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Research article

Effects of a neuromuscular training program on the performance and inter-limb asymmetries in highly trained junior male tennis players

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ABSTRACT

Background: The objective of this study was to assess the effectiveness of neuromuscular training on the performance of highly trainer junior tennis players.
Methods: Twelve male tennis players (age: 13.4 ± 0.36 years; weight: 50.2 ± 6.29 kg; height: 163 ± 4.41 cm) participated and were randomly divided into two groups. The experimental group (EG) performed neuromuscular training that included exercises for speed, strength, throws, agility, jumps and coordination twice a week for a duration of 10 weeks. Performance was evaluated using various variables, including bilateral and unilateral countermovement jump, 30 cm drop jump and horizontal jump, 505 change of direction test conducted with both the right and left legs, 20-m sprint, and overhead 3 kg medicine ball throw. Asymmetries were also evaluated during the unilateral tests. The impact of the training was assessed through the utilization of ANCOVA tests and effect size measurements.
Results: The results indicated a significant enhancement in the EG, specifically in bilateral vertical jump and horizontal jump, as well as explosive strength and speed. Conversely, the control group (CG) did not display similar advancements. Furthermore, there was no increase in asymmetries.
Conclusion: This suggests that the implementation of a neuromuscular training program could prove to be an effective approach in enhancing explosive power in the lower limbs among young competitive tennis players. Finally, this training program could contribute to the enhancement of their physical attributes in lower body of young tennis players.

1. Introduction

Tennis is a sport which is played individually or in pairs, with the main objective being to hit a ball over the net so that the opponent cannot return the hit. It is a sport in which more than 300 million people participate worldwide, making it one of the top 10 most played sports in the world [1]. In addition, the number of licenses has risen to 83.318, of which more than half are U-19 in Spain [2].

Despite the simplicity of its definition, it is a much more complex sport in terms of physical aspects. It has evolved into one of the most demanding sports in terms of physical condition. Not only is a high technical level required, but also other physical components

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are in demand such as strength, power, endurance, speed, agility and repeated sprinting capacity, but also a need of strong aerobic and anaerobic metabolic pathways [3,4]. The average duration of the points ranges from 4 to 10s, with 10–20s of recovery and 60–90s at certain times of the match [3]. This is in addition to an average of 3–4 changes of direction (COD) and sprints of between 8 and 15 m [5]. This data should be taken into consideration prior to the design of training programs for tennis players, the physical and physiological requirements of the players, which may vary in relation to the level, style of play, sex or the surface where the game is played [5].

This sport has many known advantages, such as better bone health compared to other activities and reduced risk of cardiovascular disease, lower levels of body fat or the possession of a higher aerobic capacity [6]. However, we must also look at the negative side of this sport, and that is that tennis is related to various traumatic injuries and syndromes [7]. The lower limbs at the top of this list (39–59%), followed by the upper limbs (20–40%) and the trunk (11–30%) [8,9]. To put an end to most of these injuries, especially those caused by overuse, there should be a reduce in the loads to which these limbs are exposed and improve the technique of execution within these actions that cause the most injury.

One of the main risk factors when talking about these injuries is the asymmetries between lower extremities. These vary depending on the type of test or technical gesture being performed, so the risk of injury also varies [10,11]. The degree to which physical factors such as fatigue, load or concentration level affect asymmetries cannot be determined with any degree of precision, due to the limited literature that can be found on the subject [11].

According to the scientific literature the best combination is a training program that takes place pre/post and during [12]. The objective of this is pre/post evaluation and observation of progression during [13]. For the creation and development of this training regimen, we were inspired by previous work in other sports modalities [14–16], specifically FIFA11+ and Sportsmetrics®, in which neuromuscular training (NMT) methods were combined with exercise for the improvement of sports performance. With respect to the Sportmetrics® program, research indicates that it reduces the likelihood of anterior cruciate ligament injuries in female athletes [17,18], corrects excessive valgus during jumping tests thus improving lower extremity alignment [19] and increases hamstring moment of force allowing for increased knee flexion and ground reaction forces at the end of training [18,19]. FIFA11+ is an injury prevention program that simply consists of the introduction of 10 warm-up exercises for conditioning. Above all, the reduction of those injuries associated with deficient load progressions (volume/intensity) and those caused by asymmetries between the lower limbs [20].

