

## Masa Tenisi Oyuncularında Farklı Antrenman Yaklaşımlarının Kas Kuvveti ve Patlayıcı Güç Performansı Üzerine Etkilerinin İncelenmesi

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### Özet

Bu çalışmanın amacı, altı haftalık robot destekli çok top antrenman programının masa tenisi oyuncularında üst ve alt ekstremite izometrik kas kuvveti, dikey sıçrama performansı ve masa tenisine özgü forehand-backhand performansı üzerindeki etkilerini incelemektir. Araştırma, ön test-son test kontrollü deneysel desenle yürütülmüştür. Çalışmaya 18-25 yaş aralığında, düzenli olarak antrenman yapan ve müsabakalara katılan toplam 46 üniversite masa tenisi oyuncusu dâhil edilmiştir. Katılımcılar basit rastgele yöntemle deney grubu (n=23) ve kontrol grubu (n=23) olmak üzere iki gruba ayrılmıştır. Deney grubu, geleneksel partner destekli masa tenisi antrenmanlarına ek olarak altı hafta boyunca haftada üç gün robot destekli çok top antrenmanı uygulamıştır. Kontrol grubu ise aynı süre ve sıklıkta yalnızca geleneksel partner destekli masa tenisi antrenmanlarına devam etmiştir. Robot destekli programda forehand counterdrive, backhand counterdrive ve forehand-backhand counterdrive ayak çalışması kombinasyonları uygulanmıştır. Katılımcıların sağ ve sol quadriceps, hamstring, biceps ve triceps izometrik kas kuvvetleri el dinamometresiyle; dikey sıçrama performansları squat jump testiyle, forehand ve backhand performansları ise standartlaştırılmış robot destekli vuruş testiyle ön test ve son test olarak değerlendirilmiştir. Verilerin analizinde dağılım özelliklerine göre tekrarlı ölçümler varyans analizi, Wilcoxon işaretli sıralar testi ve Mann-Whitney U testi kullanılmış; ayrıca değişim skorları hesaplanmıştır. Anlamlılık düzeyi  $p<0,05$  olarak kabul edilmiştir. Alt ekstremite kas kuvveti ve dikey sıçrama performansı bakımından grup etkisi ve zaman  $\times$  grup etkileşimi anlamlı bulunmamıştır. Yalnızca sağ quadriceps kas kuvvetinde anlamlı zaman etkisi belirlenmiştir ( $p=0,034$ ). Üst ekstremite ölçümlerinde sol triceps ( $p=0,043$ ), sağ biceps ( $p=0,001$ ) ve sol biceps ( $p=0,007$ ) kas kuvvetlerinde anlamlı zaman etkisi saptanmış; ancak bu değişkenlerde grup etkisi ve zaman  $\times$  grup etkileşimi anlamlı düzeye ulaşmamıştır. Grup içi karşılaştırmalarda sağ biceps kuvveti her iki grupta, sol biceps kuvveti deney grubunda ve sol triceps kuvveti kontrol grubunda anlamlı artış göstermiştir. Forehand performansı hem kontrol grubunda ( $p=0,001$ ) hem de deney grubunda ( $p=0,027$ ), backhand performansı ise kontrol grubunda ( $p=0,004$ ) ve deney grubunda ( $p=0,029$ ) anlamlı biçimde gelişmiştir. Gruplar arasında son test backhand skorlarında kontrol grubu lehine anlamlı fark bulunmasına rağmen ( $p=0,006$ ), forehand ve backhand değişim skorları açısından anlamlı fark saptanmamıştır (sırasıyla  $p=0,377$  ve  $p=0,529$ ). Sonuç olarak, robot destekli çok top antrenmanı masa tenisine özgü teknik performansın geliştirilmesine katkı sağlayabilmektedir. Bununla birlikte, mevcut bulgular bu yöntemin geleneksel partner destekli antrenmana kıyasla kas kuvveti, dikey sıçrama veya teknik performansta üstün bir gelişim oluşturduğunu göstermemektedir. Bu nedenle robot destekli antrenmanın, geleneksel uygulamaların yerine geçen bağımsız bir yöntemden ziyade yüksek sayıda standartlaştırılmış tekrar sunan tamamlayıcı bir antrenman aracı olarak kullanılması daha uygun görünmektedir.

**Anahtar Kelimeler:** Masa tenisi, robot destekli antrenman, çok top antrenmanı, kas kuvveti, dikey sıçrama.

## An Investigation into the Effects of Different Training Approaches on Muscle Strength and Explosive Power Performance in Table Tennis Players

