and each set. Circles indicate pre-test, triangles, squares, and diamonds indicate 1st to 3rd sets, respectively. Significant differences between pre and post in HIGH and LOW are marked with "*" or "†", respectively. Significant differences between HIGH and LOW in post are marked with "‡". (B–E) Heart rate, % Heart rate reserve, oxygen uptake and pulmonary ventilation at each time point (game 1, game 8 and Hitting test). Circles, squares, and diamonds indicate 1st to 3rd sets, respectively. Significant differences between time points are marked with "*". (F) Respiratory exchange ratio at each time point (set 1, set 2 and set 3). The HIGH group is indicated by a white symbol and the LOW group by a black symbol. Circles indicate pre-test, triangles, squares, and diamonds indicate game 1, game 8 and the hitting test, respectively. Significant differences in RER between sets at each time point, game 1, game 8 and the hitting test are marked with "*", "†" and "‡", respectively.

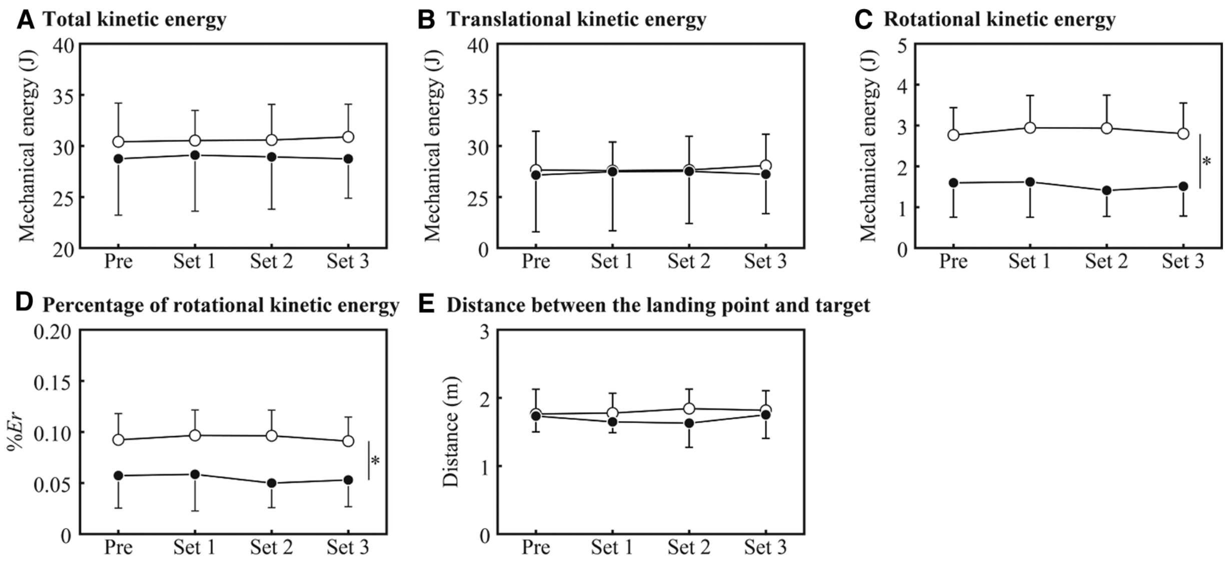

FIGURE 3
Results of the hitting test at each time point. White and black circles indicate the HIGH and LOW groups, respectively. An asterisk indicates a main effect between groups.

accuracy at high intensity was reduced, but that at moderate loading the accuracy was comparable to that at rest (9). In that report, the average HR was 171 ± 7 bpm, even at moderate intensity, which would be higher than that in the hitting test in the present study. It can therefore be inferred that the load of the reported hitting test was not high enough to affect the accuracy of the groundstrokes. On the other hand, a study using a fatiguing intermittent exercise combining stroke and serve reported that stroke (accuracy: −25.6%, consistency: −15.6%) and serve (speed: −4.5%, accuracy: −11.7%) both declined over this interval (23).

However, compared to the present study, which used intermittent running (approximately 1 h and 40 min), this 40-minute fatigue session included serve and groundstrokes, resulting in differences to the present study in exercise intensity, duration, and upper extremity activity. There are reports examining the decrease in serving ability in long matches, based on match statistics from actual five-set matches. While some studies reported no reduction in serve accuracy or speed between the first and fifth sets (24), some found that the average speed of first serves was higher in the first set than in the third through fifth sets (25). However, the latter study only reported an average decrease by 0.6 m/s from set 5 to set 1, and the second serve did not differ in speed between sets. Although it cannot be stated categorically, it can be thus be concluded that this study's cumulative fatigue (due to running simulation) was insufficient to affect groundstroke performance. Thus, the effects of fatigue have been the subject of disagreement in previous studies, and further investigation is needed.

In addition, no differences in groundstroke accuracy were observed between sets in this study. This may be due to the fact that the protocol did not include decision-making such as return course selection, or locomotion that occurs in an actual match, and thus presented easier conditions than under realistic conditions. Therefore, the results of this study do not allow any discussion of the effect of these factors. However, player-specific movements may be closely related to fatigue. This study showed that the type of stroke (more or less spin on the ball) affects the degree of fatigue. In a previous study that performed motion analysis before, at the midpoint, and after a 3-hour match, it was reported that the timing of maximum angular velocity was maintained before and after the match, while serving performance and joint kinetics decreased, suggesting that advanced players are able to maintain the temporal pattern of their serve even as muscle fatigue progresses (26). We therefore suggest that in future studies it is necessary to combine the analysis of movement and physiological responses.

In this study, physiological responses in both the HIGH and LOW groups were associated with activity types such as running or hitting, but did not depend on match progression (the set progress) or differ between groups. No significant differences in HR, %HRR, or VO_2 were found between groups during the simulation protocol, suggesting that physical fitness levels were identical. However, stroke execution, which is an instantaneous movement, is an important energy-demanding factor. As Fernandez-Fernandez et al. (4) discussed, it is possible that not only the upper-body muscles required for the ball stroke but also additional muscles (e.g., biarticulate leg muscles such as biceps femoris, rectus femorus, and hip adductors during the stroke position) are required for the ball stroke. Although tennis is a combination of sprinting and hitting, a singles tennis match was found to result in higher blood glucose concentration than running (27). Therefore, differences in physiological responses between running and hitting in tennis may be caused by different metabolic demands depending on differing muscle mobilization. This is because upper-body muscle involvement is required for the ball hitting action, as indicated by previous studies. In the present study, even the basic hitting protocol with submaximal groundstroke velocity and standing position differed from running. Further study using a simulated match-play tennis protocol involving a hitting action may be warranted.

RER declined during match progression regardless of group or activity types in physiological responses. Endurance athletes can have the ability to achieve a steady state even in high-intensity interval exercise (28). Wallner et al. (29) also reported that short intermittent sprint exercise is characterized as mostly aerobically balanced exercise even if the cardiorespiratory and lactate responses oscillate intensively. Tennis is a repetitive sprint sport with medium to high aerobic and anaerobic demands (1). It is possible that tennis players in the present study, which belonged to a national level college tennis club, experienced the simulated match-play tennis protocol as mostly aerobically balanced exercise, and thus generated cardiorespiratory and lactate responses similar to the endurance athletes in the study mentioned above. This is in accordance with Ferrauti et al. (27), who showed that players of a singles tennis match demonstrated a gradual decline in RER while retaining higher glycolysis and glycogenolysis activity levels during tennis match play compared to continuous running exercise at a similar mean VO_2 (30). However, it is possible that RER might be influenced by other factors, such as dietary fat intake, muscle glycogen content and circulating substrates (31).

Limitations

The study is subject to several limitations. For mechanical measurements, we only measured the mechanical energy of the ball and did not take the energetics of the player's body motion into account. In addition, because individual subjects were not measured when applying different ratios of spin to speed, there may have been player-specific differences in form. In future studies, it will be necessary to have the same subjects hit groundstrokes with different ratios of spin and speed and to compare the mechanical work. In the physiological part of the study, players performed running and hitting groundstrokes fed by a ball machine during the warm-up period. The effort of running in the warm-up was not standardized, while hitting groundstrokes was set up similar to the hitting test in order to ensure equal effort. Because maximum HR was not measured by a graded exercise test before the hitting test, we employed the commonly used equation of HRmax = 220- age for prediction. This equation is frequently used in prescribing exercise intensity, but is acknowledged to be quite variable in its accuracy, with estimates having a standard deviation of 10–12 bpm (32), and the validity of alternative formulas is under discussion (33). In addition, since there exist maximum HR equations that differentiate between genders (34), further research should employ these more specific equations.

Conclusion

In this study, we hypothesized that the amount of ball spin on groundstrokes would be related to blood lactate concentration. We tested this hypothesis by combining a match simulation protocol and hitting tests. In support of this hypothesis, despite no difference in E_k between groups, $\%E_r$ was higher in the high BLa group than in the low BLa group. In addition, the progression of the simulation protocol did not affect the result of the hitting test, and there were no significant changes in physiological responses. In other words, simple hitting ability, which does not include decisions, is not affected by the progression of the game, but may be more influenced by the activity intensity of the previous match point. The effect of fatigue on hitting ability has been controversial in previous studies, but in any case, a match simulation protocol that does not include a hitting task may not be able to accurately evaluate comparative game progression between players who do or do not apply heavy spin to the ball on a groundstroke.

Our results suggest that physiological load differs depending on the type of groundstroke (high or low spin rates). Therefore, players should plan their fitness training according to their groundstroke type. In addition, as discussed with regard to the importance of pacing on the serve (25), it seems essential to adjust the spin rate of groundstrokes according to fatigue during the match, qualified by game strategy and other factors.

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 human participants were reviewed and approved by National Institute of Fitness and Sports in Kanoya. The patients/participants provided their written informed consent to participate in this study.

Author contributions

MM and TN designed the study. MM and TN performed the experiment, analyzed the data, and prepared the manuscript. All authors contributed to the article and approved the submitted version.

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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Relevance of force-velocity and change of direction assessments for the ranking position in elite junior tennis players

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Purpose: This study aimed to correlate sprint mechanical parameters (SMP) of a linear sprint (LS) and a tennis specific modified 505 (Tm505) change of direction (CoD) test obtained with a motorized resistance device (MRD) to the current tennis ranking position (RP).
Methods: 107 male and 86 female elite junior tennis players nationally ranked in the German Tennis Federation between 10 and 18 years participated in the study. According to their age at peak height velocity (PHV), players were divided into pre-PHV, circa-PHV, and post-PHV groups. SMP were derived from instantaneous time-velocity data of two 20 m all-out LS measured with 333 Hz. Further, mean values from two Tm505 trials with constant 3 kg loading over acceleration-deceleration (1a) and reacceleration (1b) phases were measured with an MRD. SMP of LS and CoD measurements were partially correlated with the current RP in the overall national ranking by controlling for biological maturation.
Results: Low to moderate correlations (r_s = –0.1 to –0.3) were found between SMP and the RP in all male and female age groups. Correlations of the CoD measurements were overall more pronounced, particularly in girls (r_s = –0.44). All linear SMP, like maximal theoretical force (F_0; N/kg), and maximal theoretical velocity (v_0; m/s), maximal power (P_{max}; W/kg), improved over maturation for both genders with P_{max} being most important for sprint performance. Further, P_{max} was shown to correlate with the girls ranking position (r_s = –0.31). During the Tm505, matured players achieved significantly faster overall total and CoD times. Positioning of CoM before CoD enlarged over maturation and was found to correlate to the RP in both sexes. In addition, nearly all SMP significantly correlated to the primary performance outcomes in the Tm505 test in both genders (r = –0.3 to –0.6).
Conclusion: CoD performance has a moderate and higher impact on tennis performance compared to LS. CoD performance as well as P_{max} achieved a higher relevance for the ranking position predominantly in girls compared to boys. Hence, particularly P_{max} as well as the transfer to on-court CoD motor skills should be a central training goal in elite junior tennis players besides technical skills and should depend on maturation status and gender.

KEYWORDS
sprint, maturation, peak height velocity, acceleration, deceleration, female

1. Introduction

Movement speed is considered essential for success in many team and racket sports (1, 2). Movement speed in racket sports consists of several factors, including the capacity to accelerate fast and effectively in various directions. Therefore, precise footwork patterns must be used during the stroke preparation, and quick change of direction must be made (e.g., deceleration, reorientation, and acceleration). Many of these actions happen according to external stimuli that must be detected and processed rapidly (3). Match play analysis at the highest level showed that average running distance ranges between 2.5 and 4.5 m and four changes of direction per point (4), with roughly 20% of these movements involving a medium or high time pressure (5). Players usually cover their backhand side more and therefore sprint frequently towards an open forehand side with a subsequent change of direction after the stroke (5). In addition, more than 70% of movements during tennis match play are lateral, with up to 1,000 direction changes during competitive games (6).

Numerous studies highlight the significance of different speed characteristics as crucial parts of the physical demands of tennis (1, 7, 8). Consequently, various fitness testing for elite tennis players is mandatory, focusing on linear sprint (LS) and change of direction (CoD) tests. These are often part of an extensive testing battery (9). During LS, players need to effectively apply forces to the ground in a way to accelerate forwards (10). Thereby, the highest horizontally orientated forces can be found at the beginning of the sprint. Players increase their speed as they keep accelerating towards the finish line, trying to effectively apply force at high velocities to reach their maximum speed. A 20 m distance is recommended for testing tennis players (11), although running speed could theoretically increase as some players are likely to not reach top speed for the given distance. As a result, an extrapolated linear force-velocity (F-v) and parabolic power-velocity (P-v) relationship may accurately describe the overall mechanical capability to produce horizontal force and velocity at low and high speeds during sprint running (10). Research has shown that sprint performance (e.g., 20 m time) highly depends on the maximal horizontal power output during sprint acceleration (12). On the other hand, change of direction tests are considered independent motor skills with a high degree of neuromuscular and biomechanical specificity (13). Altering the distance and velocity in the initial run-up implies different loading for the player (14). Using reliable tests (e.g., 505) can provide differentiated information for tennis performance since deceleration and acceleration depend on different and numerous muscle actions (15). During the 505 test, athletes accelerate towards a predefined turning point before decelerating to perform a 180° change of direction and sprinting back to the starting line. Additionally, technical abilities should be considered because an efficient deceleration technique is essential to apply optimal braking forces (15).