Recently, neuromuscular training (NMT) has been studied for its great benefits in terms of performance, injury prevention and helping improve developing deficiencies in basic skills [21].

In addition, it has been concluded that this training methodology had significant improvements in speed, agility, and abdominal endurance [7]. Concerning the impact of this type of training on young tennis players, several studies have been found to assess its effects. Barter-Westin et al. observed improvements in neuromuscular indices such as speed, power, agility, aerobic capacity, reaction capacity, anticipation, and correction of asymmetries, after a 6-week neuromuscular training program [7]. Fernandez-Fernandez et al. observed improvements in physical fitness after regular training combined with neuromuscular training and after 5 weeks of implementation [22]. Overall, neuromuscular training can have clear positive effects on the performance and fitness of young tennis players. However, more research is needed to determine the exact parameters, duration, time, intensity, and so on, depending on age and different skill levels.

Both bilateral and unilateral training are options when prescribing strength training programs, although the most important actions are performed unilaterally (jumps, COD, etc.) [23]. Which has been considered when planning exercise selection as it mainly uses unilateral movements. According to the scientific literature, strength training may improve maximal strength, as well as reduce the injury rate and accelerate the recovery process [24]. Plyometric training (PT) seems to give positive results in terms of the physical abilities of young tennis players (explosive strength) [25,26]. PT consists of stretching at maximum speed of a muscle (eccentric contraction) followed by shortening it (concentric contraction) [27]. In this training study, the subjects (21 young tennis players, of whom 11 boys and 10 girls) improved the variables of 20-m sprint, COD, countermovement jump (CMJ), medicine ball throwing test and horizontal jump test [25]. Fernández-Fernández et al., who also proposed plyometrics as a training method, showed that the athletes (60 boys aged 12–13 years) improved after 8 weeks in jumping test, serving speed and throwing among other variables [26].

The practice of competitive tennis demands a high level of physical, technical, tactical and psychological performance. Therefore, adequate training for young tennis players is of great importance. One of the factors that affect the performance of tennis players is endurance. This capacity allows repeating technical actions throughout the match without falling into extreme fatigue that could lead to an increase in unforced errors or reduce the ability to execute winning strokes [28,29]. At the same time, there is a need to be aware that this is a sport where chronic injuries due to repetitive and excessive use account for 59.15% of the total [30], so strengthening the structures of athletes will be crucial to achieve long periods without incapacitating injuries. However, despite its wide global popularity, research on different training programs in young competitive tennis players is scarce, being an essential aspect to identify and develop the most effective and safe methods [31]. As it is an individual sport, each training must be adapted to the individual characteristics of each athlete, as abilities, strengths, and limitations vary from player to player. The study of training methodologies will allow physical trainers, coaches, and other technical staff to expand the possibilities of choice when creating training plans.

Therefore, the aim of the present study was to analyze the effects of a 10-week neuromuscular training program on jumping, sprinting, upper body strength, and COD in highly trained male junior tennis players.

2. Materials and methods

2.1. Design

The study protocol is summarized (Fig. 1). The design and reporting of the study followed the CONSORT guidelines [32].

Tennis players aged between 13 and 14 years from the Federación Aragonesa de Tenis were recruited. Players were only eligible to be included in this study if they had not experienced; serious injuries, undergone surgeries, or participated in any sports-related rehabilitation in the year preceding the study's beginning. Moreover, participants were not allowed to perform any organized strength training programs, such as plyometric or power exercises, in the four weeks prior to the start of the study.

2.2. Participants

Twelve highly trained male junior tennis players voluntarily participated in this experiment with ages ranging from 13 to 14 years (mean age: 13.4 ± 0.36 years; weight: 50.2 ± 6.29 kg; height: 163 ± 4.41 cm; body mass index: 18.8 ± 1.55 kg/m^2) (Table 1). Ten players were right-handed and two were left-handed.