### Abstract

The aim of this study was to investigate the effects of a six-week robot-assisted multi-ball training programme on upper- and lower-extremity isometric muscle strength, vertical jump performance, and table tennis-specific forehand and backhand performance in table tennis players. The study was conducted using a pre-test–post-test controlled experimental design. A total of 46 university table tennis players aged 18–25 years who regularly trained and participated in competitions were included in the study. The participants were randomly allocated to either an experimental group ( $n = 23$ ) or a control group ( $n = 23$ ) using a simple randomisation procedure. In addition to traditional partner-based table tennis training, the experimental group completed a robot-assisted multi-ball training programme three times per week for six weeks. The control group continued to perform only traditional partner-based table tennis training at the same frequency and for the same duration. The robot-assisted programme included forehand counterdrive, backhand counterdrive, and forehand–backhand counterdrive footwork combinations. Isometric muscle strength of the right and left quadriceps, hamstrings, biceps, and triceps was assessed using a handheld dynamometer. Vertical jump performance was evaluated using the squat jump test, while forehand and backhand performance was assessed through a standardised robot-assisted stroke test. All measurements were conducted before and after the intervention. Depending on the distributional characteristics of the data, repeated-measures analysis of variance, the Wilcoxon signed-rank test, and the Mann–Whitney U test were used. Change scores were also calculated. The level of statistical significance was set at  $p < 0.05$ . No significant group effect or time  $\times$  group interaction was observed for lower-extremity muscle strength or vertical jump performance. A significant time effect was identified only for right quadriceps muscle strength ( $p = 0.034$ ). Regarding upper-extremity measurements, significant time effects were observed for left triceps ( $p = 0.043$ ), right biceps ( $p = 0.001$ ), and left biceps muscle strength ( $p = 0.007$ ); however, neither the group effect nor the time  $\times$  group interaction reached statistical significance for these variables. Within-group comparisons revealed a significant increase in right biceps strength in both groups, in left biceps strength in the experimental group, and in left triceps strength in the control group. Forehand performance improved significantly in both the control group ( $p = 0.001$ ) and the experimental group ( $p = 0.027$ ). Similarly, significant improvements in backhand performance were observed in both the control group ( $p = 0.004$ ) and the experimental group ( $p = 0.029$ ). Although a significant between-group difference in post-test backhand scores was found in favour of the control group ( $p = 0.006$ ), no significant differences were detected between the groups in the forehand and backhand change scores ( $p = 0.377$  and  $p = 0.529$ , respectively). In conclusion, robot-assisted multi-ball training may contribute to the development of table tennis-specific technical performance. However, the present findings do not indicate that this training method produces superior improvements in muscle strength, vertical jump performance, or technical performance compared with traditional partner-based training. Therefore, robot-assisted training appears to be more appropriately used as a complementary training tool that enables a high number of standardised repetitions rather than as an independent method replacing traditional training practices.

**Keywords:** Table tennis, robot-assisted training, multi-ball training, muscle strength, vertical jump.

## Introduction

Motor skills which are power, strength, and speed are important for athletes (Taskın et al., 2018). Table tennis is a dynamic racket sport that requires high reaction speed, agility, coordination, technical skill and explosive strength. During competition, players perform short bursts of high-intensity movements, sudden changes of direction and repeated forehand-backhand strokes. Consequently, table tennis performance depends not only on technical skills but also on physical performance components such as muscle strength, neuromuscular coordination, movement speed and explosive power (Kondrič et al., 2013; Zagatto et al., 2018). Recent evidence indicates that table tennis is characterised by high-intensity intermittent efforts involving repeated accelerations, rapid changes of direction, explosive movements, and frequent stroke combinations. Accordingly, muscular strength, power, agility, and neuromuscular capacity are considered key determinants of competitive performance in table tennis (Pradas et al., 2022).

Studies in the literature examining the physiological and performance requirements of table tennis indicate that the sport involves a mixed structure utilising both aerobic and anaerobic energy systems. Zagatto et al. (2010) reported that athletes are exposed to high-intensity loads during official matches and that physical fitness plays a significant role in the sustainability of performance. Similarly, Malagoli Lanzoni and colleagues (2014) demonstrated that footwork, forehand–backhand transitions and shot-direction strategies are decisive factors in match success among elite players. Recent evidence suggests that expert table tennis players are able to anticipate the incoming ball more effectively, position themselves efficiently, and execute more accurate and timely strokes through superior perception–action coupling (Lin & Liu, 2025). Schaefer and Scornaienzi (2020) highlighted the relationship between technical performance and neuromuscular characteristics, noting that the cognitive-motor performance of table tennis specialists is more advanced than that of novice athletes. Recent evidence also indicates that movement-specific training combined with balance exercises can significantly improve change-of-direction ability and movement efficiency in young table tennis players, further emphasizing the importance of integrating physical conditioning with technical training (Chen et al., 2025).

Traditional partner drills and multi-ball training are widely used to support performance development. The multi-ball method offers athletes the opportunity to perform more repetitions, increase training intensity and develop technical skills under more standardised conditions. In particular, robot-assisted systems contribute to the standardisation of training load by enabling control over the ball's speed, direction and serving frequency (Apostu et al., 2018). Gu and colleagues (2019) reported that multi-ball training can improve dynamic postural control, whilst Widodo and colleagues

(2024) demonstrated that circuit training has positive effects on reactive agility and endurance. In addition, recent evidence suggests that robot-assisted multiball training can improve reaction time while providing a highly standardized training environment with consistent ball speed, direction, and frequency, making it an effective supplementary training method for table tennis players (Rachiwong & Ratanapanadda, 2025).

Muscle strength and neuromuscular adaptations are recognised as key mechanisms in the development of sporting performance. Resistance training programmes based on the principles of progressive overload, appropriate exercise selection, training volume and intensity are fundamental for improving muscular strength and physical performance (Kraemer & Ratamess, 2004). Improvements in motor unit activation, contraction coordination and force production capacity resulting from resistance and strength training can positively influence performance in jumping, sprinting and changing direction (Cormie et al., 2011; Suchomel et al., 2016).

It has been reported that training programmes specifically targeting the development of explosive strength increase movement speed and power output. McBride et al. (2002) reported that an 8-week jump squat training programme resulted in significant improvements in power production, movement speed and jumping performance among athletes. Similarly, Cronin and Hansen (2005) reported that relative power output and jumping performance are key determinants of athletic speed. These findings highlight the importance of strength and power development in table tennis, given the frequent sudden changes of direction, short bursts of acceleration and rapid stroke combinations characteristic of the sport.