Regarding movement speed, path analysis has highlighted change of direction speed as the most important factor for tennis performance (ranking position) in elite junior tennis (8). Although linear speed has a minor influence on tennis performance, it was shown to be an essential determinant of CoD speed (8). Unfortunately, most studies have only used light gate measurements for linear sprint and change of direction tests in tennis testing. Testing with light gates requires the athlete to start 0.3 m up to 1 m behind the starting line. Hence, the detection of the trigger signal to start the time measurement represents a flying start which in turn does not reflect the initial force production capabilities of the athlete. Furthermore, the development of movement speed as a consequence of forces acting on the ground, and maximal sprint speed, cannot be detected accurately with only a few split times over a certain running distance. Force and power output are usually overestimated, while maximal speed is underestimated when using split times to calculate SMP. To account for these discrepancies, literature suggests manually adding 0.5 s to the sprint times for all players (16). Similarly, for CoD tests, split times from light gates are the main parameters reported limiting the understanding of deceleration qualities and split times achieved. Due to this methodological limitation, a detailed individual analysis beyond split times was not yet presented in literature. As a result, there is still a lack of information about how tennis players move during linear sprint and CoD tasks as they mature. Using only split times impairs information about how two players might achieve the same respective split times during a LS or CoD. The subsequent training intervention is likely only beneficial for one player. Hence it is necessary to investigate individual strengths and weaknesses of the sprint mechanical parameter and the cause of CoD performance in detail during the maturation process of junior tennis players. Quantifying the relevance of these measurements for tennis performance and to which extent LS abilities might transfer to specific parts of the CoD can provide detailed and individualized information to understand and improve the players physical abilities and, subsequently, tennis performance.

Therefore, the study aimed to detect the influence of sprint mechanical parameters and change of direction performance measurements to the tennis performance indicated by the ranking position for different gender and maturation groups. It was hypothesized that CoD measurements are more prominent and higher correlated to the gender-specific ranking position than SMP and that SMP are correlated to COD performance. Further, the relevance of SMP and CoD parameters differs depending on maturation and gender.

2. Methods

2.1. Subjects

107 male and 86 female elite junior tennis players nationally ranked in the German Tennis Federation between 10 and 18 years participated in the study. Boys and girls were divided according to their age at peak height velocity (PHV) into pre-PHV (boys: $n = 42$, 12.2 ± 0.8 years, 152.3 ± 6.8 cm, 40.9 ± 5.2 kg), circa-PHV (boys: $n = 33$, 14.1 ± 0.6 years, 170.8 ± 7.4 cm, 56.1 ± 7.8 kg; girls: $n = 37$, 12.3 ± 0.8 years, 157.4 ± 6.8 cm, 45.0 ± 6.7 kg), and post-PHV (boys: $n = 32$, 16.2 ± 0.8 years, 181.9 ± 7.1 cm, 71.3 ± 9.9 kg; girls: $n = 48$, 14.4 ± 1.2 years, 168.3 ± 5.0 cm, 57.2 ± 5.7 kg) groups. The female pre-PHV group consisted of only one player and was therefore not mentioned. Data were collected in the spring of 2022 at the respective national and regional training facilities all over Germany under standardized

conditions (indoor hard court) during the regular biannual physical testing of the German national tennis federation (9).

All tested players were selected by the regional coaches as the currently best ones which regularly participated in tennis matches in their age groups and were free from injury on the test day. The players signed a written consent form to participate in the physical test battery and provided their data for *post-hoc* anonymous group statistics. All procedures were in accordance with the declaration of Helsinki. Ethical clearance was provided by the ethics committee of the Ruhr University Bochum, submitted (26.02.2013, No. 4621-13).

2.2. Procedure

A standardized test battery consisting of anthropometric and physical performance tests was implemented in 2010 by the National Tennis Federation (The German Physical Condition Tennis Test). Since then, nationally ranked junior players have been recruited twice a year to participate (9). The tests always took place under standardized conditions on indoor courts (hard court surface) in a predefined testing order. After a 15-min individual warm-up, the athletes went through four test stations. All tests were performed in the same sequence and with the same test equipment (9). Within the framework of the standardized test battery linear sprint and change of direction measurements were conducted at the beginning of the testing day (station one). Anthropometric data were taken later on the same day during the test procedure.

2.3. Measurements

2.3.1. Anthropometrics

Anthropometric measurements included body weight, body height, and sitting height. Body weight was measured with a digital scale (±0.1 kg, ADE Electronic Column Scales, Hamburg, Germany) and body height with a fixed stadiometer (±0.1 cm, Holtain Ltd., Crosswell, UK). To measure the sitting height, a table was used in addition to the stadiometer. Trained test supervisors performed all measurements in accordance with the ISAK guidelines (17). The timing of puberty was estimated using the maturity offset method (18). Age at the time of maximum linear growth (PHV) indicates somatic maturity (19). Maturity (in years) was obtained by subtracting the chronological age at the time of measurement from PHV. The resulting value (YAPHV) indicates how far the current maturity level is away from the player's PHV. Biological age groups were defined as: pre-PHV (>−1.0 YAPHV), circa-PHV (−1.0 to 1.0 YAPHV), and post-PHV (>1.0 YAPHV).

2.3.2. Ranking position

Overall tennis performance was evaluated in terms of the gender-specific ranking position (RP) on the overall annually published national ranking lists. The rankings were published at the time of the diagnostics. Only players who were tested and positively identified on the national ranking lists were included in the study. The players' original rankings on the overall list were revised so that the top-ranked player was placed first and the lowest-ranked player last. Male players tested were within the top 1%–94% of the gender-specific rankings, while female players tested were within the top 2%–87%.

2.3.3. Twenty-meter linear sprint and force-velocity profile

2.3.3.1. Sprint testing

Athletes performed two 20 m all-out linear sprints (LS) from a staggered standing stance with 2–3 min of passive recovery between trials to ensure no fatigue-related performance decrease (9). All sprints were commenced from a static position, meaning that leaning backward before accelerating forward was not allowed. After the test leader gave a ready signal, the athletes started on their own initiative. Instantaneous velocity-time data were recorded (333 Hz) using a motorized resistance device (MRD; 1080 Sprint, 1080 Motion, Lidingö, Sweden). The MRD was placed 3 m behind the starting line, with the cord attached to the athlete by a centrally located ring (sacrum) on a belt firmly tightened around the pelvis. A resistance of 1 kg was applied over the entire sprint. The no-flying weight mode was selected because the 1080 Sprint offers different modes. Settings were controlled by a computer application (1080 Sprint, 1080 Motion, Lidingö, Sweden). The average values of the two trials for 5, 10, 20 m split times and the average speed of the best 5 m during the sprint (peak velocity) were taken as performance measurements.

2.3.3.2. Force-velocity profile

Each sprint was separately analyzed using the velocity-time raw data to compute sprint mechanical parameters (SMP). The method used was previously described in detail (10, 20, 21). Briefly, this computation method using the raw data is based on a macroscopic inverse dynamics analysis of the center-of-mass motion. Instantaneous velocity data were combined with the system mass and aerodynamic friction to compute the athlete's propulsion capacities over different velocities. These can be described by the individual linear horizontal F-v-Profile. F-v-Profiles were extrapolated to calculate relative theoretical force (F_0: N/kg, force capabilities), theoretical maximal velocity (v_0: m/s, velocity capabilities), and maximal power output (P_{max}: W/kg, power capabilities) in the antero-posterior direction. The ratio between the independent variables F_0 and v_0 corresponds to the slope (S_{Fv}) of the F-v-relationship. Further, "technical" abilities can be computed as the maximal ratio of the horizontal force applied to the ground (RF_{max}) and its rate of decrease as velocity increases (D_{RF}) (21). The average values of the two trials were taken for further analysis. Due to injuries or no valid ranking position on the test day, three male and four female players were not able to perform the LS and were subsequently excluded from the analysis.

2.3.4. Tennis modified 5-0-5 change of direction test

In addition, a modified version of the 505 change of direction test according to the demands of the tennis court was introduced

(Tm505; **Figure 1**). Athletes performed two all-out trials only to their forehand side. Instantaneous velocity-time data were recorded using a MRD (333 Hz; 1080 Sprint, 1080 Motion, Lidingö, Sweden). Participants started in a ready position facing the net on the ad-court side of the indoor hard-court (right-handed) with both their feet planted on the floor. The starting line was positioned 0.65 m laterally from the center service line. The MRD was placed 3 m perpendicular behind the doubles sideline to allow the Tm505 to be performed on the tennis court. The string from the MRD was attached to the athlete's pelvis using a pear-shaped carabiner and a tightly laced sling rope. The tightening knot was placed on the contralateral side of the turning foot to allow an undisturbed swivel of the carabiner. A permanent loading of 3 kg was applied to the participant using the built-in servo motor (2000 RPM OMRON G5 Series Motor; OMRON Corp., Kyoto, Japan) according to the reliability analysis of Eriksrud and colleagues (22). The no-flying weight mode was selected because different modes are offered by the 1080 Sprint. Settings were controlled by a computer application (1080 Sprint, 1080 Motion, Lidingö, Sweden). Due to injuries, no valid ranking position on the test day, or incorrect execution, eleven male and ten female players were not able to perform the Tm505 and were subsequently excluded from the analysis.

After the ready signal from the test leader, the athletes started on their own initiative. Any movement of the center of mass (CoM) greater than 0.2 m/s initiated the time measurement. From this, the entry phase before the CoD was defined as the acceleration and deceleration towards the doubles sideline (1a). From the moment of the CoD, the reacceleration phase started until the end of the test (1b). A successful trial was confirmed when the athlete at least touched the doubles sideline with their outside foot and ran across the starting line. The following performance outcome measurements were obtained during the Tm505 test with respect to Eriksrud and colleagues (22): total time ($Tm505_{time}$), total distance ($Tm505_{dist}$), time phase 1a ($Tm505_{1a\_time}$), average velocity during phase 1a ($Tm505_{1a\_vel}$), time phase 1b ($Tm505_{1b\_time}$), average velocity during phase 1b ($Tm505_{1b\_vel}$), the distance of the CoM to the CoD point at 0.5 s before the CoD ($Tm505_{dist\_-0.5s}$), the time for a fixed distance (1.37 m; distance between singles and doubles sideline) before and after the CoD (; $Tm505_{time\_CoD}$), and the time needed from peak velocity during phase 1a to stop before CoD ($Tm505_{time\_decel}$).

2.4. Statistical analysis

Raw data sets of each trial for LS and CoD were individually processed using custom-made R scripts (Rstudio, PBC, Boston, MA; version 4.1.3) and Microsoft Excel (Microsoft Corp., Redmond, WA, United States) spreadsheets. Mean values of trials for the variables of interest were used for further analysis. The overall gender-specific ranking position was taken from the annually published ranking lists of the German Tennis Federation. The highest-ranked player in the overall gender-specific ranking who participated was assigned first place and the lowest-ranked player last. Main statistics were done using JAMOVI (The jamovi project, Sydney, Australia; version 2.2.5.0). Spearmans' Rho rank correlation (r_s) was used to correlate the performance measurements of linear sprint and change of direction with the external criterion of ranking position. Biological maturation (YAPHV) was partialized out to account for maturation status. Further, linear sprint and change of direction measurements were partially correlated using Pearson's correlation (r) analysis by controlling for biological maturation (YAPHV). The following magnitude thresholds were applied: <0.10, trivial; from 0.10 to 0.30, small; from 0.30 to 0.50, moderate; from 0.50 to 0.70, large; from 0.70 to 0.90, very large; and from 0.90 to 1.00, almost perfect (23). A significance level of $\alpha = 0.05$ was accepted.

3. Results

The main results are presented as mean ± standard deviation in **Table 1**. Matured male and female athletes represent faster split times over all distances. All SMP improve from pre-PHV to post-PHV for both genders. Changes between maturation groups are generally more pronounced in males than females. Especially, P_{max} is emphasized more than other SMP over maturation. Changes in v_0 mainly increase compared to F_0. Consequently, the slope of the F-v-Profile (S_{Fv}) becomes less negative over

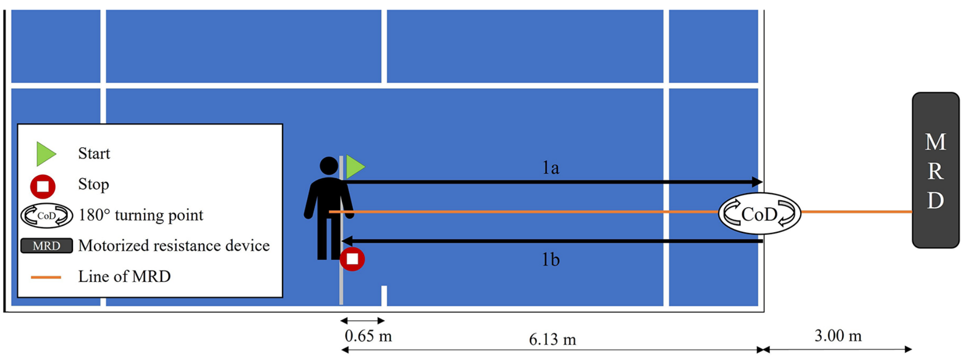

FIGURE 1
Set-up of the modified 505 change of direction test (Tm505) on a tennis court.

TABLE 1 Descriptives presented as mean ± standard deviation of linear sprint performance and mechanical as well as change of direction parameters split by sex and biological maturation.