A post hoc sample size calculation was carried out using G-Power software Version 3.1.9.7 (University of Düsseldorf, Düsseldorf, Germany). The specifications were as follows: F tests via ANCOVA with fixed effects, main effects, and interactions. The effect size (ES) was deemed high to very high [33–35]. The total sample size was considered with 2 groups, and the numerator df was set at 1. The determined sample size with 12 participants yielded a power (1-β error probability) of 0.75. On average, the participants had a training background with a minimum of 6 years. They engaged in approximately 8 h of tennis training per week (technical and tactical skills), and 3 h a week of physical training (cardiovascular fitness and tennis-specific strength). The CG only engaged in their regular tennis training, while the EG underwent a ten-week NMT program, consisting of two 30-min sessions per week. The regional Federation identified promising young players through its coaching staff. The selection process consisted of evaluations of the players' technical or tactical abilities and their competitive performance. All players were ranked among the 100 best players in the national singles ranking category (Under 14).

The sampling strategy employed was non-probabilistic intentional, based on their skill level (ranking), and availability to participate in the training program throughout its duration. The inclusion criteria were: participants should not have prior experience in strength training, should not have had any injuries, undergone surgeries, or taken part in sports-related rehabilitation in the year preceding the study's commencement. Additionally, participants were required to abstain from engaging in any organized strength training programs, such as plyometric or power exercises, in the four weeks leading up to the study's initiation. Moreover, they needed to be tennis players training within a competitive group, aged between 13 and 14 years old, and possess a valid tennis license.

Having any type of injury throughout the intervention or failing to attend at least 80% of the training sessions was the exclusion

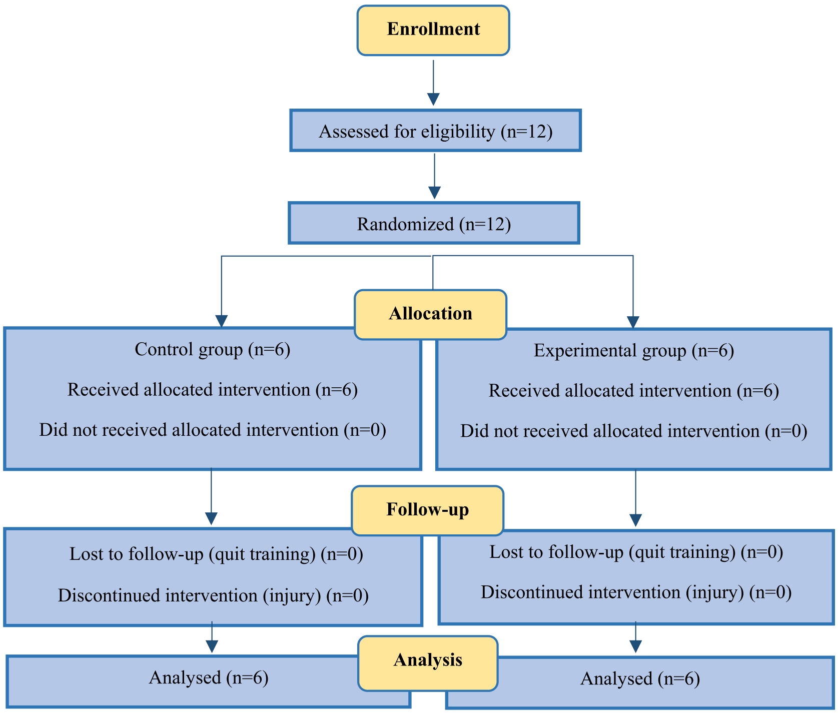

Fig. 1. Recruitment process described in a CONSORT diagram.

Table 1
Descriptive data of the participants. Mean ± SD.

	Age (y)	Maturity Offset	Height (cm)	Body mass (kg)	BMI (kg/m^2)
Control group	13.2 ± 0.31	−0.55 ± 0.50	163.4 ± 4.43	50.2 ± 7.10	18.7 ± 1.68
Neuromuscular training group	13.6 ± 0.29	−0.52 ± 0.43	162.7 ± 4.80	50.3 ± 6.05	18.9 ± 1.60

BMI: Body-mass index.

criteria.

One researcher assessed the initial characteristics of the participants. Subsequently, an independent researcher used a computer-generated list of random numbers [36] to allocate 12 participants randomly into the experimental group (EG = 6) or the control group (CG = 6). Each athlete was assigned an identifier to ensure the evaluator remained blinded during the assessments. Another professional was responsible for carrying out the intervention and, therefore, could not remain blinded due to the nature of the training and study. Another researcher (blinded) conducted the statistical analysis. The experimental group was supervised and led by qualified exercise experts to ensure adherence to this protocol.