Studies conducted in recent years have shown that strength and neuromuscular training can improve strength, jumping performance, balance and sport-specific performance indicators in table tennis (Haghighi et al., 2021; Wang et al., 2024; Sun et al., 2025). Xiong et al. (2022) reported that integrative neuromuscular training improves strength, balance and jumping performance, whilst Zhu et al. (2024) demonstrated that upper-limb strength and anaerobic power development positively influence sport-specific performance in table tennis. Similarly, the sports science literature emphasises that muscle strength and explosive power are key determinants of sporting performance. Cormie et al. (2011) noted that neuromuscular activation, rate of force development and muscle architecture all play a role in the generation of maximal power. Suchomel et al. (2016), on the other hand, reported that high muscle strength enhances performance in jumping, sprinting and changing direction. Markovic (2007) demonstrated that plyometric training leads to significant improvements in vertical jump performance, whilst Deng et al. (2023) showed that plyometric training applied to racket sports players enhances muscle strength, sprint performance and reaction time. Fernandez-

Fernandez and colleagues (2009) also emphasised that the development of strength and power is of critical importance for performance in racket sports.

However, a significant proportion of existing studies have focused on agility, postural control, reaction time or technical performance. It appears that there are limited controlled experimental studies examining the combined effects of robot-assisted multi-ball training on upper and lower limb strength, explosive strength performance and sport-specific stroke performance. Therefore, it is important to investigate the effects of robot-assisted multi-ball training on the physical and sport-specific performance of table tennis players.

The aim of this study is to investigate the effects of robot-assisted multi-ball training, administered over a 6-week period, on upper and lower limb isometric muscle strength, vertical jump performance, and forehand and backhand performance in table tennis players.

Accordingly, it is hypothesised that robot-assisted multi-ball training will have a positive effect on upper and lower limb isometric muscle strength, vertical jump performance, and forehand and backhand performance. Furthermore, it is hypothesised that differences will emerge in terms of physical and sport-specific performance parameters between athletes undergoing robot-assisted multi-ball training and those undergoing traditional partner-based drill training.

## **Materials and Methods**

### ***Experimental Design***

This study was conducted using a pre-test–post-test controlled experimental design. A total of 46 table tennis players were included in the study. The participants were divided into two equal groups: the experimental group and the control group ( $n = 23$  for each group). The experimental group took part in a robot-assisted multi-ball training programme in addition to the traditional partner-based training method throughout the 6-week training period. The control group, meanwhile, continued their training using only the traditional partner-based training method throughout the same period. The aim of the study was to investigate the effects of the robot-assisted multi-ball training programme, applied in addition to the traditional partner-based training method, on the physical performance parameters of table tennis players. Written informed consent was obtained from all participants prior to their inclusion in the study.

## ***Participants***

A total of 46 table tennis players aged 18–25 years were included in the study. The study sample comprised university-level table tennis players who were actively training and representing Karabük University in competitions during the 2025–2026 academic year. Participants were recruited voluntarily from the university table tennis team and had engaged in structured table tennis training regularly for at least two years. Using a simple randomisation procedure, participants were allocated equally to either the experimental group ( $n = 23$ ) or the control group ( $n = 23$ ). Randomisation was performed using the RAND() function in Microsoft Excel. A random number was generated for each participant, after which the participants were ranked in ascending order according to the generated values. The first 23 participants were assigned to one group and the remaining 23 participants to the other group, thereby ensuring random and equal group allocation. The demographic characteristics of the participants are presented in Table 1.

The training programme was carried out three days a week for six weeks, with all training sessions taking place at the same time each day. The inclusion criteria for the study were: being an active university table tennis player, being aged between 18 and 25, having participated in regular table tennis training at least three times per week during the previous year, not having suffered a serious musculoskeletal injury within the previous six months, and having signed a written informed consent form. Exclusion criteria were defined as being outside the specified age range; having a chronic medical condition or taking regular medication; having a neurological, orthopaedic or cardiovascular disorder; having any health issue that could prevent consistent participation in the training programme; missing more than 10% of the scheduled training sessions, and refusing to sign the informed consent form. An a priori sample size calculation was performed using G\*Power software (Version 3.1.9.7; Heinrich Heine University, Düsseldorf, Germany) (Faul et al., 2009). Based on a mixed-design analysis of variance (ANOVA) with two groups and two measurement time points, assuming a medium effect size ( $f = 0.25$ ), an alpha level of 0.05, and a statistical power of 0.80, the minimum required sample size was calculated as 34 participants. To compensate for potential dropouts and increase statistical power, 46 participants (23 per group) were included in the study.

## ***Experimental Procedure***

The experimental and control groups were formed, each comprising 23 athletes. Following the pre-test measurements, the participants took part in the relevant training programmes for a period of 6 weeks. The intervention programme was conducted over a total of 6 weeks, three days a week, with training sessions taking place on Tuesdays, Thursdays and Fridays. Each training session lasted approximately 90 minutes.

Whilst the control group undertook only traditional partner-based drill training, the experimental group undertook robot-assisted multi-ball training in addition to the traditional partner-based training method. Each training session began with a standard warm-up protocol lasting approximately 10 minutes, consisting of a 400 m low-intensity run and dynamic stretching exercises targeting the upper and lower extremities (Katsikadelis et al., 2017). Following the warm-up, both groups performed three table tennis-specific combined drill training exercises.