	Male			Female	
	pre-PHV	circa-PHV	post-PHV	circa-PHV	post-PHV
Athlete characteristics					
Age (years)	12.2 ± 0.8	14.1 ± 0.6	16.2 ± 0.8	12.3 ± 0.8	14.4 ± 1.2
Mass (kg)	40.9 ± 5.2	56.1 ± 7.8	71.2 ± 9.9	45.0 ± 6.7	57.2 ± 5.7
Height (cm)	152.3 ± 6.8	170.8 ± 7.4	181.9 ± 7.1	157.4 ± 6.8	168.3 ± 5.0
Sprint times and peak velocity					
5 m (s)	1.50 ± 0.11	1.38 ± 0.07	1.31 ± 0.07	1.45 ± 0.08	1.41 ± 0.09
10 m (s)	2.45 ± 0.15	2.24 ± 0.10	2.11 ± 0.10	2.38 ± 0.11	2.29 ± 0.12
20 m (s)	4.16 ± 0.25	3.77 ± 0.16	3.51 ± 0.15	4.04 ± 0.19	3.84 ± 0.19
peak velocity (m/s)	5.99 ± 0.41	6.58 ± 0.50	7.27 ± 0.66	6.06 ± 0.54	6.47 ± 0.55
Force-velocity-characteristics					
F_0 (N/kg)	7.53 ± 1.02	8.10 ± 0.80	8.50 ± 0.79	7.69 ± 0.78	7.80 ± 0.75
v_0 (m/s)	6.34 ± 0.49	7.03 ± 0.42	7.73 ± 0.48	6.48 ± 0.44	6.90 ± 0.43
P_{max} (W/kg)	12.0 ± 2.46	14.2 ± 1.67	16.4 ± 1.94	12.5 ± 1.54	13.5 ± 1.75
S_{Fv} ($-F_0/v_0$)	−1.19 ± 0.12	−1.16 ± 0.14	−1.10 ± 0.12	−1.19 ± 0.14	−1.13 ± 0.11
RF_{max} (%)	57.4 ± 4.64	60.5 ± 3.44	62.4 ± 3.31	58.4 ± 3.76	59.1 ± 3.42
D_{RF} (%)	−9.0 ± 0.79	−8.2 ± 0.95	−7.6 ± 0.77	−8.9 ± 0.98	−8.3 ± 0.73
Change of direction characteristics					
$Tm505_{time}$ (s)	4.12 ± 0.24	3.78 ± 0.15	3.58 ± 0.11	3.99 ± 0.20	3.82 ± 0.17
$Tm505_{dist}$ (m)	12.37 ± 0.37	12.23 ± 0.29	12.02 ± 0.24	12.40 ± 0.41	12.15 ± 0.22
$Tm505_{1a\_time}$ (s)	2.14 ± 0.14	2.01 ± 0.10	1.95 ± 0.09	2.10 ± 0.12	2.04 ± 0.10
$Tm505_{1a\_vel}$ (m/s)	2.91 ± 0.19	3.05 ± 0.15	3.09 ± 0.15	2.96 ± 0.14	2.98 ± 0.14
$Tm505_{1b\_time}$ (s)	1.98 ± 0.14	1.77 ± 0.09	1.63 ± 0.09	1.89 ± 0.11	1.78 ± 0.10
$Tm505_{1b\_vel}$ (m/s)	3.15 ± 0.21	3.46 ± 0.17	3.71 ± 0.17	3.29 ± 0.14	3.43 ± 0.20
$Tm505_{dist\ -0.5s}$ (m)	0.81 ± 0.21	0.93 ± 0.14	0.98 ± 0.14	0.81 ± 0.16	0.91 ± 0.13
$Tm505_{time\_CoD}$ (s)	1.38 ± 0.10	1.28 ± 0.06	1.21 ± 0.04	1.34 ± 0.05	1.29 ± 0.06
$Tm505_{time\_decel}$ (s)	1.04 ± 0.12	0.98 ± 0.10	0.92 ± 0.10	1.03 ± 0.10	0.99 ± 0.08

Peak velocity (m/s), averaged velocity over best 5 m; relative theoretical force, F_0; theoretical maximal velocity, v_0; maximal power output, P_{max}; slope of F-v-Profile, S_{Fv}; maximal ratio of the horizontal force applied to the ground, RF_{max}; decrease in RF, D_{RF}; total time, $Tm505_{time}$; total distance, $Tm505_{dist}$; time phase 1a, $Tm505_{1a\_time}$; average velocity phase 1a, $Tm505_{1a\_vel}$; time phase 1b, $Tm505_{1b\_time}$; average velocity phase 1b, $Tm505_{1b\_vel}$; distance of CoM 0.5 s before the CoD, $Tm505_{dist\_-0.5s}$; time for a fixed distance of 1.37 m before and after the CoD, $Tm505_{time\_CoD}$; time from peak velocity in phase 1a to CoD, $Tm505_{time\_decel}$.

maturity (**Figure 2**). Regarding the specific tennis-modified change of direction task, matured boys and girls achieve faster total times along with better CoD times (**Table 1**). Phase-specific results show more substantial improvement in phase 1b compared to phase 1a. The distance of the CoM 0.5s prior to the CoD increased by 12% for females and by 23% for males over maturation.

Low to moderate significant correlations ($r_s = -0.22$ to -0.33) were found between SMP and RP across all male and female athletes (**Table 2**). However, separated by gender, low significant correlations between SMP and RP were found in females, whereas none were found in males. Regarding sprinting performance (20 m time), P_{max} showed the highest correlation of all SMP in both males ($r = -0.77$) and females ($r = -0.86$). During the sprint acceleration, the correlations of F_0 and v_0 to the split times vary in opposite directions as a function of sprint length. The correlations of F_0 decrease while values for v_0 increase for longer sprint distances. Unlike linear sprint measurements, significant correlations of CoD parameters to the RP were generally more pronounced ($r_s = -0.24$ to 0.44). Correlations of CoD measurements to RP are more dominant in females than males (**Table 3**). The total time ($Tm505_{time}$) and the time of the exclusive change direction time ($Tm505_{time\_CoD}$) represent the highest correlations to RP ($r_s = 0.44$) in girls. With respect to the $Tm505_{time\_CoD}$, the distance of the CoM prior to the CoD displays low to moderate significant correlations to the RP ($r_s = -0.24$ to -0.31) for both sexes. In addition, F_0, v_0, P_{max}, and RF_{max} significantly correlate to the main performance outcomes in the Tm505 test ($Tm505_{time}$ and $Tm505_{time\_Cod}$) in both genders ($r = -0.3$ to -0.6).

4. Discussion

This study aimed to correlate sprint mechanical parameters of a linear sprint (LS) and a tennis-specific change of direction test (Tm505) obtained with a motorized resistance device to the current gender-specific ranking position and the maximum sprinting performance of elite junior male and female junior tennis players. The main finding of this study is that correlations of the Tm505 to the gender-specific ranking position are generally more pronounced than LS parameters in youth tennis players. SMP like F_0, v_0, P_{max}, and RF_{max} significantly correlate to the main performance outcomes in the Tm505 in both genders. P_{max} was shown to correlate significantly with the girls ranking position as well.

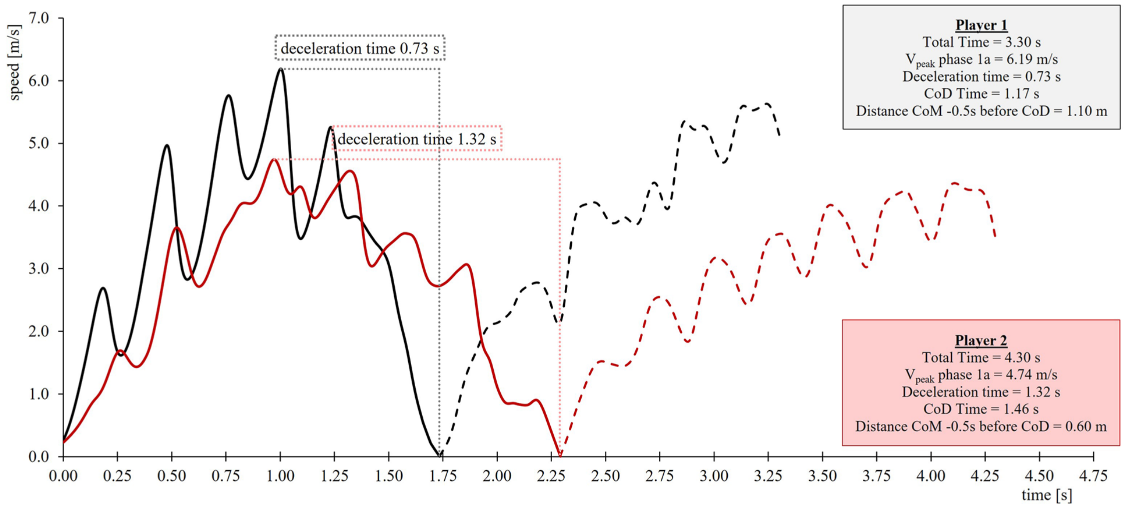

FIGURE 2
Velocity-time data from the Tm505 for two players with different total times, peak velocities, deceleration and change of direction times, and distances of their CoM at a fixed time point (0.5s) prior to the CoD. Player 1 represents a male player from the post-PHV, and Player 2 is from the male pre-PHV group. Solid lines correspond to phase 1a, dashed lines phase 1b, dotted lines visualize the deceleration time from vpeak to the point of CoD.

TABLE 2 Partial correlation of mechanical sprint parameters to gender specific ranking position split by sex and in combination while controlled for years away from peak height velocity (YAPHV).

	Male (*n* = 104)		Female (*n* = 82)	
	r_s	sig	r_s	sig
F_0 (N/kg)	−0.13		−0.20	
v_0 (m/s)	−0.05		−0.33	**
P_{max} (W/kg)	−0.11		−0.31	**
S_{Fv} ($-F_0/v_0$)	0.15		0.05	
RF_{max} (%)	−0.13		−0.22	*
D_{RF} (%)	0.06		−0.01	

Controlling for YAPHV.
*$p < 0.05$.
**$p < 0.01$.
***$p < 0.001$.

TABLE 3 Partial correlation of change of direction performance parameters to gender specific ranking position split by sex and in combination while controlled for years away from peak height velocity (YAPHV).

	Male (*n* = 96)		Female (*n* = 76)	
	r_s	sig	r_s	sig
$Tm505_{time}$ (s)	0.10		0.44	***
$Tm505_{dist}$ (m)	−0.09		0.08	
$Tm505_{1a\_time}$ (s)	0.09		0.31	**
$Tm505_{1a\_avgvel}$ (m/s)	−0.11		−0.35	**
$Tm505_{1b\_time}$ (s)	0.10		0.27	*
$Tm505_{1b\_avgvel}$ (m/s)	−0.13		−0.26	*
$Tm505_{dist\_-0.5s}$ (m)	−0.24	*	−0.31	**
$Tm505_{time\_CoD}$ (s)	0.25	*	0.44	***
$Tm505_{time\_decel}$ (s)	0.01		0.27	*

Controlling for YAPHV.
*$p < 0.05$.
**$p < 0.01$.
***$p < 0.001$.

To the best knowledge of the authors, this paper is the first to look at the correlation of sprint mechanical parameters to the RP in elite youth tennis players. Previous literature has attempted to identify crucial physical performance contributors to the ranking position of youth tennis players (8, 24). However, different split times were mainly used during a 20 m all-out sprint test or change of direction test which limit the informative value about how the players move. This lack of information can be covered by using a more detailed measure and analysis of the sprint. Using a valid MRD (25) combined with Samozino and colleagues (10) simplification model allowed us for the first time to evaluate the sprint mechanical properties of the sprint acceleration of different age groups and both sexes in junior tennis. Low to moderate correlations of F-v-parameters to the RP were found for players (**Table 2**). According to the results of Samozino and his research group, sprint acceleration performance is directly related to the average power output in the horizontal direction throughout the sprint and has the most impact on sprint performance (12). Our results are consistent with this research showing the highest impact of P_{max} on sprint performance. In the present study, superior values of P_{max} correlate to a better ranking position, particularly in girls ($r_s = 0.31$).

The present findings indicate that the overall importance of linear speed for the national ranking is relatively low. These findings are in accordance with previously reported results (8). This can mainly be attributed to the dimensions of the tennis court and the typical short distances for acceleration and deceleration. Additionally, the high demands of technical and tactical skills are most likely dominating over the athletic abilities in junior tennis. In this regard, previous studies have shown that sport specific-skills, e.g., serve speed, showed the highest correlations to ranking position (24). These consistent results suggest that technical demands are paramount in tennis players compared to linear sprint measurements. However, the results of the Tm505 highlight a stronger relevance as performance limiting factors compared to the linear sprint performance (Tables 2, 3). Especially in girls, the $Tm505_{time}$ and $Tm505_{time\_CoD}$ demonstrate the highest significant correlations to the RP ($r_s = 0.40$ and $r_s = 0.44$, respectively; Table 3). These results are in agreement with current studies reporting CoD qualities as the most relevant factor for tennis performance (8, 7). During tennis matches, players must change their direction by running primarily toward the forehand side. They may also run into a backhand or a ball near the net, recovering to the baseline in between. With four CoDs per point and a majority of distances between 2.5 and 4.5 m, 20% of these actions must be completed quickly (4, 26). The specific importance of the CoD performance in girls for reaching a higher-ranking position can be attributed to the different playing styles of men and women during match play and the specificity of the external loads in elite female tennis (4). Since service velocities are far below the values obtained in men's tennis, the game of females usually includes longer rallies with more change of directions, whereas the games of men are more powerful with shorter rallies (4). Additionally, an increasing speed of baseline shots, especially with the two-handed backhand, dominates the female baseline rallies, forcing them to perform under progressive time pressure to move fast during and after changes of direction. Recent research pointed out that elite junior players had better developed speed-accuracy trade-offs than sub-elite players (27). Given these demands, superior CoD abilities along with good speed capabilities might be more advantageous for ranking potion particularly in females.

Linear sprint qualities might influence the ability to execute a good CoD to a certain amount (8). Harper et al. (15) consolidate various strength qualities, potentially contributing to enhanced CoD performance. In this regard, these results confirm improved CoD performance in mature players representing increased speed and strength levels (Table 1). The present findings demonstrate a significant correlation of F_0, v_0, P_{max}, and RF_{max} to the primary performance outcomes in the Tm505 test without meaningful differences between gender. Interestingly, both P_{max} and v_0 show the highest correlations amongst SMP to the $Tm505_{time}$ ($r \approx -0.56$) and $Tm505_{time\_CoD}$ ($r \approx -0.50$) across all tested athletes. Similarly, force-related SMP like F_0 and RF_{max} are significantly correlated to $Tm505_{time}$ ($r \approx -0.51$) and $Tm505_{time\_CoD}$ ($r \approx -0.35$). The contribution of different linear sprint abilities might vary over the course of the Tm505. In detail, the Tm505 is divided into the entry phase (1a) and the reacceleration (1b) after the CoD. The former consists of initial acceleration and subsequent deceleration, while the latter is entirely acceleration dependent. Consequently, phases should be considered separate ($r = 0.28$) with respect to technical and physical demands. All the above-mentioned SMP measurements correlate to a higher amount to phase 1b compared to 1a, independent of gender. This seems rational since SMP are measurements of acceleration and not deceleration. Despite initial accelerations in both phases, the amount and orientation of force in the horizontal direction correlates more with phase 1b ($r \approx 0.50$). This is probably due to better shin angels immediately after the CoD and no deceleration component influencing the time. Better propulsion during linear sprinting can therefore be transferred specifically to a CoD. After the CoD, higher values of P_{max} and v_0 correlate to a better time for phase 1b in both genders ($r \approx 0.57$). In essence, P_{max} peaks during full acceleration without deceleration components and is a measure of the overall power output during sprint acceleration (12). The transfer of linear speed mainly to the acceleration phase during CoD was described previously (8). Over the short re-acceleration distance, higher P_{max} values are crucial for a better CoD performance. This is highlighted by the fact that boys and girls improved their time for phase 1b twice as much, which can predominantly be attributed to the improvements in P_{max}.