The local tennis club was informed about the study, and contact information was provided for parents/legal guardians of the athletes to get in touch with the principal investigator for voluntary enrollment. Participants and their parents/legal guardians were briefed about the study requirements and objectives, and they provided consent to participate. The study was conducted in accordance with the ethical principles of the Declaration of Helsinki and was approved by the Ethics Committee of the University, Approval No. 46/2/22–23.

2.3. Procedures

At the beginning and then 10 weeks after the training, participants received physical assessments performed by an identical team of investigators throughout the study which took place during the mid-season of the competition period. These assessments always took place at the same time of day (19:00–21:00) on a tennis court, with unchanging environmental conditions (~18–20 °C and ~20% humidity).

The pre-training measurements were conducted one week prior to start of the study. Before conducting the tests, a set of each was performed twice in order for the participants to familiarize themselves. The training sessions took place every Tuesday and Thursday, within their regular schedule, lasting 30 min.

The post-training tests were carried out in the same manner as the initial ones: (a) bilateral/unilateral countermovement jump (CMJ), (b) bilateral/unilateral drop jump (DJ), (c) bilateral/unilateral horizontal jump (HJ), (d) modified 505 COD test, (e) 20 m sprint, and (f) medicine ball throw, in the same order for each subject. All tests were performed on a hard tennis court surface. Participants wore specific tennis shoes for this type of surface. Furthermore, prior to conducting both the tests and the training sessions, an 8-min warm-up was performed, including aerobic exercise, general mobilization, and ballistic exercises.

2.3.1. Bilateral and unilateral horizontal jump test

Horizontal jump was performed to assess the explosive strength of the lower limbs. A standard measuring tape (30 m) was used to measure it. The subjects started from a vertical position, with their feet just behind the line marking the start of the tape. Upon the researcher's signal, they were required to push off and jump forward as far as possible. The landing had to be controlled, and balance maintained for 2/3 s to record the value. Each athlete had two attempts with a 60-s rest between them. The highest value was used for statistical analysis. Both bilateral and unilateral jumps were performed (first with the dominant leg and then with the non-dominant leg, allowing for balanced flexion of the leg). In both tests, the use of arms and swinging of one leg was allowed. The intra-class correlation (ICC) recorded 0.89 for bilateral and 0.86 for unilateral horizontal power.

2.3.2. Bilateral and unilateral countermovement jump test

Countermovement jump was used to measure the explosive strength in the lower body of the tennis players. To obtain the values, "MyJump 2" App was used, which used video recording to capture flight height [37,38]. The athletes started from a standing position with their arms on their hips. Upon the researcher's command, they performed a downward movement to reach a squat position and then executed a vertical jump. The legs had to remain extended during the movement. Two attempts were made with a 45-s rest between them (9). This test was conducted both bilaterally and with the dominant leg and non-dominant leg. The highest jump was selected for the study. The ICC showed 0.91 for bilateral and 0.92 for unilateral vertical power.

2.3.3. Bilateral and unilateral drop jump test

Drop jump test was used to evaluate explosive strength in the lower body due to its characteristic "elastic-explosive reflex" (stretch-shortening cycle) manifestation [39]. "MyJump 2" App was used for measurement [37,38]. The participants started from a 30 cm-high box [40,41]. They had to drop and upon contact with the ground, perform a maximal vertical jump. Throughout the movement, the arms had to remain at the waist. Two jump attempts were made with a 45-s rest. This test was conducted both bilaterally and unilaterally. In the unilateral variant, the use of swinging the other leg was not allowed. The order for performance was first with the dominant leg and then with the non-dominant leg. The highest jump was selected for the study. ICC values were 0.87 and 0.85 for bilateral and unilateral vertical drop power, respectively.

2.3.4. Modified 505 change of direction test

The test was conducted to analyze the COD and sprinting ability of the players. The "COD timer" App was used for data recording marking the start, 10-m in and 15-m line with cones [42]. The players sprinted 15-m and then performed a 180° turn off (first with the dominant leg and then with the non-dominant leg) coming back to the 10-m line. Two attempts were made with a 3-min passive rest to recover adequately. As this was a modified version of the test, a 10-m sprint was not performed before recording the 5-m COD time [43]. The fastest time was selected for the study. The ICC was 0.92.