As part of the pre-test, participants' height, body weight, body mass index, countermovement jump (CMJ) performance and isometric muscle strength values were assessed. For isometric muscle strength measurements, the hamstring and quadriceps muscle groups were assessed for the lower limbs, whilst the biceps and triceps muscle groups were assessed for the upper limbs. All assessments were carried out at a standardised time of day ( $\pm 1$  hour) and under similar environmental conditions. Participants were asked to maintain their usual dietary habits, fluid intake and sleep patterns prior to the test sessions, and to avoid strenuous physical activity. Once the intervention period was complete, all measurements were repeated under the same conditions to obtain the post-test data. The effectiveness of the training programme was assessed by comparing the pre-test and post-test results.

## ***Measurements***

### *Anthropometric Measurements*

The participants' height was measured using a stadiometer with a precision of 0.01 m. During the measurement, participants stood upright, barefoot, with their heels together and their knees fully extended. Height values were recorded in centimetres (cm) (Norton and Olds, 1996). Body weight measurements were carried out using the InBody 270 professional bioelectrical impedance body analysis device. In this context, participants' body weight (kg) and body mass index ( $\text{kg/m}^2$ ) values were recorded. To enhance the reliability of the measurement results, participants were asked not to consume any food or drink for at least 4–5 hours prior to the test, not to exercise within the 12 hours preceding the test, and not to consume any food or drink containing caffeine within the 24 hours prior to the test (Moon, 2013).

### *Vertical Jump Measurement*

Participants' vertical jump performance was assessed using the squat jump test. The squat jump test was measured using a Smartspeed jump mat (Fusion Sport, Austria). For the squat jump, participants were instructed to maintain an isometric squat with their knees bent to an estimated  $90^\circ$  for 3 seconds before jumping vertically (Hughes et al., 2019). Participants were asked to perform the

highest possible vertical jump whilst maintaining a stable stance on the jump mat with their knees bent to approximately 90 degrees (Bosco, 1999). Each participant was allowed two attempts, and the highest performance value was used in the analysis. A 3-minute rest period was observed between trials.

#### *Isometric Muscle Strength Test Isometric Muscle Strength Measurement*

Participants' isometric muscle strength values were assessed using a Lafayette brand handheld dynamometer. It has been reported that handheld dynamometers provide objective, valid and reliable measurements of isometric muscle strength, particularly when standardized testing procedures and external fixation methods are used (Thorborg et al., 2010; Thorborg et al., 2013; Mentiplay et al., 2015). In this study, isometric muscle strength measurements were performed on the right and left biceps and right and left triceps in the upper extremities; and on the right and left quadriceps and right and left hamstring muscle groups in the lower extremities. During the measurements, participants were positioned in the standard test position appropriate for the muscle group being assessed. The dynamometer was positioned on the relevant anatomical region, and participants were asked to apply maximum isometric force without changing the angle of movement. To enhance the reliability of the measurements, the test positions, instructions and measurement procedures were standardised for all participants. Isometric muscle strength values were recorded in kilogram-force (kgf).

#### *Forehand and Backhand Performance Test*

Participants' sport-specific forehand and backhand performance was assessed using a standardised test protocol. The robotic system used in training sessions was employed for the tests, and the ball delivery speed, test duration, target zones, sequence of execution and rest intervals were standardised for all participants. The protocol was designed according to the technical demands of table tennis and contemporary sport-specific skill assessment principles (Widodo et al., 2024). The ball delivery frequency was set at 80 balls per minute. Accordingly, over a 30-s test period, a total of 40 balls were served to each participant, who were instructed to direct the balls towards predetermined diagonal target zones. This protocol was established to ensure standardised and reproducible assessment conditions consistent with robot-based table tennis skill evaluation procedures reported in the literature (Kong et al., 2024). The target zones were determined by considering the playing areas where forehand and backhand diagonal shots are directed in table tennis, and the same zones were used for all participants. Each shot that successfully reached the target zone was awarded 1 point, whilst shots that landed outside the target zone or were unsuccessful were awarded 0 points. Accordingly, the maximum score achievable in the forehand and backhand tests was set at 40. The forehand and backhand tests were conducted separately, with a 3-minute passive rest period between

tests. To reduce the risk of measurement bias, the assessor who evaluated the forehand and backhand performance tests was blinded to participants' group allocation during all performance assessments.

### *Training Protocol*

Athletes in the experimental group participated in a robot-assisted multi-ball training programme for 6 weeks, in addition to their routine table tennis training. Training sessions were held three days a week, and all sessions were conducted under the supervision of the same coach. The Y-T S-27-T table tennis robot was used for the robot-assisted sessions. The robot was positioned at the centre point opposite a standard-sized table tennis table and remained stationary throughout all sessions. The robot's positioning and ball-serving characteristics were standardised in line with approaches used in robot-assisted table tennis training (Schaefer & Scornaienchi, 2020). Each training session lasted approximately 90 minutes. The sessions consisted of the following sections: general warm-up, table tennis-specific warm-up, robot-assisted multi-ball training, technical-tactical drills and a cool-down. During the cool-down, low-intensity recovery and stretching exercises were performed. As part of the robot-assisted multi-ball training, three technical combinations were practised: Forehand Counterdrive (FHCD), Backhand Counterdrive (BHCD) and Forehand–Backhand Counterdrive Footwork (FBCF). These combinations were adapted from exercises designed to develop fundamental stroke skills and footwork in table tennis (Tepper, 2003).

Before the drills began, the coach explained each technical combination and demonstrated the movements in practice. The athletes were asked to maintain the correct stroke technique throughout the exercises, use appropriate footwork and maintain the ready position. In the Forehand Counterdrive drill, the athletes returned balls directed to the forehand zone with cross-forehand strokes, whilst in the Backhand Counterdrive drill, they returned balls directed to the backhand zone with cross-backhand strokes. In the Forehand–Backhand Counterdrive Footwork exercise, athletes alternated between hitting balls directed at the forehand and backhand zones using side-step movements (Katsikadelis et al., 2017).