The ability to change direction quickly and efficiently in multiple directions can be considered a determining factor in tennis performance (8). A more prominent open forehand can be observed during match play in recent years, along with change of directions appearing mostly to the forehand side (5). The accompanying higher speeds prior to the CoD require adequate neuromuscular and biomechanical qualities to optimize braking impulse to achieve the desired reduction in whole-body momentum (15). With the intention of testing these demands, athletes were pulled with additional 3 kg loading toward the doubles sideline. Due to the amplified speed, enhanced braking forces paired with improved kinematic positions are essential. A current review suggests, besides other factors, an increased posterior CoM position relative to the lead braking foot as an efficient strategy (15). Consequently, this allows the athlete to apply more horizontally orientated braking forces, thereby prolonging the time in which these forces can be applied (15). In addition, generating more eccentric force is a critical requirement for developing high levels of concentric force in tasks requiring rapid countermovement (e.g., CoD) which might relate to overall better deceleration abilities (15) and is associated with superior CoD performances (14). Improvements can be found in $Tm505_{1a\_time}$ and $Tm505_{1b\_time}$, and overall time (Table 1). All mentioned time measurements of the Tm505 do correlate in female players (Table 3) indicating a positive influence of elevated acceleration and deceleration capacities for the tennis performance. The relevance of deceleration capacities for the RP in both genders is supported by the significant correlation of the time to decelerate ($r_s = 0.25–0.44$, Table 3). It is reasonable to assume that matured players optimized their strategy during the CoD tasks, especially during deceleration (Figure 3). The enlarged distance at a fixed time point (0.5s) before the CoD (21%; Table 1) can be interpreted as a measure of CoM position shortly before the CoD, which benefits the task (15). This favorable kinematic position correlates to the RP in boys and girls (Table 3).

During maturation, boys and girls naturally improve their sprint acceleration and CoD (Table 1). The greatest improvements can be observed in boys from pre-PHV to circa-PHV. Male and female players develop a more velocity-oriented F-v-Profile over maturation (Figure 2), which is mainly responsible for the increase in P_{max}. Under the consideration of YAPHV, mature players generally rank better with increased levels of P_{max}, and this is statistically significant in girls (Table 3) but can also be seen in boys (Figure 4A,B). However, the post-PHV group in males is most likely responsible for disrupting the overall likewise correlation to the RP (Figures 4C). Until this point, comparable regression lines between similar performance

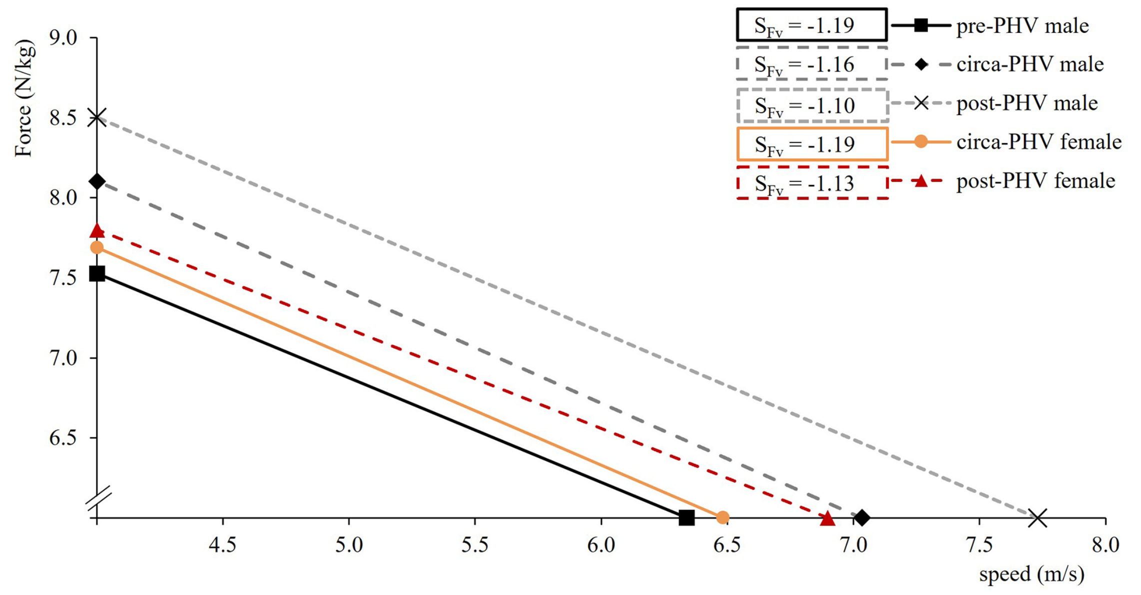

FIGURE 3
F-v-Profiles for male and female players according to their maturation status. Please note the scales of the *x*- and *y*-axis.

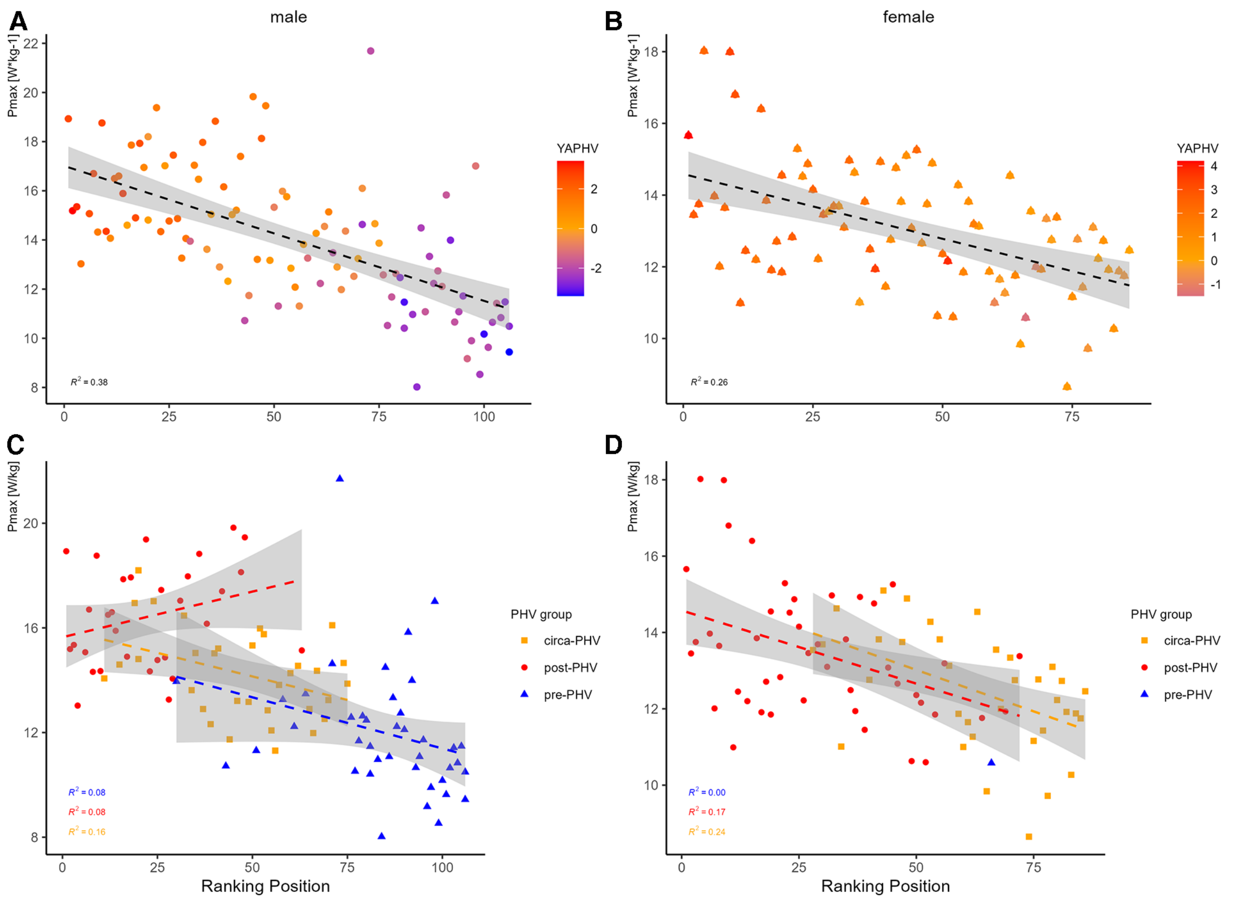

FIGURE 4
Correlation of p_{max} (W/kg) to gender-specific ranking position taking YAPHV into account (**A,B**) and with reference to PHV groups (**C,D**).

levels (e.g., pre-PHV males and circa-PHV females) can be found. This seems reasonable since women mature earlier than males but have lower physical performance levels due to physiological differences. Thus, the influence of physical development is more evident in boys than girls. In line with previous literature, relative F_0 and RF_{max} demonstrate only minor changes, while changes in v_0 are more pronounced (28). Recent research suggests that the increase in body mass (including muscle mass) from circa-PHV to post-PHV in males did not likely have a positive effect on relative maximal strength, leading to no improvement in the ability to apply relative horizontal force at low velocities (28). In the same way, matured players rank better in the Tm505 time measurements (supplements). Albeit only significant correlations were mainly found in girls, similar data distribution was displayed in boys. Again, pots-PHV males seem to develop less in phase 1a than 1b, so total time is influenced. $Tm505_{time\_CoD}$ continuously develops across maturation groups in both genders.

The present findings are essential for both talent identification and age- and gender-specific youth training. As stated previously (8), speed and change of direction are multifactorial for tennis performance. Thus, appropriate testing procedures to access specific qualities during linear and change of direction are crucial. Profound diagnostics provide information about strengths and weaknesses in particular parts (e.g., deceleration) and operate as indicators for tailored training prescriptions. The present outcomes are in line with previous results indicating that the improvement of CoD should be prioritized (8). Training of linear speed can reinforce CoD performance and act as subcomponents in this context, especially in the reacceleration phase. Fundamentally, this requires the implementation of appropriate training interventions to improve acceleration and deceleration effectively and thus create the foundation to develop CoD performance. Training should be advised based on the individual needs of the athlete. Practitioners should aim to improve the lower limbs' force-producing capabilities, technique, and coordination in junior tennis players during maturation to enhance performance (10, 29). Additionally, testing and training motor abilities and skills are essential to consider when discussing performance improvements during maturation. However, challenging to test this, these factors might be a valuable contributor to understanding performance differences. Successful training regimes include methods such as coordination, specific resistance training, maximum strength training, plyometric training, and resisted or assisted sprint training (8, 15, 30, 31). Besides physicality, improvements in deceleration technique might further positively influence performance (15). On this basis, the present results provide indications of a more posterior body position shorty before the CoD linked with a better performance. Regardless of the method used, when implying such interventions, consideration should be given to (training) age and individual maturity status. Better sprint and CoD performance can result in using different strokes and having more choices during the rally because the player has more time to prepare for the stroke. Moreover, tennis performance is a very complex phenomenon, and tennis-specific movements in a game-like context are mandatory to achieve the required performance on the court.

5. Conclusion

Conclusively, CoD performance has a moderate and higher impact on tennis performance compared to linear sprint. CoD performance as well as maximal horizontal power (P_{max}) achieved, show a higher relevance for the ranking position in girls compared to boys. SMP partly explain the CoD performance, with P_{max} showing the highest correlation to the CoD performance. Besides, all other more pronounced SMP mainly improve the acceleration phase. From a kinematic perspective, a more posterior positioning of the CoM shortly before the CoD positively benefits the deceleration to improve overall CoD performance. During maturation, players primarily improve their P_{max} due to increases in v_0 alongside all other F-v-metrics resulting in better overall sprint and CoD performance. Hence, the development of maximal power as well as the transfer to on-court CoD motor skills, should be a central training goal in elite junior tennis players. Further, CoD testing should be considered an important marker for performance as well as talent identification, especially in girls. Detailed analysis of the CoD can reveal in-depth insight into how players move and show strengths and weaknesses to prioritize and adjust training programming to improve overall tennis performance. It should be noted that these statements can only be made for the forehand side (open stance) and not the backhand side, where open and closed stances occur. Further, technical and tactical skills should not be neglected since tennis is a prominent technical and tactical sport. A direct transfer from isolated tests might be limited because of the void of cognitive and reactive components.

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

Ethical clearance was provided by the ethics committee of the Ruhr University Bochum, submitted (26.02.2013, No. 4621-13). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

NV and AF designed the study. NV performed the experiment, analyzed the data, and prepared the manuscript. All authors read and approved the final manuscript. All authors contributed to the article and approved the submitted version.