2.3.5. 20-M sprint test

Subjects performed a 20-m sprint at maximum speed. "My Sprint" App was used for test measurement, recording time through video recording [44]. The start, finish and the different distance lines were marked with cones. The tennis player had to stand just behind the starting line (0.3-m) to ensure a uniform and fair start and wait for the investigator's order. Two attempts were made with a 3-min passive rest to allow the subject to recover for the next sprint to be performed with maximum intensity. The ICC was 0.95.

2.3.6. Medicine ball throw test

This test was conducted following the protocol described by Ublicht et al. [45]. A medicine ball weighing 3 kg (O'Live Fitness, Barcelona, Spain) was used to perform the test. For test measurement, a surface was used where the ball's mark was imprinted, and the distance was subsequently determined using a measuring tape. Two attempts were made, with a 60-s rest between them. The ICC was 0.92 in this test.

2.3.7. Maturity offset

Chronological age was calculated as the difference between date of birth and the date of assessment. To measure maturity status, an age at peak height velocity (PHV) prediction equation was used [46]. Years from PHV was calculated for each subject by subtracting the age at PHV from chronological age.

2.4. Training

The training program consisted of two 30-min sessions per week (Table 2). One of them was focused on strength development, and the other on agility (COD, sprint, jumps …).

Progressive overload was applied to each of the exercises by increasing the weight, intensity, or duration of each exercise within the working methodology (circuit). The exercises were initially conducted with a weight of 3 kg for both dumbbells and the medicine balls. In the initial weeks of the study, the work-to-rest ratio used was 30s/15s. Starting from week 3, the time increased to 40s/20s. Throughout the project, the rest between sets was 3 min, with a total of 3 sets.

The selection of exercises was based on a review of the following articles [4,7,25,26,31,47–49], their potential effectiveness, variability and progression, and their applicability to the requirements of tennis. An attempt was made to include exercises that either

Table 2
Design of the Neuromuscular training program.

Week	Series	Work/ rest (s)	Rest (min)	Strength	Agility
1	3	30/15	3	Medicine ball throw, lounges, push-up, squat, bicep curl, glute bridge, BOSU plank	Multijumps, agility Ladder (different patterns), jump rope, DJ, CMJ, horizontal single leg jump, hurdle jumps
2	3	30/15	3	Military press, lateral raises, bulgarian Split squat, TRX flyes, jump squat, resistance band row, deadlift, crounches	5 m sprint, lateral shuffle, lateral steps + 10 m sprint, resisted sprint
3	4	40/20	3	Medicine ball throw, thruster, around the body, unilateral resistence band row + lounge, bench press, russian twits	Multijumps, unilateral DJ, jump + 3 m sprint, cone coordination, COD
4	4	40/20	3	Dumbbell row, triceps, dumbbell lateral raises, push-ups, abdominal exercises	Resisted sprints, sprints
5	4	40/20	3	Medicine ball throw, lounges, push ups, squats, bicep curl, glute bridge, BOSU plank	Multijumps, Agility Ladder, jump rope, DJ, CMJ, single leg jumps, high jumps
6	4	40/20	3	Military press, lateral raises, bulgarian Split squat, TRX flyes, jump squat, resistance band row, deadlift, crounches	5 m sprint, lateral shuffle, lateral steps + 10 m sprint, resisted sprint
7	4	40/20	3	Medicine ball throw, thruster, around the body, unilateral resistence band row + lounge, bench press, russian twits	Multijumps, unilateral DJ, jump + 3 m sprint, cone coordination, COD
8	4	40/20	3	Dumbbell row, triceps, dumbbell lateral raises, push-ups, abdominal exercises	Resisted sprints, sprints
9	4	40/20	3	Jump squat, BOSU push-ups, single leg jump box, crounches, dumbbell deadlift, plank, dumbbell row	Coordinative games
10	4	40/20	3	Throws, lounges, push ups, squats, glute bridge, BOSU plank	20 m sprint, 5, COD, Agility circuit (competition)

COD: change of direction.

repeated from one source to another or had shown positive results in improving the targeted quality.