Each technical combination was performed in 5 sets. The duration of each set was set at 30 seconds, with 30 seconds of active rest between sets. Following the completion of each combination, 3 minutes of passive rest was provided. The ball delivery rate was set at 80 balls per minute, meaning that a total of 40 balls were delivered to the athletes during each 30-second set (Katsikadelis et al., 2017). Athletes in the control group, meanwhile, continued with traditional partner-based table tennis training for the same duration and at the same frequency, and did not participate in the robot-assisted multi-ball training. Both groups followed a similar technical and tactical training programme

throughout the study; the key difference between the groups was that the experimental group undertook robot-assisted multi-ball training in addition to traditional training.

### **Data Analysis**

The data obtained from the study were analysed using the SPSS 26 Statistics software package. The suitability of the data for a normal distribution was assessed using the Shapiro Wilk test. Non-parametric tests were preferred for variables that did not follow a normal distribution. The Wilcoxon Signed-Rank Test was used for within-group comparisons (pre-test–post-test). For between-group comparisons, the Mann–Whitney U test was applied. Furthermore, to assess the extent of change, difference values ( $\Delta$  = post-test – pre-test) were calculated for each variable, and between-group comparisons were carried out based on these values. For variables meeting the parametric assumptions, repeated measures analysis of variance (ANOVA) was applied, and the effects of time, group and the time  $\times$  group interaction were examined. Effect sizes were calculated using Cohen's  $d$  and partial eta-squared ( $\eta^2p$ ). In all analyses, a significance level of  $p < 0.05$  was adopted.

### **Research Ethics**

The study was approved by the Karabük University Non-Interventional Clinical Research Ethics Committee (Approval Date: 3 November 2025; Approval No: 2025/2564). The research was conducted in accordance with the Higher Education Institutions Scientific Research and Publication Ethics Directive. All participants were informed about the purpose and procedures of the study, and their voluntary participation was ensured. Written informed consent was obtained from all participants prior to their participation in the study.

## **RESULTS**

**Table 1.** Demographic characteristics of the participants

| Variable                 | Group      | N  | Minimum | Maximum | Mean $\pm$ SD     |
|--------------------------|------------|----|---------|---------|-------------------|
| Age (years)              | Control    | 23 | 19.00   | 25.00   | 21.13 $\pm$ 2.24  |
|                          | Experiment | 23 | 18.00   | 25.00   | 21.00 $\pm$ 2.04  |
| Height (cm)              | Control    | 23 | 158.00  | 186.00  | 173.74 $\pm$ 8.33 |
|                          | Experiment | 23 | 165.00  | 190.00  | 174.48 $\pm$ 7.42 |
| Weight (kg)              | Control    | 23 | 50.00   | 115.00  | 74.70 $\pm$ 16.92 |
|                          | Experiment | 23 | 54.00   | 100.00  | 71.96 $\pm$ 13.36 |
| BMI (kg/m <sup>2</sup> ) | Control    | 23 | 18.82   | 35.49   | 24.54 $\pm$ 4.16  |
|                          | Experiment | 23 | 18.52   | 33.03   | 23.56 $\pm$ 3.53  |

The anthropometric characteristics of the participants in the study are shown in Table 1.

**Table 2.** Pre-test and post-test comparisons of lower limb muscle strength

| Variable               | Group      | Pre-test<br>(Mean ± SD) | Post-Test<br>(Mean ± SD) | Δ<br>(Mean ± SD) | <i>p</i> | Cohen's<br><i>d</i> | Effect       | <i>F</i> | <i>p</i> | $\eta^2p$ |
|------------------------|------------|-------------------------|--------------------------|------------------|----------|---------------------|--------------|----------|----------|-----------|
| Right<br>Quadriceps    | Control    | 37.23 ± 9.52            | 39.19 ± 8.63             | 1.96 ± 5.32      | .092     | 0.37                | Time         | 4.807    | .034*    | 0.098     |
|                        | Experiment | 34.92 ± 7.19            | 36.98 ± 7.24             | 2.06 ± 6.99      | .171     | 0.29                | Group        | 1.016    | .319     | 0.023     |
|                        |            |                         |                          |                  |          |                     | Time × Group | 0.003    | .955     | 0.000     |
| Left<br>Quadriceps     | Control    | 36.68 ± 10.34           | 38.29 ± 8.50             | 1.60 ± 4.91      | .132     | 0.33                | Time         | 2.630    | .112     | 0.056     |
|                        | Experiment | 34.65 ± 7.58            | 36.13 ± 8.56             | 1.48 ± 7.68      | .366     | 0.19                | Group        | 0.751    | .391     | 0.017     |
|                        |            |                         |                          |                  |          |                     | Time × Group | 0.004    | .947     | 0.000     |
| Right<br>Hamst<br>ring | Control    | 18.25 ± 6.03            | 18.06 ± 6.02             | -0.19 ± 3.25     | .780     | 0.06                | Time         | 0.322    | .573     | 0.007     |
|                        | Experiment | 20.18 ± 5.30            | 19.79 ± 5.13             | -0.39 ± 3.65     | .616     | 0.11                | Group        | 1.337    | .254     | 0.029     |
|                        |            |                         |                          |                  |          |                     | Time × Group | 0.037    | .849     | 0.001     |
| Left<br>Hamst<br>ring  | Control    | 17.18 ± 6.62            | 17.43 ± 5.17             | 0.25 ± 5.04      | .812     | 0.05                | Time         | 0.007    | .932     | 0.000     |
|                        | Experiment | 19.80 ± 5.27            | 19.43 ± 4.54             | -0.36 ± 3.46     | .622     | 0.10                | Group        | 2.448    | .125     | 0.053     |
|                        |            |                         |                          |                  |          |                     | Time × Group | 0.232    | .633     | 0.005     |

\**p* < 0.05.