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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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Technical skills in complex tennis situations: Dutch talented players U15 compared to players U17

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Introduction: Technical skills in complex situations appear crucial for progress towards elite tennis performance. However, it is unknown how these skills develop in different age categories in a group of talented youth players. The aim of this study is to evaluate possible differences in technical skills among Dutch talented youth tennis players U15 compared to U17.
Methods: A total of 19 players (12 males, 7 females; age 14.6 ± 1.4 years) were tested on ball speed, accuracy, percentage errors and spin rate using the on-court Dutch Technical-Tactical Tennis Test. With a ball machine, four games were simulated which were either fixed (game 1 and game 2) or variable (game 3 and game 4), depending on the complexity of the task. Each game consisted of two offensive, two neutral and two defensive rallies, representing different tactical situations.
Results: A two-way ANOVA revealed a statistically significant interaction between the effects of age category and sex for ball speed ($F(1,15) = 5.472$, $p = 0.034$, $\eta^2 = 0.267$), indicating that males U17 produced higher ball speed compared to males U15, whereas no differences were found between females U15 and U17. A one-way ANCOVA showed that, regardless of sex, players U17 scored significantly higher on accuracy than players U15 ($F(1,16) = 5.021$, $p = 0.040$, $\eta^2 = 0.239$). No differences were found between players U15 and U17 for spin rate and percentage errors ($p > .05$), although there was a medium to large effect size for males U17 to produce higher spin rates compared to males U15. A closer examination of accuracy revealed that players U17 scored significantly higher compared to players U15 in game 4 ($F(1,17) = 6.358$, $p = .022$, $\eta^2 = .272$) and in defensive situations ($F(1,17) = 9.602$, $p = .007$, $\eta^2 = .361$).
Discussion: In conclusion, the results of the current study suggest that technical skills, especially ball speed for males and accuracy in complex situations for both males and females, continue to develop in adolescence in talented tennis players. There is an increased understanding about underlying technical skills that contribute to progress towards elite tennis performance. To effectively develop technical skills, coaches are encouraged to design specific practices where these skills are performed in complex situations under high cognitive and temporal pressure.

KEYWORDS
technique, racket sports, expertise, cognition, precision, performance

Introduction

Many structured talent development programs have been developed for sports, including tennis (1, 2). National tennis associations provide specialized training programs with the aim of developing and perfecting tennis performance. Offering the best facilities, training and guidance is thus a priority for associations in order to develop talented players optimally.

Unfortunately, our understanding of talent development processes is rather limited and it is difficult to provide specific recommendations for tennis associations (3). A thorough understanding of tennis-specific skills during a player's adolescence is required to facilitate the development of talents performing at a level where details make the difference.

Outstanding technical skills are considered essential for performance in sports. Most of the studies in a recent systematic review found that technical skills discriminate between performance levels, explain past performance or predict future performance (4). Studies on tennis-specific technical skills underline that players at a higher performance level outscore players at a lower performance level on measures such as ball speed, percentage errors and accuracy (5). An increased ball speed reduces the time for an opponent to return the ball successfully (6, 7). The amount of errors seems particularly important for reaching professional level, as the error rate is lower among professional players compared to elite youth players (8). To be in control in a match, players should also hit their strokes with sufficient accuracy as hitting the ball to a specific location on the court allows them to keep the ball far enough from their opponents to produce a winner or cause the opponent to make an error (9). Spin rate, however, may be equally important, because the amount of spin imparted to the ball affects its ball trajectory. This is useful to overcome constraints of the game (i.e., net and court boundaries) or for a tactical advantage (10).

The relevance of technical skills for youth tennis performance was confirmed by a recent prospective study showing that ball speed and accuracy measured under 14 years (U14) were significant predictors of tennis performance at the same time and 4 years later (11). Technical skills were assessed with the Dutch Technical-Tactical Tennis Test (D4T), a reliable and valid on-court test (12). Games were simulated which were either fixed or variable. In the fixed situations, players needed to direct their strokes to predetermined target areas, whereas in the variable situations the players were required to consider the direction of their strokes (e.g., respond to an imaginary opponent). Variable situations were considered more complex compared to fixed situations, due to the presumed higher cognitive load. More in depth-analyses of this prospective study revealed that the ability to maintain accuracy in variable situations, not in fixed situations, was considered essential to reach the elite level under 18 years (U18). In other words, players who reached the elite level U18 were more accurate in variable situations in their younger years (i.e., U14) compared to lower performing players U18. However, how these technical skills develop during adolescence, especially from the age of 12–16 years, and what important technical changes take place during this period remains open to debate. Adolescence is regarded as a key developmental phase in the course of talented players' careers. Development occurs in combination with physical change, including puberty, the pubertal growth spurt, and accompanying maturational changes (13). By exploring the technical skills of talented players in different age categories, we may acquire a better understanding of underlying technical skills that contribute to progress towards elite tennis performance. Knowledge about the important technical changes during adolescence may be of value for the adaptation of talent development programs.

From a constraints-led perspective, technical performance emerges from the interaction between the person (e.g., anthropometry, physical skills), the environment (e.g., court surface, type of competition) and the task at hand (e.g., complexity, intensity) (14, 15). Through systematically manipulating constraints it is possible to construct and mimic a tennis-specific situation. With the D4T, task constraints are manipulated by changes in the complexity of the task. From the literature it is apparent that if the complexity of the task increases, there is a decrease in technical performance in a range of sports including ice hockey, rugby and soccer (16–18). By means of simulating fixed and variable situations, the D4T allows tennis players to experience technical demands in situations of different complexity. Another way to adjust the complexity in the D4T is by changes in time constraints. The impact of time constraints on tennis performance is reflected by simulating offensive, neutral and defensive situations in the D4T. Players need to make quick and accurate decisions in order to perform accurately under high time pressure (19). In a defensive situation, there is less time for anticipating the direction of an opponents' stroke and keeping the accuracy of strokes high compared to an offensive situation where players are in control of the rally (20). The speed-accuracy tradeoff is highlighted in a group of youth tennis players with less accuracy in defensive compared to offensive situations (12). Given that technical skills are always executed in a particular context, we must consider the tennis-specific context when examining the technical skills in a group of talented youth players.

Technical skills in complex situations appear crucial for progress towards elite tennis performance, however, it is unknown how these skills develop in different age categories in a group of talented youth players. Therefore, our aim of this study is to evaluate possible differences in technical skills of Dutch talented youth tennis players under 15 (U15) compared to under 17 years (U17). We hypothesized that (a) players U17 have superior technical skills compared to players U15 and (b) differences between players U17 and U15 are most pronounced in complex situations (i.e., variable and defensive situations).

Method

Ethical approval

Ethical approval for this research protocol (PSY-1819-S-0262) was obtained from the Psychology Department of the University of Groningen (Groningen, Netherlands, September 19th, 2019). We obtained advanced written informed consent or assent from all players and advanced written informed consent from parents or legal guardians of all players under 16 years of age (the legal age for giving consent in the Netherlands).

Participants

Nineteen youth players between 12 and 17 years old (12 males, 7 females; age 14.6 ± 1.4 years) participated in this study. All participants were within the national high-performance program of the Royal Dutch Lawn Tennis Association (KNLTB). According to their year of birth, males were ranked between position 2 and 14 on the national ranking list of the KNLTB, while females were ranked between position 1 and 5. Table 1 shows the age, anthropometric characteristics, tennis history, tennis practice and additional physical practice for players U15 and U17 and males and females separately.

Measures

Anthropometry

Anthropometric data were obtained, which included body height, sitting height and body mass. Players' body height and sitting height were measured with a SECA height tape instrument to the nearest 0.1 cm (SECA, model 206, Seca Instruments, Ltd., Hamburg, Germany). Players were standing with bare feet against the wall (or were sitting on a bench for sitting height) and were asked to take a deep breath and to hold it. Body mass was measured to the nearest 0.1 kg (UWE, model ATM B150, Universal Weight Enterprise Co., Ltd., Taiwan). Leg length was calculated by subtracting sitting height from body height. Maturity status was estimated by the non-invasive method of calculating the age at peak height velocity using sex-specific predictive equations (21).

Technical skills

Ball speed, accuracy, percentage errors and spin rate were measured with the Dutch Technical-Tactical Tennis Test (D4T), a reliable and valid instrument to measure technical skills in youth players (12). The D4T requires players to hit 72 balls, grouped in four games of six rallies, in which each rally includes three strokes fed by a ball machine. Each game consists of two offensive, two neutral and two defensive rallies, representing different tactical situations as displayed in Figure 1. The difficulty of the ball projections was slightly increased compared to the original D4T, making it more suitable for a group of talented youth players. Offensive rallies consist of three ball projections just beyond the service line. Neutral rallies comprise of three ball projections to the area around the middle of the court a half to one meter before the baseline, and defensive rallies includes three ball projections to the sideline and beyond the service line. The different tactical situations occurred in random order in each game.

The various games have increasing complexity. In the first and second game, players have to return their strokes to the left target area (deuce side) and right target area (advantage side), respectively (Figure 1). In the third game, players have to alternate their strokes between the left and right target area. For example, if players direct their strokes to the left-right-left target area in the first rally, they should aim their strokes to the right-left-right target area in the second rally. In the fourth game, players have to return their strokes to the left or right target area, as indicated by a simulated opponent (research assistant) who moves either 1.5 meters to the left or right side of the court. Hence, players have to return their strokes to the opposite side of the side where the opponent is moving to. This is a modification from the original D4T where the target area in the fourth game was determined by lights which turned red either on the left or right side of the court. The simulated opponent was used instead of lights to increase the ecological validity of the D4T. The conditions in the first and second game were more fixed compared to the variable and complex conditions in the third and fourth game. During the test, players were allowed to rest for 15 s in between the rallies and 90 s after three games, which was similar to match play. More detailed information on the D4T has been reported previously (12).

Technical skills were recorded with PlaySight SmartCourt, a system for video-review and analytics and equipped with 10 on-court cameras. This system allows for the valid registration of ball speed, ball placement, spin rate and the registration of session video material (Playsight, 2015). For accuracy, a total of nine, six and three points were awarded to balls landing inside the small, middle and large target area, respectively (Figure 1). One point was awarded to balls landing outside the target areas, but still in the court on the correct side (determined by the given game situation). Balls landing in the wrong side of the court, outside the singles lines or in the net, were awarded with zero points. Percentage errors was calculated as the number of faults divided by the total number of strokes multiplied by hundred.

TABLE 1 Descriptive statistics (mean ± SD) of talented youth tennis players ($n = 19$).

	U15			U17		
	Male ($n = 7$)	Female ($n = 4$)	Total ($n = 11$)	Total ($n = 8$)	Male ($n = 5$)	Female ($n = 3$)
Age (years)	13.7 ± 0.7	13.2 ± 0.5	13.5 ± 0.6	16.0 ± 0.5	16.1 ± 0.6	15.7 ± 0.2
Height (cm)	168.2 ± 12.9	166.5 ± 5.8	167.6 ± 10.5	176.3 ± 5.8	177.7 ± 3.5	174.1 ± 9.1
Weight (kg)	52.1 ± 11.8	51.1 ± 5.1	51.7 ± 9.6	67.4 ± 6.2	69.2 ± 5.4	64.3 ± 7.4
Maturity offset (years)	−0.2 ± 1.4	1.4 ± 0.6	0.4 ± 1.4	2.3 ± 0.7	2.0 ± 0.4	2.7 ± 1.0
Age starting tennis (years)	6.4 ± 1.8	5.5 ± 0.6	6.0 ± 1.5	4.3 ± 1.5	4.3 ± 1.7	5.7 ± 1.2
Tennis experience (years)	7.4 ± 1.5	7.7 ± 1.0	7.5 ± 1.3	11.8 ± 1.6	12.1 ± 1.9	11.3 ± 1.4
Tennis practice (hours/week)	11.8 ± 2.5	10.9 ± 1.5	11.5 ± 2.2	14.5 ± 2.4	14.5 ± 2.4	14.5 ± 3.0
Physical practice (hours/week)	3.8 ± 1.1	4.5 ± 0.5	4.0 ± 1.0	5.3 ± 1.0	5.1 ± 0.9	5.7 ± 1.2

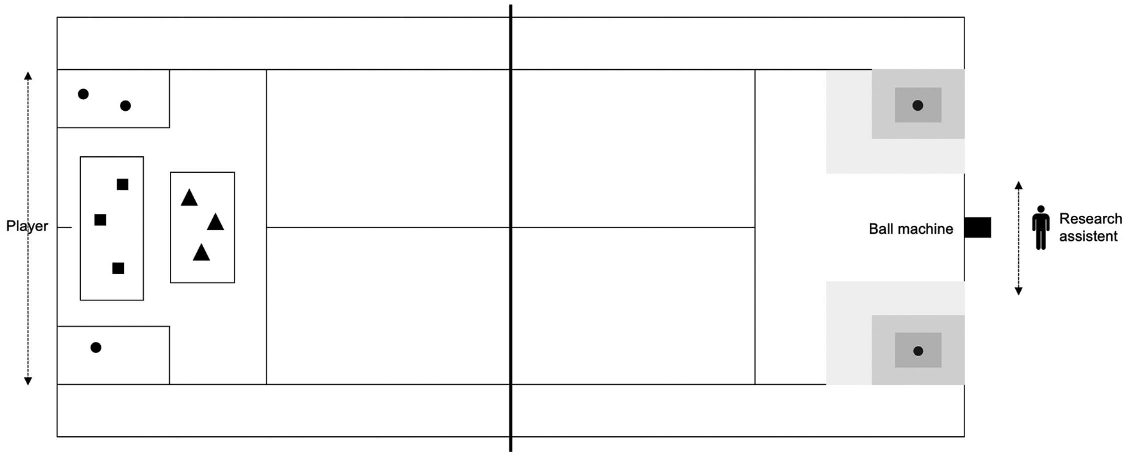

FIGURE 1
Illustration of the D4T with various tactical situations. This figure shows the test situation of the D4T with various tactical situations. The symbols represent the three ball projections in an offensive (▲), neutral (■) and defensive (●) tactical situation.

TABLE 2 Descriptive statistics of technical skills (mean ± SD) and differences between talented tennis players U15 and U17.

	U15			U17		
	Male ($n = 7$)	Female ($n = 4$)	Total ($n = 11$)	Total ($n = 8$)	Male ($n = 5$)	Female ($n = 3$)
Ball speed (kmh)	95.7 ± 7.2*	93.8 ± 5.7	95.0 ± 6.5	101.3 ± 10.0	107.4 ± 3.6*	91.1 ± 8.8
Accuracy (pts)	2.5 ± 0.5	2.5 ± 0.5	2.5 ± 0.5*	2.9 ± 0.3*	2.9 ± 0.3	2.9 ± 0.3
Errors (%)	27.8 ± 10.0	26.4 ± 6.5	27.3 ± 8.5	26.8 ± 5.5	26.5 ± 4.1	27.3 ± 8.4
Spin rate (rpm)	840.7 ± 243.9	659.6 ± 105.9	774.8 ± 217.7	884.6 ± 287.7	1015.9 ± 273.9	665.9 ± 157.3

*$p < 0.05$ significantly different between players U15 and U17.