2.5. Statistical analysis

The statistical analysis was executed using SPSS for MAC (Version 28.0; SPSS Inc, Chicago, IL). The data are expressed as the mean ± standard deviation (SD). The normality assumption was evaluated using the Shapiro-Wilk test. To detect significant differences between the pre-test and post-test variables within both groups, paired Student's *t*-tests were conducted. Moreover, the impact of training was evaluated through an analysis of covariance (ANCOVA) statistical model, where baseline measurements were included as covariates. Between groups, comparisons were analyzed using a series of independent t-tests. Statistical significance was established at a significance level of $p < 0.05$. Cohen's *d* effect size was calculated to gauge the extent of pairwise comparisons for the pre- and post-test variables within and between groups [50]. Cohen's *d* effect size values were classified as follows: trivial (<0.2), small (>0.2), moderate (>0.5), and large (>0.8).

Inter-limb asymmetry was calculated using the following formula [51]:

Inter-limb asymmetry = 100/Max Value (right and left)*Min Value (right and left)*-1+100.

3. Results

There were no notable differences between the groups in terms of the variables analyzed during the initial assessment. The performance outcomes of the physical fitness tests are presented in Table 3. There was no noteworthy interaction between the groups and

Table 3
Results of all tests performed in Control Group and Neuromuscular training Group. Mean ± SD.

	Control Group				Neuromuscular training program group					
Variable	Pre-test	Post-test	*p*	Cohen's d (within group)	Pre-test	Post-test	*p*	Cohen's d (within group)	ANCOVA, p	Cohen's d (between group)
CMJ (cm)	25.5 ± 4.15	25.9 ± 3.92	0.35	−0.16	28.3 ± 4.30	30.8 ± 4.03	0.01*	−1.88	0.04$	0.42
CMJ_R (cm)	11.5 ± 0.64	12.1 ± 0.80	0.09	−0.65	11.1 ± 0.61	12.5 ± 1.14	0.02*	−2.05	0.20	0.86
CMJ_L (cm)	11.9 ± 1.23	12.7 ± 1.37	0.05*	−0.85	10.44 ± 1.46	12.18 ± 0.94	0.01*	−2.19	0.38	0.76
% As UCMJ	9.04 ± 4.90	5.27 ± 3.85	0.06	0.77	8.87 ± 4.57	3.86 ± 3.53	0.06	0.79	0.54	−0.20
DJ (m)	25.5 ± 1.5	25.8 ± 1.38	0.06	−0.75	24.0 ± 1.48	26.2 ± 1.26	0.01*	−1.85	0.02$	1.22
DJ_R (m)	13.3 ± 0.83	13.5 ± 1.10	0.10	−0.59	12.7 ± 1.31	14.1 ± 1.10	0.01*	−1.60	0.02$	1.08
DJ_L (m)	12 ± 0.71	12.1 ± 0.61	0.10	−0.57	11.85 ± 1.40	13.4 ± 1.98	0.01*	−1.57	0.01$	0.97
% As UDJ	9.21 ± 9.69	10.25 ± 9.60	0.08	−0.67	8.58 ± 11.4	6.93 ± 12.2	0.18	0.39	0.19	−0.30
HJ (cm)	177.8 ± 19.6	181.3 ± 19.8	0.11	−0.56	181.3 ± 21.5	195.6 ± 26.9	0.01*	−1.56	0.05$	0.45
$_{HJR}$ (cm)	144.6 ± 9.58	147.6 ± 11.1	0.02*	−1.15	156.3 ± 15.9	159.3 ± 13.8	0.10	−0.57	0.68	0.11
$_{HJL}$ (cm)	145.6 ± 12.2	146.6 ± 9.99	0.32	−0.19	149.3 ± 12.2	162.8 ± 26.8	0.01*	−1.77	0.20	0.20
% As UHJ	3.92 ± 4.19	3.57 ± 2.72	0.39	0.11	3.81 ± 2.52	4.58 ± 1.35	0.22	−0.33	0.34	0.91
MBT (m)	5.56 ± 0.64	5.62 ± 0.69	0.16	−0.43	5.97 ± 0.77	6.79 ± 1.31	0.02*	−1.11	0.07	0.68
20 m (s)	3.37 ± 0.04	3.37 ± 0.39	0.35	0.16	3.34 ± 0.04	3.30 ± 0.04	0.01*	1.34	0.04$	−0.66
180°COD_R (s)	2.82 ± 0.04	2.80 ± 0.03	0.06	0.74	2.84 ± 0.04	2.80 ± 0.06	0.04*	0.89	0.54	−0.29
180°COD_L (s)	2.82 ± 0.05	2.81 ± 0.05	0.16	0.44	2.85 ± 0.07	2.82 ± 0.05	0.04*	0.93	0.65	−0.18
% As COD	1.05 ± 0.38	0.88 ± 0.65	0.27	0.25	0.92 ± 0.67	0.94 ± 0.94	0.47	−0.03	0.67	−0.17