In the analyses of quadriceps muscle strength, the effect of time was found to be statistically significant only for right quadriceps muscle strength (*p* < 0.05). No significant effect of time was found for left quadriceps muscle strength (*p* > 0.05). Neither the group effect nor the time × group interaction was significant for either variable (*p* > 0.05). In within-group comparisons, no significant change was observed between the pre-test and post-test in either the control or experimental groups (*p* > 0.05). In analyses of hamstring muscle strength, it was determined that the effect of time was not statistically significant for either right or left hamstring muscle strength (*p* > 0.05). Furthermore, neither the group effect nor the time × group interaction was found to be significant for either variable (*p* > 0.05). In within-group comparisons, no significant change was observed between the pre-test and post-test in either the control or experimental groups (*p* > 0.05).

**Table 3.** Pre-test and Post-test Comparisons of Upper Limb Muscle Strength

| Variable         | Group      | Pre-test<br>(Mean ± SD) | Post-Test<br>(Mean ± SD) | Δ<br>(Mean ± SD) | <i>p</i> | Cohen's<br><i>d</i> | Effect       | <i>F</i> | <i>p</i> | $\eta^2p$ |
|------------------|------------|-------------------------|--------------------------|------------------|----------|---------------------|--------------|----------|----------|-----------|
| Right<br>triceps | Control    | 21.10 ± 6.05            | 21.72 ± 6.81             | 0.61 ± 3.12      | .356     | 0.20                | Time         | 0.518    | .476     | 0.012     |
|                  | Experiment | 19.19 ± 5.19            | 19.43 ± 5.67             | 0.23 ± 4.71      | .813     | 0.05                | Group        | 1.612    | .211     | 0.035     |
|                  |            |                         |                          |                  |          |                     | Time × Group | 0.103    | .750     | 0.002     |
| Left<br>Triceps  | Control    | 20.67 ± 5.68            | 22.67 ± 7.01             | 2.00 ± 4.14      | .030*    | 0.48                | Time         | 4.357    | .043*    | 0.090     |
|                  | Experiment | 18.86 ± 5.44            | 19.30 ± 5.37             | 0.44 ± 3.80      | .581     | 0.12                | Group        | 2.486    | .122     | 0.053     |
|                  |            |                         |                          |                  |          |                     | Time × Group | 1.771    | .190     | 0.039     |
| Right<br>biceps  | Control    | 24.62 ± 8.45            | 27.93 ± 7.90             | 3.30 ± 6.21      | .018*    | 0.53                | Time         | 13.430   | .001*    | 0.234     |
|                  | Experiment | 23.34 ± 6.50            | 25.93 ± 7.10             | 2.59 ± 4.57      | .013*    | 0.57                | Group        | 0.630    | .432     | 0.014     |
|                  |            |                         |                          |                  |          |                     | Time × Group | 0.199    | .658     | 0.005     |
| Left<br>biceps   | Control    | 24.94 ± 8.93            | 26.97 ± 7.84             | 2.03 ± 6.58      | .154     | 0.31                | Time         | 8.140    | .007*    | 0.156     |
|                  | Experiment | 23.03 ± 7.17            | 25.76 ± 7.10             | 2.73 ± 4.53      | .009*    | 0.60                | Group        | 0.532    | .470     | 0.012     |
|                  |            |                         |                          |                  |          |                     | Time × Group | 0.177    | .676     | 0.004     |

\**p* < 0.05.

In the analyses of triceps muscle strength, the time effect was found to be statistically significant for left triceps muscle strength (*p* < 0.05), whilst no significant time effect was found for right triceps muscle strength (*p* > 0.05). Neither the group effect nor the time × group interaction was significant for either variable (*p* > 0.05). In within-group comparisons, a significant change in left triceps muscle strength was observed only in the control group; no significant differences were found in the other comparisons (*p*

> 0.05). In the analyses of biceps muscle strength, the time effect was found to be statistically significant for both right and left biceps muscle strength ( $p < 0.05$ ). In contrast, the group effect and the time  $\times$  group interaction were not significant ( $p > 0.05$ ). In within-group comparisons, a significant increase was observed in right biceps muscle strength in both groups ( $p < 0.05$ ), whilst a significant increase in left biceps muscle strength was detected only in the experimental group ( $p < 0.05$ ); no significant change was found in the control group ( $p > 0.05$ ).

**Table 4.** Pre-test and Post-test Comparisons of Vertical Jump Performance

| Variable      | Group      | Pre-test<br>(Mean $\pm$ SD) | Post-Test<br>(Mean $\pm$ SD) | $\Delta$<br>(Mean $\pm$ SD) | $p$  | Cohen's d | Effect              | $F$   | $p$  | $\eta^2p$ |
|---------------|------------|-----------------------------|------------------------------|-----------------------------|------|-----------|---------------------|-------|------|-----------|
| Vertical Jump | Control    | 27.26 $\pm$ 7.07            | 26.93 $\pm$ 7.66             | -0.33 $\pm$ 2.56            | .546 | 0.13      | Time                | 0.002 | .962 | 0.000     |
|               | Experiment | 28.16 $\pm$ 7.55            | 28.45 $\pm$ 7.42             | 0.29 $\pm$ 2.27             | .541 | 0.13      | Group               | 0.313 | .579 | 0.007     |
|               |            |                             |                              |                             |      |           | Time $\times$ Group | 0.758 | .389 | 0.017     |

Upon examination of Table 4, it can be seen that the effect of time was not statistically significant in the analyses of vertical jump performance ( $p > 0.05$ ). Similarly, neither the group effect nor the time  $\times$  group interaction was found to be significant ( $p > 0.05$ ). In within-group comparisons, no significant change was observed between the pre-test and post-test in either the control or experimental groups ( $p > 0.05$ ).