Procedures

All measurements took place at the National Training Center of the KNLTB in Amstelveen in the Netherlands. Measurements took place on a hard-court indoor tennis court with PlaySight SmartCourt system for video-review and analytics using 10 on-court cameras. Before the D4T, players performed a warm-up of 10 min, including 5 min of hitting groundstrokes. Players were alternately tested with the remaining players conducting a training session at low to medium intensity. Measurements took place in the morning or afternoon (10.00 a.m. to 18.00 p.m.), depending on players' time of training. Participants were fed with moderately used tennis balls (Dunlop Fort Max TP) by a manually programmed ball machine (Promatch SmartShot Xtra, Mubo, Gorinchem). Participants used their own tennis racket during the test protocol. Before the measurements, a research assistant was trained to move 1.5 meters to either the left or right side of the court just after the ball was fed by the ball machine. The research assistant moved according to a predetermined program, with half of the movement being to the left and right, respectively.

Data analysis

For the statistical analyses, we used SPSS Statistics for Mac, version 28 (IBM Corp., Armonk, N.Y.). For all significance tests, we used an α-level of 0.05. We screened the data to ensure variables met the assumptions necessary for the use of parametric statistics before data analysis. We performed a one-way ANCOVA with age category as grouping factor (U15 versus U17) for each technical skill separately (i.e., ball speed, accuracy, percentage errors and spin rate), whilst controlling for sex which we considered a covariate. When heterogeneity of regression slopes was found, we performed a two-way ANOVA to analyze the effect of age category and sex on the relevant technical skill. We considered an effect size of $\eta^2 = 0.01$ as small, $\eta^2 = 0.06$ as medium and $\eta^2 = 0.14$ as large (22). In the case of a significant covariate and for the technical skills that were statistically different between players U15 and U17, we performed additional analyses. We conducted one-way ANOVAs to further unravel differences between age categories for the relevant technical skills in complex situations. First, we assessed differences between players U15 and U17 for the relevant technical skill in fixed and variable game situations. Second, we measured differences between players U15 and U17 for the relevant technical skill in different tactical situations.

Results

Table 2 illustrates the mean scores of technical skills for players U15 and U17 and males and females separately. A one-way

ANCOVA revealed a significant interaction between age category and the covariate sex for ball speed, indicating that the assumption of homogeneity of regression slopes was violated. Therefore, a two-way ANOVA was performed to analyze the effect of age category and sex on ball speed. There was a statistically significant interaction between the effects of age category and sex [$F(1,15) = 5.472$, $p = 0.034$, $\eta^2 = 0.267$]. Simple main effects analyses showed no statistically significant effect of age category on ball speed [$F(1,15) = 2.128$, $p = 0.165$, $\eta^2 = 0.124$], while there was a statistically significant effect of sex on ball speed [$F(1,15) = 8.568$, $p = 0.010$, $\eta^2 = 0.364$]. Males U17 produced higher ball speed compared to males U15 [$F(1,10) = 11.017$, $p = 0.008$, $\eta^2 = 0.524$], while no differences were found between females U15 and U17 [$F(1,5) = 0.250$, $p = 0.638$, $\eta^2 = 0.048$].

A one-way ANCOVA revealed a significant main effect of age category on accuracy after controlling for sex [$F(1,16) = 5.021$, $p = 0.040$, $\eta^2 = 0.239$]. No differences were found between players U15 and U17 for spin rate [$F(1,16) = 1.221$, $p = 0.286$, $\eta^2 = 0.071$] and percentage errors [$F(1,16) = 1.2711$, $p = 0.885$, $\eta^2 = 0.001$], although sex was found a significant covariate for spin rate [$F(1,16) = 5.861$, $p = 0.028$, $\eta^2 = 0.268$]. No differences were found between females U15 and U17 [$F(1,5) = 0.004$, $p = 0.952$, $\eta^2 = 0.001$] and males U15 and U17 [$F(1,10) = 1.363$, $p = 0.270$, $\eta^2 = 0.120$] for spin rate, although the medium to large effect size for males indicates that males U17 produced higher spin rates than males U15.

Accuracy in tennis-specific situations

Based on the significant difference between age categories for accuracy, we performed additional analyses for accuracy in complex situations. **Figures 2**, **3** show the accuracy for players U15 and U17 in fixed and variable game situations and different tactical situations, respectively. A significant difference was found between players U15 and U17 on accuracy in game 4 [$F(1,17) = 6.358$, $p = 0.022$, $\eta^2 = 0.272$] and accuracy in defensive situations [$F(1,17) = 9.602$, $p = 0.007$, $\eta^2 = 0.361$].

Discussion

To evaluate possible differences in technical skills among talented tennis players in different age categories, players of the Dutch national high-performance program U15 and U17 were compared on different technical skills. Males U17 produced higher ball speed compared to males U15, while no differences were found between females U15 and U17. A difference was found between age categories for accuracy for both male and female players, with players U17 being more accurate than players U15. A closer examination of accuracy demonstrates that players U17 scored higher in complex situations than players U15, given the higher accuracy in the variable game 4 and in defensive situations. These findings were in line with our hypotheses and suggest that technical skills, especially ball speed for males and accuracy in complex situations for both males and females, continue to develop in adolescence in a group of youth talented tennis players.

According to the constraints-led approach, changing task constraints requires an adaptation of the current motor behavior. By differences in task complexity, players were forced to deal with various situations in order to maintain or improve the accuracy of their strokes. In line with earlier research, our findings reveal that under increased task complexity (i.e., high temporal and cognitive pressure), the older and more experienced players were better able to maintain their accuracy than their younger and less experienced counterparts (23). Tennis players are confronted with situations in which motor

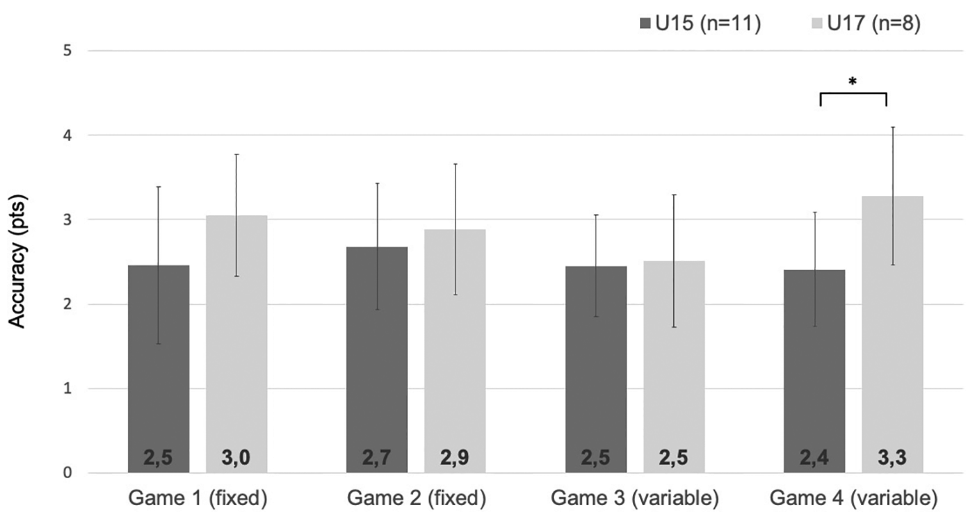

FIGURE 2
Accuracy in fixed and variable games for players U15 and U17. This figure shows the mean accuracy in various game situations (errors bars represent standard deviations of the mean); *$p < 0.05$ significant difference between players U15 and U17 for accuracy.

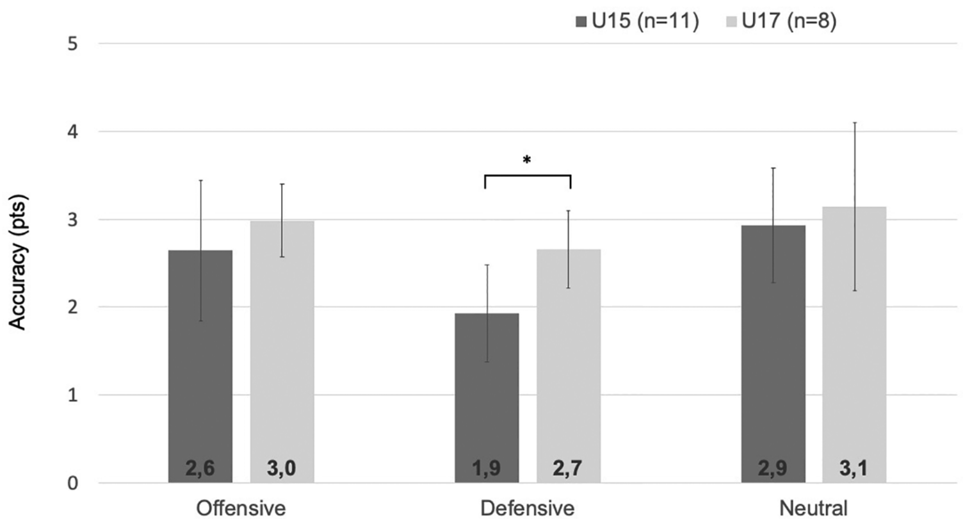

FIGURE 3
Accuracy in tactical situations for players U15 and U17. This figure shows the mean accuracy in tactical situations (errors bars represent standard deviations of the mean); *$p < 0.05$ significant difference between players U15 and U17 for accuracy.

and cognitive tasks have to be executed simultaneously (24, 25). For example, players need to anticipate the next ball, recall strategies and play the ball with adequate speed and accuracy while being aware of their opponents' strengths and weaknesses. Usually, performance decreases under increased task complexity. Unlike the fixed situations of the D4T, the variable situations required players to consider the direction of their next ball, possibly increasing the demands on attention and working memory (26, 27). This is also apparent from the results of a previous study with the D4T in which future elite players (mean age 13.7 ± 0.5 years) were able to maintain their accuracy throughout the game situations, while competitive players (mean age 13.3 ± 0.5 years) became less accurate during the variable, more complex situations (11). Both players U15 and U17 were able to maintain their accuracy throughout the game situations, possibly due to their higher performance level compared to the competitive players in the previous study. Where players U17 were more accurate in game 4 than players U15, no differences between these age categories were found in game 3. An explanation for these findings might be related to the less pronounced task complexity in game 3 compared to game 4 where players needed to look at the other side of the net to see which side the simulated opponent moved in order to play the ball to the opposite side. The accuracy of players U17 even seemed to benefit from the increased task complexity in game 4 as indicated by the slightly higher accuracy compared to the others game situations. Due to more years of tennis experience, players U17 might have developed a higher degree of automatization, resulting in a greater resistance to skill decrement under more complex situations than players U15 (23, 28). While it is uncommon for players, especially novices, to perform more accurately in variable than in fixed situations, previous research has shown increased performance in complex situations in experienced hockey players (29). One possibility is that the diversion of attention to another task (e.g., focusing on the simulated opponent) attenuates disruptive conscious processing of movements that can occur in fixed situations.

In contrast to players U17, players U15 were unable to maintain their accuracy under high temporal demands, imposed by ball projections to the sidelines of the court in the defensive situations. The decrease in accuracy in players U15 suggests that the task complexity in the defensive situation might have been too high, causing them to play less accurately due to the greater information processing load (30). In neutral and offensive situations, the task complexity is relatively low, remaining substantial attentional capacity for additional tasks (e.g., focusing on the next ball projection). However, as the temporal pressure increases, greater attention is required to be devoted to maintain stroke accuracy, resulting in reduced processing capacity for anticipating the next ball in the defensive situation. Another explanation for players U17 to be more accurate in defensive situations than players U15 might be related to differences in anthropometry and physical skills such as sprint speed (31, 32) and agility (33). During adolescence, there is an increase in height and players develop more strength and power (13). In the present study, players U17 were taller, heavier and more mature than players U15. Individual differences in growth and maturation, and associated increases in running speed and agility, could translate into an advantage for older youth players in defensive situations.

There was an interaction effect between age category and sex for ball speed, indicating that males U17 produced higher ball speed compared to males U15, while no differences were found between females U15 and U17. These findings were not surprising, given that the maturational time course of males and females is quite different (13). On average, females mature earlier than males. Several studies have shown a relationship between ball speed in groundstrokes and anthropometric factors such as height, weight and maturity status (6, 7, 11). In the present study, females U15 have already experienced their growth spurt as opposed to males U15. During the pubertal transition from early through mid-adolescence, males become taller, heavier and stronger, increasing the differences between males U17 and males U15 on outcomes related to anthropometry and physical skills, such as ball speed. This may also apply to spin rate, given the significant main effect of sex and the medium effect size of age category. Males generated more spin than females, and the medium to large effect size for males indicates that males U17 produced higher spin rates compared to males U15. The effect of anthropometry and physical skills on spin rate merits further investigation, but earlier research studying the mechanics of spin rate also mention the impact angle and racket speed as factors affecting spin rate (34).

There are a few strengths and weaknesses to consider. The design of the D4T provides interesting insights for tennis performance, however it is not completely representative of tennis performance demands. Players were forced to direct their strokes to a specific side of the court, depending on the fixed or variable game situation. The location of the ball projections has impacted the direction of players' stroke, which was either more cross-court or down the line. Changing the ball angle of a ball projected to the side line, by attempting to play it down the line, possibly increases the amount of lateral errors (35). In actual tennis competition, players are free to decide the direction of their strokes, which may result in a different amount of errors than during the D4T. Another weakness related to the lack of representativeness is the use of a ball machine, where players cannot use relevant kinematic information from the opponent (e.g., distal cues from arm and racket) to anticipate the direction of strokes (36, 37). Returning strokes from a ball machine could result in different swing timing and movement coordination, limiting the generalization of the results (38). However, the use of a ball machine allows for the reliable and valid comparison of technical skills between age categories due to the standardized test design. Another strength of this study was the use of a homogeneous group of talented players, with all participants playing at the highest level in their age category in the Netherlands. Understanding the underlying technical skills of this sample can help optimize talent development programs. Future studies should examine how technical skills measured with the D4T, particularly accuracy in complex situations, relate to on-court tennis performance under high temporal and cognitive pressure. The association of on-court test performance with match activities is considered a feasible approach for evaluating ecological validity (39).