R: Right; L: Left; CMJ: countermovement jump; UCMJ: unilateral countermovement jump; CMJ_R: one-egged vertical right jump; CMJ_L: one-legged vertical left jump; UDJ: unilateral drop jump; DJ_R: one-legged drop right jump; DJ_L: one-legged drop left jump; HJ: horizontal jump; HJ_R: horizontal right jump; HJ_L: horizontal left jump; MBT: Medicine ball throwing; 180°COD: 5 + 5 m sprint test with a 180° change of direction; SD: standard deviation; As: asymmetry; cm: centimetres; s: seconds; m: meters.

* Significant difference between the pre-test and post-test ($p < 0.05$).

$ Significant group by time interaction ($p < 0.05$).

time for the changes observed between the pre-test and post-test measurements for unilateral CMJ, unilateral HJ, medicine ball throw, COD, and inter-limb asymmetry tests. However, when running ANCOVA, significant variations between the groups and time emerged for various tests. These include CMJ ($p = 0.04$; ES: 0.42), DJ ($p = 0.02$; ES: 1.22), DJ on the right side ($p = 0.02$; ES: 1.08), DJ on the left side ($p = 0.01$; ES: 0.97), HJ ($p = 0.05$; ES: 0.45), and the 20-m sprint ($p = 0.04$; ES: 0.66).

4. Discussion

This study aimed to observe the effects of a 10-week neuromuscular training program on physical performance in highly trained male junior tennis players. The primary outcome of this study showed that an NMT program led to improvements in bilateral vertical jump, bilateral horizontal jump, as well as elastic-explosive strength and speed among elite adolescent tennis players. However, it is important to note that the NMT program did not produce gains in unilateral vertical and horizontal jumps, COD and asymmetry parameters.

As previously stated, tennis is a sport that requires some specific physical abilities such as speed, agility (understood as the capacity to respond to an external stimulus before generating COD or speed [52], COD and power [3,4]. In previous research, it has been demonstrated that strength training [7,53], plyometric training [25,26,31] and agility training [4,25,26] improved performance indicators in tennis players such as CMJ, MBT or sprint [4]. Regarding the players of this study, jump variables have been improved significantly through the between group comparison. The NMT was effective improving the bilateral CMJ ($p = 0.04$; ES: 0.42), in contrast to unilateral, where no significant differences were found. The programmed exercises in this study were generally focused on the bilateral execution, so that aligns with the final results. These results are consistent with the findings of other studies which shown improvements in this ability after completion of the training program (ES: 0.31 to 0.46) [25,26,54].

The NMT approach employed in this research was an optimal program to improve DJ ($p = 0.02$; ES: 1.22), DJ on the right side ($p = 0.02$; ES: 1.08), DJ on the left side ($p = 0.01$; ES: 0.97). These effect size values were extracted through the between group comparisons. A systematic review and meta-analysis reported that PT was a highly effective methodology to enhance DJ height performance [55]. It also indicates that these effects are greater when the duration of the training program is $>$ 10 weeks, seeing how the greatest performance improvements were achieved in 12 weeks and the lowest results in 6 weeks. Due to the fact that tennis is a sport in which limb asymmetries arise from repetitive use of the dominant hand/leg [56] and considering that unilateral tests such as DJ could be a predictor of lower limb asymmetries, it would be interesting to incorporate it. Moreover, He et al. [57] reported that DJ training could affect positively in some other jumps like CMJ, which could be interesting to include both jumps in training programs for young tennis players. The literature suggests that plyometric training increases lower limb power in HJ [58,59]. Aloui et al. examined the effects of plyometric and sprint with COD program [60]. Significant improvements were observed in HJ resulting in a 15% increase in performance. In the present study, HJ was evaluated (p = 0.05; ES: 0.45), revealing remarkable improvements after the NMT program. However, when analyzing the HJ test results for both the right and left leg, no significant differences were observed. In contrast to the results of other studies [7,25] in which tennis players showed improvements in unilateral performance, our study differs in this aspect. This discrepancy could be attributed to the incorporation of more specific unilateral exercises in other investigations.