**Table 5.** Pre-test and Post-test Comparisons of Forehand and Backhand Performance

| Variable | Group      | Pre-test<br>(Mean $\pm$ SD) | Post-test<br>(Mean $\pm$ SD) | $\Delta$<br>(Mean $\pm$ SD) | $Z$    | $p$   |
|----------|------------|-----------------------------|------------------------------|-----------------------------|--------|-------|
| Forehand | Control    | 21.30 $\pm$ 7.21            | 25.52 $\pm$ 4.87             | 4.22 $\pm$ 2.56             | -3.274 | .001* |
|          | Experiment | 21.04 $\pm$ 7.30            | 24.17 $\pm$ 5.83             | 3.13 $\pm$ 2.27             | -2.206 | .027* |
| Backhand | Control    | 23.13 $\pm$ 6.23            | 26.65 $\pm$ 3.49             | 3.52 $\pm$ 3.25             | -2.862 | .004* |
|          | Experiment | 21.13 $\pm$ 5.65            | 23.96 $\pm$ 4.19             | 2.83 $\pm$ 3.46             | -2.180 | .029* |

\* $p < 0.05$ .

Upon examination of Table 5, a statistically significant increase was observed between the pre-test and post-test in forehand performance in both the control group ( $p = 0.001$ ) and the experimental group ( $p = 0.027$ ). Similarly, when backhand performance was examined, a statistically significant increase was observed between the pre-test and post-test in both the control ( $p = 0.004$ ) and experimental groups ( $p = 0.029$ ).

**Table 6.** Between-Group Comparisons of Forehand and Backhand Performance

| Variables | Measurement | Control Group    |           | Experimental Group |           | $U$     | $p$   |
|-----------|-------------|------------------|-----------|--------------------|-----------|---------|-------|
|           |             | Mean $\pm$ SD    | Mean Rank | Mean $\pm$ SD      | Mean Rank |         |       |
| Forehand  | Pre-test    | 21.30 $\pm$ 7.21 | 23.37     | 21.04 $\pm$ 7.30   | 23.63     | 261.500 | .947  |
|           | Post-test   | 25.52 $\pm$ 4.87 | 26.17     | 24.17 $\pm$ 5.83   | 20.83     | 203.000 | .174  |
|           | $\Delta$    | 4.22 $\pm$ 5.39  | 25.24     | 3.13 $\pm$ 5.68    | 21.76     | 224.500 | .377  |
| Backhand  | Pre-test    | 23.13 $\pm$ 6.23 | 26.09     | 21.13 $\pm$ 5.65   | 20.91     | 205.000 | .190  |
|           | Post-test   | 26.65 $\pm$ 3.49 | 28.93     | 23.96 $\pm$ 4.19   | 18.07     | 139.500 | .006* |
|           | $\Delta$    | 3.52 $\pm$ 5.00  | 24.74     | 2.83 $\pm$ 5.18    | 22.26     | 236.000 | .529  |

\* $p < 0.05$ .

Upon examination of Table 6, no statistically significant difference was found between the control and experimental groups in terms of pre-test ( $p = 0.947$ ), post-test ( $p = 0.174$ ) and difference ( $\Delta$ ) values ( $p = 0.377$ ) for forehand performance. However, when backhand performance was examined, no statistically significant difference was found between the groups in terms of pre-test ( $p = 0.190$ ) and difference ( $\Delta$ ) values ( $p = 0.529$ ); conversely, a statistically significant difference was found in the post-test values ( $p = 0.006$ ).

## DISCUSSION

This study investigated the effects of a 6-week robot-assisted multi-ball training programme on muscle strength, vertical jump and sport-specific performance parameters in table tennis players. The findings indicated improvements over time in certain variables. However, no significant difference was observed between the groups in lower limb muscle strength or vertical jump performance.

Improvements in both forehand and backhand performance were observed in both groups from the pre-test to the post-test. Although a significant difference was identified in the post-test backhand values when comparing the groups, no significant difference was found between the groups in terms of the change values for forehand and backhand. These findings suggest that, over a 6-week period, both robot-assisted multi-ball training and traditional partner-based training may support sport-specific performance development.

At the end of the six-week training period, no significant differences were found between the groups in quadriceps, hamstring and triceps muscle strength. Whilst some improvements in biceps muscle strength were observed over time, this development was not assessed as an effect specific to the experimental group. In other words, robot-assisted multi-ball training may have contributed to the maintenance or limited development of muscle strength; however, the current findings do not indicate that this method produces a different pattern of strength development compared to traditional partner-based training. Table tennis is a sport involving high-repetition technical drills, short bursts of acceleration, sudden changes of direction and continuous stroke combinations. However, a significant portion of table tennis training is directed towards developing technical skills, coordination, movement speed and stroke quality rather than maximal strength development. It is therefore possible that the robot-assisted multi-ball training applied in this study did not provide a level of mechanical load sufficient to produce a significant increase in muscle strength. Whilst Suchomel et al. (2016) noted that maximal strength development is largely associated with high-resistance and progressive loads, Cormie et al. (2011) emphasised the importance of the intensity of the neuromuscular stimulus in strength and power development. Viewed from this perspective, the fact that the training programme implemented in the present study focused more on technical repetitions and sport-specific movement organisation may explain the limited changes

observed in muscle strength parameters. Recent evidence indicates that substantial improvements in maximal muscle strength are primarily achieved through resistance training programmes involving moderate-to-high external loads and progressive overload, whereas sport-specific technical training alone is generally insufficient to maximise strength adaptations (Lopez et al., 2020).