The present cross-sectional study provides insight into the technical differences between players U15 and U17, increasing the understanding of underlying technical skills that contribute to progress towards elite tennis performance. However, the actual process of technical development is unknown and it is unclear whether players U15 improve their skills, and specifically accuracy in complex situations, to the current level of players U17 in 2 years. Differences between these age categories may still exist due to the earlier age of starting tennis, more years of tennis experience and higher amount of training hours for players U17. In future studies, a longitudinal study design is advised to determine the actual process of technical development over time in a group of talented tennis players.

In conclusion, the results of the current study suggest that technical skills, especially ball speed for males and accuracy in complex situations for both males and females, continue to develop in adolescence from U15 to U17 in a group of youth talented tennis players. This study increases the understanding of underlying technical skills that contribute to progress towards elite tennis performance. To effectively develop technical skills, coaches are encouraged to design specific practices where these skills are performed in situations under high cognitive and temporal pressure.

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 human participants were reviewed and approved by the Psychology Department of the University of Groningen. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

Author contributions

NK, BH, CV and ME-G contributed to the study conception and design. NK collected the data, wrote the first draft of the manuscript and analyzed the data. NK, BH, CV and ME-G reviewed and edited previous versions of the manuscript, read, and approved the final version of the manuscript. All authors contributed to the article and approved the submitted version.

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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Effects of an 8-week multimodal program on thoracic posture, glenohumeral range of motion and serve performance in competitive young tennis players

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Introduction: Intensive tennis practice is known to generate sport-specific adaptations at the shoulder region and influence the sagittal spinal curvature. However, increased thoracic kyphosis decreases the shoulder functional capacity, which could limit tennis performance. Therefore, the aim of this study was to investigate the effects of an 8-week multimodal program on thoracic posture, glenohumeral range of motion, and serve performance in competitive young tennis players.

Methods: Eighteen male and four female players (age: 16.0 ± 2.4 years, height: 170.7 ± 11.0 cm; mass: 62.1 ± 11.5 kg; International Tennis Number: 3–4) performed their regular training during 8 weeks, which was used as a reference period, and implemented a multimodal program including stretching, strengthening, and myofascial release exercises, four times per week during 8 additional weeks, which corresponded to the intervention period. The thoracic curvature angle and mobility, the biacromial and interscapular distances, the glenohumeral range of motion and the tennis serve performance were assessed three times, i.e., before and after the regular training and after the 8-week multimodal program.

Results: The results showed that the 8-week regular training had no significant effects on thoracic curvature angle [effect size (ES) = 0.02–0.36, p = 0.06–0.46] and mobility (ES = 0.05–0.26, p = 0.13–0.42), biacromial (ES = 0.05, p = 0.18) and interscapular distances (ES = 0.03, p = 0.45), ranges of motion in glenohumeral internal (ES = 0.04, p = 0.43) and external rotation (ES = 0.43, p = 0.06), and tennis serve accuracy (ES = 0.33, p = 0.07) and velocity (ES = 0.09, p = 0.35). The 8-week multimodal program increased moderately the thoracic mobility (ES = 0.55, p = 0.01), moderately to strongly the serve accuracy and velocity (ES = 0.65, p = 0.003, for both), strongly decreased the interscapular distance (ES = 1.02, $p < 0.001$), and strongly increased the range of motion in glenohumeral internal (ES = 0.90, $p < 0.001$) and external rotation (ES = 1.49, $p < 0.001$).

Discussion: These findings indicated that an 8-week multimodal program, including spine and glenohumeral mobility and shoulder girdle strength exercises, performed four times per week during 8 weeks, is moderately relevant to rectify the sagittal thoracic curvature in competitive tennis players, while such a program may help regain the range of motion in glenohumeral rotation without tennis serve performance impairment.

KEYWORDS
overhead sport, self-myofascial release, stretching, strengthening, breathing

1. Introduction

The achievement of tennis stroke is based on the kinetic chain concept (1), involving a sequential force development from the legs and trunk funneled through the shoulder complex and transferred to the upper extremity up to the racket to impact the ball with maximal velocity (2). The repetitive forceful unilateral movements lead to tennis-specific adaptations, especially at the shoulder region, such as decreased glenohumeral range of motion (3), imbalance in glenohumeral rotator muscle strength (4), or alterations in scapular positioning and motion (5). These adaptations can create disruption in the kinetic chain, possibly resulting in altered performance (1) or constituting risk factors for overuse injury, especially at the shoulder region (6). Because it must provide an efficient linkage to transfer forces from proximal to distal segments, the shoulder complex must benefit from a particular emphasis in the prevention program for tennis players.

The tennis serve is a key stroke to take advantage over an opponent during match (7). Due to the overhead arm motion, the dominant arm adopts extreme positions (8), known to increase the contact pressure and area of impingement of the rotator cuff tendon between the humeral head and glenoid cavity (9, 10). In particular, at the end of the cocking phase, the humerus is in maximal external rotation, abduction, and extension (11), and, at impact, the humerus elevates at about 100° (12) in the frontal plane (11). The achievement of these extreme positions demands coordinated motions of the humerus and the scapula (11), on the one hand, and contribution of the spine (13), on the other hand. Indeed, the trunk extension contributes to the scapular posterior tilt, which contributes itself to the humeral external rotation (14), and to the arm elevation (15). In addition, repetitive powerful overhead movements lead to imbalance in length and strength between anterior and posterior shoulder muscles, fostering forward head and shoulder posture (16, 17). Repetitive trunk forward-bending and extension also influence spinal profile of tennis players (18), in particular, increased thoracic kyphosis (19). A combination of forward head posture, forward shoulder posture, and increased thoracic kyphosis is described as slouched posture, which impairs the shoulder functions. Such a slouched posture angle is associated with decreased range of motion in glenohumeral external rotation (20, 21) and arm abduction (20, 22), decreased glenohumeral external rotator muscle strength, and decreased scapular posterior tilt (20, 23). Like positive correlations have been reported between tennis serve velocity and glenohumeral range of motion and strength (24), preventing the consequences of deficiencies in trunk extension and acquired slouched posture on shoulder functions involved to achieve tennis stroke may be a goal of prevention program for tennis players.

To preserve tennis players' shoulder functions, previous studies (25–28) have mainly focused on the glenohumeral joint to independently prevent the decrease in internal rotation range of motion (IROM) and the imbalance in strength of external and internal rotator muscles. The glenohumeral internal rotation range of motion may be preserved or increased when performing either stretching exercises (25) or self-myofascial release (28). Rebalancing the strength of glenohumeral external rotators in regard with strength of internal rotators may be achieved by isokinetic training of eccentric external rotator muscle strength (26) or by sling-based exercise for external rotator muscles (27). To the best of our knowledge, no study investigates the effects of trunk exercise on the spinal curvature in tennis players. However, in swimmers, respiratory muscle exercise by stimulating the local trunk stabilizers straightens the thoracic spine (29). A recent meta-analysis highlights that intervention programs including both strengthening and stretching exercises have large statistically significant effects for reducing the curve of thoracic angle (30). Consequently, a prevention program including strengthening and stretching of the upper trunk and glenohumeral joint may be interesting to maintain thoracic alignment and mobility and to preserve shoulder functions in tennis players.

Therefore, the aim of this study was to investigate the effects of an 8-week multimodal program on thoracic posture, glenohumeral range of motion, and serve performance in competitive young tennis players. It was hypothesized that this program would straighten the thoracic spine, increase glenohumeral rotational range of motion, and improve tennis serve performance.

2. Methods

2.1. Participants

A sample size calculation was performed using a large effect size, based on the results of the meta-analysis reported by Gonzalez-Galvez et al. (30). The *a priori* statistical power analysis indicated a sample size of a minimum of 18 participants assessed three times, with $\alpha = 0.05$, statistical power = 0.95, and effect size f = 0.40. Given the duration of the study (16 weeks), we expected a risk of 20% of players lost to follow-up.

Eighteen male and four female tennis players [age: 16.0 ± 2.4 years, height: 170.7 ± 11.0 cm; mass: 62.1 ± 11.5 kg; predicted age at peak height velocity (31): 1.4 ± 1.9 years; weekly tennis training: 7.6 ± 2.4 h; weekly strength and conditioning training: 4.2 ± 0.4 h; tennis experience: 9.8 ± 2.2 years; International Tennis Number: 3–4, advanced players] volunteered to participate in this study, which was approved by the local ethics committee. All participants were recruited from a tennis academy. Inclusion criteria were being aged between 13 and 25 years, playing competitive tennis, and training at least four times a week. Exclusion criteria were having pain during tennis playing or injury (defined as problems resulting in tennis playing time loss higher than 2 weeks), history of surgery at the dominant upper limb or trunk within the previous 6 months, or having significant postural alterations, such as scoliosis or hyperkyphosis.

2.2. Study design

A test–retest procedure was applied over a 16-week duration, during which the training workload remained similar. The players were assessed at baseline (T_0), after 8 weeks (T_1), and after 16 weeks (T_2). During the control period between T_0 and T_1, i.e., from November to January, the players performed their regular training. During the intervention period between T_1 and T_2, i.e., from January to March, the players implemented the multimodal program four times per week at the beginning of their strength and conditioning sessions.

2.3. Testing procedures

The demographic and tennis characteristics were collected at baseline (T_0). The thoracic curvature, biacromial and interscapular distances, glenohumeral ranges of motion, and serve performance were assessed by the same examiners at T_0, T_1, and T_2.

2.3.1. Thoracic spine curvature

Sagittal spinal curvatures were assessed in three trunk positions successively: neutral standing (**Figure 1A**), maximal trunk flexion with stretched legs (**Figure 1B**), and maximal trunk extension (**Figure 1C**), using the Spinal Mouse system (IDIAG-M360pro, Fehraltorf, Suisse), which provides reliable measurements of thoracic curvatures and range of motion in the sagittal profile (32). The examiner marked the spinous processes of the seventh cervical (C7) and third sacral (S3) vertebrae, then put the Spinal Mouse on C7, and guided it along the midline of the spine to S3. The thoracic spine angle (**Figure 1D**) was measured in each trunk position, and thoracic spine mobility was evaluated by differences in thoracic angles between paired trunk positions, i.e., between neutral standing and flexion positions, between neutral standing and extension positions, and between extension and flexion positions. No reliability assessments were made for these outcome measures.

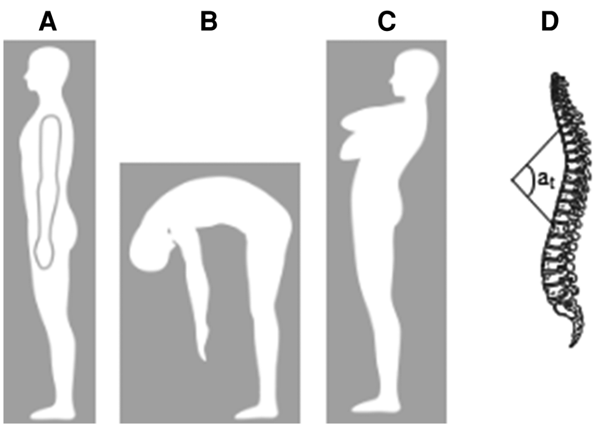

FIGURE 1
Sagittal spinal curvatures assessment in three trunk positions. (A) neutral standing, (B) maximal trunk flexion, (C) maximal trunk extension, and (D) thoracic angle a_t.

2.3.2. Biacromial distance

The biacromial distance was measured using a spreading caliper. While the player is in a neutral standing position, the examiner puts the ends of the caliper on the acromion anterior part of each shoulder to measure the biacromial distance [the intrasession reliability for the examiner performing the measurements was as follows: intraclass coefficient correlation (ICC) = 0.97; standard error of measurement (SEM) = 0.37 cm; minimal detectable change at 95% confidence level ($MDC_{95\%}$) = 1.03 cm]. The distance was measured twice and averaged for subsequent analysis. Short biacromial distance reflects the forward shoulder posture.

2.3.3. Interscapular distance

The interscapular distance was measured using a spreading caliper. While the player was in a neutral standing position, the examiner puts the ends of the caliper on the inferior part of medial border of each scapula to measure the interscapular distance (intrasession reliability: ICC = 0.97; SEM = 0.35 cm; $MDC_{95\%}$ = 0.98 cm). The distance was measured twice and averaged for subsequent analysis.

2.3.4. Glenohumeral range of motion

The range of motion at the dominant glenohumeral joint was assessed in internal (IROM) and external rotation (EROM) using using a bubble goniometer in accordance with the previously described procedure (33). The player was in a supine position with the humerus abducted at 90° and elbow flexed at 90°. An examiner maintained the coracoid process and scapular spinae, and then internally or externally rotated the upper arm to the maximum until just before the first motion of the scapula. Another examiner located the goniometer center on the olecranon process with the bubble-branch vertically and the other aligned onto the forearm to measure IROM (intrasession reliability: ICC = 0.98; SEM = 1.1°; $MDC_{95\%}$ = 3.5°) and EROM (intrasession reliability: ICC = 0.99; SEM = 0.9°; $MDC_{95\%}$ = 2.4°). The measurements were performed twice for each rotation, and averaged for subsequent analysis. Mean IROM and mean EROM were summed to compute the total arc of motion (TAM).

2.3.5. Serve performance

The serve performance was assessed by the serve accuracy and ball velocity. After a general warm-up composed of arm internal/external rotation, arm and elbow flexion/extension using elastic band, and forehand and backhand strokes, the players performed a specific warm-up composed of eight serves at 50% of maximal effort, four serves at 75%, and four serves at 90%. Then, each player was instructed to perform 12 first serves, 6 serves per diagonal, as fast as possible, while looking for ace on the "T" of the serve box. The serve accuracy was evaluated using a point system (34). Briefly, two targets of 50 cm × 50 cm and 1 m × 1 m were placed from the middle line to the serve line of the service box. A rebound in the small target accounted for 5 points, in the big target for 3 points, in another location in the serve box for 1 point, and another location and in the net for 0 point (please see **Supplementary Figure 1**). The points obtained for the 12 serves were summed to compute the score for serve accuracy. The rate of successful serves (i.e., rebound in the opposite serve box) was also computed. The ball velocity was measured using a radar gun (Stalker Pro II, Stalker Radar, Plano, TX, United States), located 2.50 m behind the player at 1.7 m height. The maximal velocity obtained for a successful serve, i.e., ball rebound in the serve box, was kept for the subsequent analysis.