Terraza-Rebollo et al. suggest that strength training with medicine ball is a suitable option to improve swing speed [61]. Analyzing the results in the post-intervention evaluation of the medicine ball throw test, improvements were found when comparing within the same group (EG), but not when comparing between groups ($p = 0.07$; ES: 0.68). As Fernandez-Fernandez et al. state, a NMT program before tennis training produces positive results in improving MBT, however, the other group that performed a NMT program after tennis training, did not show improvements [62]. Likely, the fatigue generated during tennis training can cause athletes not to train at the expected intensity, thus hindering performance improvements in various variables such as medicine ball throwing. This indicates that optimal programming is necessary to achieve the best performance results. As it is shown, performed NMT before tennis is essential to reach improvements. Also, quantifying the correct load for each athlete would be a determining factor for success. It is possible that in some studies where researchers did not find any improvements, the intensity and volume of the program were not sufficient to generate any significant adaptations.

Plyometric training has been observed to contribute improvements in speed among young male athletes aged 12–16 years [25]. Fernández-Fernández et al. asserts that NMT prior to regular tennis training proves effective in enhancing speed [26]. A meta-analysis corroborates the positive impact of PT on sprint speed for healthy tennis players [63]. In relation with the above results, the 20-m sprint ($p = 0.04$; ES: 0.66) showed a significant improvement in the present study. A recent article indicates the moderate to very large associations between horizontal jump and sprint acceleration [64]. Due to these results, it is consistent that the observed improvements in horizontal jump data are related to a reduction in time spent in the 20-m sprint test.

Zhi-Hai Wang et al. show that regular tennis training added to a NMT program could increase COD ability [47]. Also, Quemba-Joya explains that this training methodology (NMT + tennis training) improved post-intervention results: performance enhancement (jumping, speed with CODs, strength and stability improvement), mitigating the risk of injury, and aiding in the development of deficiencies in basic and specific movement skills [21]. In the current study, it has been studied 505 COD test, but no significant differences were found when comparing between groups COD right ($p = 0.54$; ES: 0.29) COD left ($p = 0.65$; ES: 0.18). According to these findings, it would be advisable to incorporate more specific COD exercises and short-distance sprints and increase the volume of unilateral exercises for the lower limbs in future training proposals to find better results.

Madruga-Parera et al. [65] analyzed limb asymmetry in both jumping and COD tasks, with the aim of observing its connection with physical performance in a cohort of elite young tennis players (aged 16.3 $\pm$ 1.4 years). Their research revealed that limb differences during CODs resulted in reduced performance in both jumping and COD. This underscores the importance of controlling for the variable of asymmetry in this specific population.

Some limitations have been found when conducting this study. First, the sample size was limited due to difficulties in finding eligible subjects. Second, the program was performed solely on young males, so expanding it to competitive female tennis players should be necessary to verify the effects of the NMT program. Additionally, further investigation into players of older age groups would be beneficial. It would be intriguing to confirm whether there are changes in the outcomes when NMT is conducted before or after tennis practice. It would be interesting to determine the success factors contributing to improved results (whether certain exercises have had an extraordinary impact, the training frequency or intensity) replicating the training program or similar ones for the knowledge and implementation by coaches. Finally, it could be observed whether this training produces similar effects in sports that require similar motor skills such as padel or badminton.

5. Conclusion

The aim of this study was to assess the impact of a 10-week neuromuscular training program on the physical performance of highly trained male junior tennis players. The primary outcomes reveal significant enhancements in vertical and horizontal jumping abilities as well as in the 20-m sprint performance, indicating superior progress compared to a regimen solely centered on tennis training. These findings highlight the efficacy of neuromuscular training in enhancing lower limb explosive power. However, unilateral tests did not exhibit notable improvements in certain areas like CMJ, HJ, and COD, suggesting a potential benefit in incorporating targeted unilateral exercises. This study signals the need for further exploration into optimized training methods tailored for young competitive tennis players.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Elena Mainer-Pardos: Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Victor Emilio Villavicencio Álvarez:** Writing – review & editing, Methodology, Formal analysis. **Nagore Moreno-Apellaniz:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Alejandra Gutiérrez-Logroño:** Writing – original draft, Investigation, Conceptualization. **Santiago Calero-Morales:** Writing – review & editing, Writing – original draft, Supervision, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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