Findings regarding forehand and backhand performance indicated improvement from the pre-test to the post-test in both the experimental and control groups. However, upon examining the inter-group change values, it was not determined that robot-assisted multi-ball training produced a development that was significantly different from that of traditional partner-based training. This result suggests that both robot-assisted multi-ball training and traditional partner-based training may contribute to the development of technical performance in table tennis. Similarly, recent studies have reported that sport-specific movement training improves stroke quality and movement efficiency in table tennis players, although these improvements are not always accompanied by superior performance compared with conventional training approaches (Chen et al., 2025).

In table tennis, successful forehand and backhand performance depends not only on technical skill but also on the ability to anticipate the incoming ball, position the body effectively, and execute rapid and accurate movements. Recent evidence indicates that expert players perform these tasks more efficiently than less experienced players (Lin & Liu, 2025). In addition, footwork, shot-direction strategies, and efficient forehand–backhand transitions are important determinants of performance in elite players (Malagoli Lanzoni et al., 2014). Therefore, the improvements in forehand and backhand performance observed in the present study may be attributed not only to the high number of repetitions but also to improvements in technical execution, movement organisation, and positioning ability.

One of the key advantages of robot-assisted multi-ball training is that it enables athletes to perform a high number of standardised repetitions in a short period of time. This can contribute to the reinforcement of specific technical movements under controlled conditions. Whilst Apostu et al. (2018) noted that multi-ball drills are an effective method for developing technical skills, Gu et al. (2019) reported that such drills may have positive effects on dynamic postural control. Robotic systems standardise the ball's speed, direction and serving frequency, enabling athletes to repeat similar technical movements numerous times. This feature may offer particular advantages in the development of basic stroke techniques. Furthermore, recent research has demonstrated that combining robot-assisted practice with multiball training can improve reaction time while maintaining high training consistency, supporting its use as a supplementary method for technical development (Rachiwong & Ratanapanadda, 2025).

However, the present study cannot conclude that robot-assisted training leads to greater performance improvement compared to traditional partner-based training. This suggests that technical

performance in table tennis is not solely dependent on the number of repetitions. In traditional partner-based training, athletes must constantly adapt to the direction and speed of the ball, as well as their opponent's movements; thus, they are exposed to more variable and game-like stimuli. Schaefer and Scornaienchi (2020) reported that table tennis specialists exhibit more advanced cognitive-motor performance and that decision-making processes play a significant role in technical performance. Consequently, the game-like conditions provided by partner-based training may have partially offset the repetition advantage of robot-assisted multi-ball training.

Overall, the findings of the present study suggest that robot-assisted multi-ball training is a useful method for increasing the number of standardised technical repetitions and supporting the development of sport-specific skills in table tennis. However, over the 6-week intervention period, it did not produce superior improvements in muscle strength or technical performance compared with traditional partner-based training. These findings indicate that successful table tennis performance depends not only on repetitive technical practice but also on athletes' ability to adapt to changing game situations, anticipate the opponent's actions, position themselves effectively, and make rapid decisions (Malagoli Lanzoni et al., 2014). Therefore, robot-assisted multi-ball training should be regarded as a complementary training method that supports traditional partner-based practice rather than replacing it.

One limitation of the present study is that significant improvements in forehand and backhand performance were also observed in the control group. Although these improvements may reflect the effects of traditional partner-based training, they may also have been partially influenced by test–retest familiarisation or learning effects associated with repeated exposure to the performance tests (Hopkins, 2000). Therefore, the contribution of repeated testing to the observed performance improvements cannot be completely ruled out, and this should be considered when interpreting the findings. Future studies should consider incorporating additional familiarisation sessions before baseline testing to minimise potential learning effects.

In addition to the potential learning effect discussed above, several other limitations should be acknowledged. Firstly, the research was conducted with 46 table tennis players aged between 18 and 25; therefore, caution should be exercised when generalising the findings to different age groups and performance levels. Secondly, the intervention period was limited to six weeks, and no long-term follow-up measurements were taken. Thirdly, performance assessments were limited to isometric muscle strength, vertical jump and forehand–backhand performance tests. It is recommended that future studies utilise larger sample sizes, include different performance levels, employ longer intervention periods and utilise comprehensive test batteries incorporating in-match performance indicators.

## Conclusions and Recommendations

The results of the study showed improvements in certain performance parameters in both the experimental group, which underwent robot-assisted multi-ball training, and the control group, which continued with traditional partner-based training. No significant difference was found between the groups in lower limb muscle strength and vertical jump performance. Improvements were observed in both groups in terms of forehand and backhand performance; however, no significant difference was found between the groups in terms of the magnitude of these changes. In light of these results, it can be said that robot-assisted multi-ball training is an approach that can support the development of table tennis-specific technical skills. However, the current findings suggest that it may be more appropriate to consider this method as a complementary tool supporting the training process, rather than evaluating it independently of traditional partner-based training. It is anticipated that future studies involving different age groups, athletes at varying performance levels, and longer-term intervention programmes will contribute to a more comprehensive assessment of the effects of robot-assisted multi-ball training on physical and sport-specific performance.

## Ethics Committee Approval Information

**Ethics committee:** Karabük University Non-Interventional Clinical Research Ethics Committee

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