2.4. Intervention program

Players and coaches were blinded for the purpose of the study, instructed to bring no technical changes in the player's serve, while maintaining the duration of the tennis training at the same level throughout the 16-week procedure. The regular tennis training consisted of general and targeted warm-up, exercises to control ball direction and depth in basic strokes, tactical games, and training matches (35). During the control period, the players performed their usual prevention protocol at the beginning of the strength and conditioning session, such as one pectoralis stretching exercise (4 min) followed by three series of 10 YWTL movements executed without additional load (8 min) to strengthen posterior upper trunk muscles. Y, W, T, and L describe the position of the upper extremities relative to the thorax (please see figures in **Supplementary Table 1**). During the intervention period, the usual prevention protocol was replaced with the multimodal program for the same duration, including three self-myofascial release exercises (2.5 min) onto anterior upper trunk and posterior shoulder areas, three stretching exercises (2.5 min) of the anterior and posterior shoulder structures, three trunk mobility exercises combined with breathing instructions (3 min), and six strengthening exercises (4 min) targeting posterior upper trunk muscles. All the sessions of both the control and intervention periods for all the players were supervised by the same strength and conditioning coaches. All the exercises are fully described in **Supplementary Tables 1 and 2**.

2.5. Statistical analyses

All data are presented as mean ± SD. After checking the normality and homoscedasticity of the raw data with the Shapiro–Wilk and Levene tests, respectively, ANOVAs for three repeated measures (Time: T_0 vs. T_1 vs. T_2) were applied to evaluate the effect of time on thoracic spine angles and mobility, shoulder girdle distances, glenohumeral ranges of motion, and serve performance with reporting partial effect sizes (f; 0.10 for small effect, 0.25 for medium effect, and 0.40 for large effect) and *p*-value. When ANOVA revealed a significant effect of time, Bonferroni-corrected *post-hoc tests* were applied to compare the results between T_0 and T_1, i.e., the changes related to the control period, and between T_1 and T_2, i.e., the changes in relation with the intervention period with reporting effect size [effect size (ES): 0.2 for small effect, 0.5 for medium effect, and 0.8 for large effect] and *p*-value. For all the statistical tests, Rcmdr package of the software R 4.1.0 (R, Foundation for Statistical Computing, Vienna, Austria) was used, and the level of significance was set at $p \leq 0.05$.

3. Results

All competitive young tennis players included in this study performed all the program sessions in both the control and intervention periods. None of them sustained injury demanding to be excluded from the study.

For the thoracic spine angles (**Table 1**), ANOVA revealed no significant effect of time in the neutral standing position (f = 0.09, low effect; $p = 0.06$), while a significant effect of time was found in flexion (f = 0.20, low-to-medium effect; $p = 0.005$) and extension (f = 0.11, low effect; $p = 0.05$) positions. In the flexion position, no significant changes were found either after the control period or after the intervention period (the significant effect between T_0 and T_2 was out of interest for our purpose). In the extension position, the mean thoracic spine angles were similar between T_0 and T_1 (ES = 0.02, low effect; $p = 0.46$) and decreased significantly between T1 and T2 (ES = 0.40, medium effect; $p = 0.04$). The changes in thoracic curvature angles are presented in **Supplementary Figure 2**.

For the thoracic spine mobility (**Table 1**), no significant effect of time was found when assessed between neutral standing and extension positions (f = 0.06, low effect; $p = 0.13$), while a significant effect of time was found when mobility was measured between neutral standing and flexion positions (f = 0.17, low-to-medium effect; $p = 0.01$), and extension and flexion positions (f = 0.20, low-to-medium effect; $p = 0.005$). For these last two

TABLE 1 Mean (±SD) postural outcome measures at baseline (T_0), after the control period (T_1). and after the intervention period (T_2).

	Position	T_0	T_1	T_2	
Thoracic spine angle (°)	Neutral standing	37.5 ± 9.9	40.2 ± 9.3	37.4 ± 7.4	
	Flexion	48.6 ± 12.9	52.8 ± 10.9	56.3 ± 12.1	
	Extension	34.6 ± 15.3	34.4 ± 12.7	29.3 ± 12.4	*
Thoracic spine mobility (°)	Neutral standing–flexion	12.0 ± 10.8	12.6 ± 11.8	18.9 ± 13.3	**
	Neutral standing–extension	−2.5 ± 14.4	−5.8 ± 12.2	−8.1 ± 11.4	
	Extension–flexion	14.4 ± 20.8	18.4 ± 16.4	27.0 ± 15.1	**
Biacromial distance (cm)		32.9 ± 2.2	33.0 ± 2.3	33.3 ± 2.9	
Interscapular distance (cm)		15.4 ± 1.9	15.3 ± 1.5	14.3 ± 1.6	***

*Significant difference between T_1 and T_2, with for $p \leq 0.05$; **Significant difference between T_1 and T_2, with for $p \leq 0.01$; ***Significant difference between T_1 and T_2, with for $p \leq 0.001$.

mobilities, no changes were reported after the control period (ES = 0.05, low effect; $p = 0.41$, and ES = 0.21, low effect; $p = 0.16$, respectively), while significant increases were observed after the intervention period (ES = 0.53, medium effect; $p = 0.01$ and ES = 0.55, medium effect; $p = 0.009$, respectively).

For the shoulder girdle distances (**Table 1**), no effect of time was observed on the biacromial distance (f = 0.04, low effect; $p = 0.18$). ANOVA revealed a significant effect of time on the interscapular distance (f = 0.42, large effect; $p < 0.001$), which were similar at T_0 and T_1 (ES = 0.03, low effect; $p = 0.45$), and significantly lower at T_2 compared to T1 (ES = 1.02, large effect; $p < 0.001$).

For the glenohumeral ranges of motion (**Table 2**), ANOVA revealed a significant effect of time for IROM (f = 0.36, medium-to-large effect; $p < 0.001$), EROM (f = 0.55, large effect; $p < 0.001$), and TAM (f = 0.59, large effect; $p < 0.001$). IROM, EROM, and TAM were similar at T_0 and T_1 (ES = 0.04, low effect; $p = 0.43$; ES = 0.33, low effect; $p = 0.06$; and ES = 0.34, low effect; $p = 0.06$, respectively), and increased significantly between T_1 and T_2 (ES = 0.90, large effect; $p < 0.001$; ES = 1.49; large effect; $p < 0.001$; and ES = 1.52, large effect; $p < 0.001$, respectively).

Regarding the serve performance (**Table 3**), ANOVA revealed a significant effect of time on accuracy (f = 0.35, medium-to-large effect; $p < 0.001$), rate of successful serves (f = 0.23, medium-to-large effect; $p = 0.002$), and velocity (f = 0.14, low-to-medium effect; $p = 0.02$). The mean accuracy, rate of successful serves, and velocity remained similar between T_0 and T_1 (ES = 0.33; low effect; $p = 0.07$; ES = 0.03; low effect; $p = 0.44$; and ES = 0.07; low effect; $p = 0.34$, respectively), and all increased significantly between T_1 and T_2 (ES = 0.65; medium-to-large effect; $p = 0.003$; ES = 0.68; medium-to-large effect; $p = 0.003$; and ES = 0.54; medium effect; $p = 0.003$, respectively).

4. Discussion

This study aimed to investigate the effects of an 8-week multimodal program on thoracic posture, glenohumeral range of motion, and serve performance in competitive young tennis players. The main findings were that the 8-week multimodal program erected the thoracic posture in trunk extension position, improved thoracic mobility, increased scapular medially rotated position, increased internal and external rotation range of motion at the dominant glenohumeral joint, and improved tennis serve performance.

TABLE 2 Mean (±SD) ranges of motion (in °) in IROM and EROM rotation and TAM at dominant glenohumeral joint at baseline (T_0), after the control period (T_1), and after the intervention period (T_2).

	T_0	T_1	T_2	
IROM	39.0 ± 8.1	39.3 ± 8.3	46.7 ± 5.4	***
EROM	87.0 ± 13.1	91.0 ± 10.1	100.0 ± 7.6	***
TAM	126.0 ± 15.4	130.3 ± 13.8	146.7 ± 7.4	***

IROM, internal rotation range of motion; EROM, external rotation range of motion; TAM, total arc of motion.

***Significant difference between T_1 and T_2, with for $p \leq 0.001$.

TABLE 3 Mean (±SD) tennis serve performance at baseline (T_0), after the control period (T_1), and after the intervention period (T_2).

	T_0	T_1	T_2	
Accuracy (points)	10.8 ± 6.1	13.1 ± 7.3	18.1 ± 6.1	**
Successful serves (%)	41 ± 19	41 ± 16	55 ± 13	**
Velocity (km h^{-1})	163.3 ± 16.8	162.7 ± 16.9	166.2 ± 16.5	**

**Significant difference between T_1 and T_2, with for $p \leq 0.01$.

Long-term exposure to tennis practice leads to morphological (36), muscular (4), and bony adaptations (37) enlarged when practice begins at young age (38). Our players with an average experience about 10 years of tennis practice presented with upper trunk and shoulder adaptations commonly observed with cumulative overhead activity exposure in overhead sport athletes (39) and tennis players (18, 19). Mean thoracic curvature angles in the neutral standing position for our players were near the upper values for normal thoracic kyphosis, i.e., between 20° and 45° (40), and remained close to those reported in tennis players of similar ages (19). Regarding glenohumeral flexibility, the limitation in internal rotation range of motion at the dominant side is not fully compensated by the increase in external rotation range of motion, leading to decreased total arc of motion (3, 33). The tennis players involved in this study presented with similar ranges of motion in internal and external rotation than previously reported for tennis players of similar age and level (3) (Le Gal, 2018), and lower than those reported for controls (41). Currently, there is a consensus on the relationship between reduced glenohumeral range of motion, glenohumeral strength unbalance, and increased risk of shoulder injury (6); therefore, regaining the range of motion and strength balance at the dominant glenohumeral joint may be an integral part of any prevention strategy to recover shoulder functions in overhead athletes (42). Although our tennis players performed their regular tennis training and prevention program composed of one stretching exercise and the four YWTL exercises without load, no changes in either trunk posture (18) or glenohumeral flexibility (Le Gal, 2018) were observed after the 8-week control period. Consequently, implementing exercises targeting stretching, strengthening, and mobility of the upper trunk and shoulder region may help counteract the effects of long-term tennis practice on upper trunk curvature angle and shoulder range of motion to preserve tennis performance and preserve shoulder functions.

The achievement of tennis strokes, especially tennis serve, applies asymmetric loads, creating the progression of muscular asymmetry and spine alterations (18). Particularly, movements combining trunk flexion and hyperextension motions result in shortening the anterior muscles and lengthening the posterior muscles, leading to increased forward head and shoulder posture, and thoracic kyphosis (16). When implementing four times per week during 8 weeks, stretching exercises for anterior trunk and shoulder muscles, strengthening exercises with load for posterior muscles, and mobility exercises while performing deep breathing resulted in medium statistically significant changes in thoracic alignment in extended body position and thoracic mobility.

Although the design of our multimodal program respected the content, frequency, and duration recommended by the systematic review of Gonzalez-Galvez et al. (30), the changes in thoracic alignment obtained in our tennis players remained lesser than expected. Such discrepancies may be explained by differences in terms of participant characteristics, initial thoracic posture, or nature of the study. However, small changes in thoracic posture have immediate effect on shoulder range of motion (43). An erect thoracic posture is known to increase scapular posterior tilt (20), scapular upward rotation (14), and scapular medial rotation (14); such scapular positioning contributes to reaching a more extreme external rotated position of the arm when it is abducted, as at the end of the cocking phase of the tennis serve (13). Interestingly, our multimodal program also resulted in a more medially rotated position of the scapulae, which, concomitant with thoracic realignment in extension trunk posture, may possibly enlarge the subacromial space during arm elevation (43). Additionally, the stretching exercises and self-myofascial releases of the dominant shoulder region included in our multimodal program lead to an increase close to 20% in glenohumeral internal rotation range of motion, which was in accordance with previous reported gains (28). It may be hypothesized that the benefits in upper trunk posture associated with this increase in dominant glenohumeral range of motion may contribute to the increase in the range of motion of the cocking phase and then the course of the acceleration phase of the tennis serve, which may explain the gain in serve velocity. Moreover, it may be also supposed that the gain in thoracic, scapular, and glenohumeral movements may improve the intersegmental positioning of the upper limb to increase the accuracy of the tennis serve. Our findings thus indicated that a multimodal program focusing on upper trunk and shoulder including stretching, strengthening, mobility, and respiratory exercises performed four times per week during 8 weeks was not effective enough to alter the thoracic postural curvature in the standing position, but programming such a program was relevant to increase spine and shoulder mobility and improve tennis serve performance.

This study presents limitations that warrant discussion. First, strength assessments were not performed neither for glenohumeral muscles nor for scapular muscles, not allowing the effects of strength exercises to be related to scapular positioning. Second, a tennis serve kinematic analysis may help evaluate whether a transfer of the decreased thoracic curvature during trunk extension occurred during the tennis serve motion. Third, the effects of the multimodal program on postural and shoulder adaptations may be influenced by the large range in tennis experience due to age dispersion of our players and/or by the natural evolution of the tennis practice when control and intervention periods were performed successively in different periods of the tennis season. This study was, however, the first investigating the effects of a multimodal program acting on both the spine and shoulder girdle region in competitive young tennis players. Further studies need to evaluate whether such a multimodal program may have effects on the forward posture in the long term, as well as to better understand the transfer of such multimodal program effects into the sport-specific performance.

5. Practical applications

A multimodal program focusing on upper trunk and shoulder including stretching, strengthening, mobility, and respiratory exercises performed four times per week during 8 weeks has no effect on the thoracic spine alignment; but it is relevant to gain in thoracic, scapular, and glenohumeral mobility in competitive young tennis players. Such a program could be implemented regardless of the season periodization because its gains are transferred to the tennis-specific performance.

6. Conclusion

The findings of the present study showed that a multimodal program including spine and glenohumeral mobility and shoulder girdle strength exercises resulted in improved thoracic mobility, decreased interscapular distance, increased glenohumeral rotation range of motion, and increased tennis serve performance. This study brings new knowledge to tennis and strength and conditioning coaches, and clinicians to prevent shoulder function limitations without altering sport performance in overhead athletes.

Data availability statement

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

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the participants' legal guardian/next of kin was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

All the authors contributed to conception and design of the study, organized the database, performed the statistical analysis, and wrote the manuscript. All authors contributed to the article and approved the submitted version.

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

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2023.1128075/full#supplementary-material.

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