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Effects of a Neuromuscular Warm-Up on Y-Balance, Countermovement Jump Performance, and Stroke Velocity in Adolescent Table Tennis Players

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Abstract

Background/Objective: Adolescent table tennis players are exposed to substantial physical and psychological demands during a period of ongoing growth and development, placing high demands on movement control, explosive performance, and sport-specific stroke execution. This study investigated the effects of an 8-week neuromuscular warm-up on dynamic balance, countermovement jump (CMJ) performance, and stroke velocity in adolescent male table tennis players.

Methods: Thirty adolescent male table tennis players were randomly assigned to either a neuromuscular warm-up group or a control group performing a conventional warm-up before regular training sessions. The intervention lasted 8 weeks, with 2 sessions per week. Outcome measures included upper quarter Y-balance test composite score (YBT-UQ), lower quarter Y-balance test composite score (YBT-LQ), CMJ height, and forehand and backhand topspin stroke velocity, assessed before and after the intervention. Linear mixed-effects models were used to examine the effects of group, time, and group × time interaction for each outcome.

Results: Linear mixed-effects models revealed significant group × time interactions for YBT-UQ ($p < 0.001$, $\eta p^2 = 0.32$), YBT-LQ ($p = 0.003$, $\eta p^2 = 0.25$), CMJ height ($p < 0.001$, $\eta p^2 = 0.54$), forehand topspin velocity ($p = 0.001$, $\eta p^2 = 0.30$), and backhand topspin velocity ($p < 0.001$, $\eta p^2 = 0.35$). Significant pre-to-post improvements were observed in the neuromuscular warm-up group, whereas no significant changes were found in the control group.

Conclusion: These findings suggest that neuromuscular warm-up may be an effective strategy to enhance dynamic balance, jumping performance, and stroke velocity in adolescent male table tennis players.

Keywords: adolescent athletes, countermovement jump, dynamic balance, neuromuscular warm-up, stroke velocity, table tennis

Introduction

Table tennis is a physically and mentally demanding sport that requires explosive power, speed, accuracy, dynamic balance, and rapid decision-making to execute rapid rallies, repeated high-intensity strokes, frequent changes in direction, and continuous postural adjustments [1,2]. The match structure alternates brief high-intensity rallies (averaging 3.4 seconds) with rest periods (averaging 8.1 seconds), resulting in a low work-to-rest ratio of 0.4 [3]. Consequently, players must execute up to 35.3 rapid strokes per minute to meet the sport's fast-paced demands [3]. These repeated explosive and technically complex actions require effective coordination between the lower limbs, trunk, and upper extremities, as force must be generated, transferred through the kinetic chain, and expressed through rapid racket movement. Therefore, physical qualities such as dynamic balance, lower-limb explosive power, and stroke velocity are highly relevant to table tennis performance.

These demands may be particularly challenging for adolescent table tennis players. Adolescents represent a high-risk population for sports-related injuries [4]. Their susceptibility to serious injuries such as anterior cruciate ligament tears and meniscal injuries is significantly higher compared to children. This elevated risk stems from multiple factors: firstly, adolescents' developing skeletons contain growth cartilage at three key sites (epiphyseal plates, joint surfaces, and apophyses [5]), creating structural vulnerability; secondly, increasing competitive levels and weekly training volumes expose them to greater training loads and competition intensity, further amplifying injury risk [6,7]. For adolescent athletes whose technical skills and physical conditioning are still developing and whose movement patterns remain unstable, the significant psychological and physiological requirements of table tennis may increase their injury risk [8].

Warm-up is widely recognized as an important component of both injury prevention and performance preparation [11,12]. Appropriately designed warm-up strategies can enhance subsequent exercise performance through temperature-related mechanisms, including increased muscle temperature, blood flow, and oxygen delivery, as well as non-temperature-related mechanisms such as increased neural activation, improved motor unit recruitment, and enhanced cardiovascular readiness [9]. Compared with passive warm-up methods, active warm-up protocols generally produce greater improvements in subsequent performance[10]. This is particularly relevant in sports such as table tennis, where athletes must rapidly transition from preparatory movements to explosive, accurate, and coordinated sport-specific actions. In addition, because a large proportion of musculoskeletal injuries occur during routine training sessions, implementing effective warm-up strategies in daily practice may also contribute to safer long-term athletic development [11].

Among active warm-up strategies, neuromuscular warm-up programs have attracted increasing attention because they typically integrate multiple exercise components, including dynamic stability, strength, core training, plyometrics, agility, and movement-control exercises [12]. Neuromuscular warm-up programs have been shown to reduce injury risk and improve neuromuscular control, movement quality, and physical performance in youth athletes [13–15]. From a performance perspective, these programs may be especially valuable because they target several capacities that are directly relevant to table tennis, including postural control, lower-limb force production, trunk stability, and coordinated upper-limb movement. For example, improved dynamic balance may support more stable positioning during rapid lateral movements and stroke preparation, while enhanced explosive power may contribute to faster repositioning and more effective force generation.

Despite growing evidence supporting neuromuscular warm-up interventions in youth sport, several important gaps remain. First, previous studies have rarely focused on adolescent table tennis players, even though this population is exposed to substantial physical, technical, and psychological demands [8]. Second, much of the existing literature has emphasized injury incidence, whereas evidence regarding performance-related outcomes remains limited and, in some cases, inconsistent. For instance, findings on the effects of neuromuscular warm-up on dynamic balance are contradictory [16,17]. Third, sport-specific performance indicators that are directly relevant to table tennis, such as forehand and backhand topspin stroke velocity, have received limited attention. As a result, it is not yet clear whether neuromuscular warm-up can serve not only as an injury prevention strategy but also as an effective supplement to conventional warm-up routines in adolescent table tennis athletes.

Therefore, the aim of this study was to investigate the effects of an eight-week neuromuscular warm-up intervention on Y-balance test (YBT) performance, countermovement jump (CMJ) height, and stroke velocity in adolescent table tennis athletes. By examining both physical and sport-specific performance outcomes, this study seeks to provide evidence that may inform injury prevention practice and performance enhancement strategies for adolescent table tennis athletes.

Materials and Methods

Study Design

This study employed a between-participants randomized experimental design, matched for age and maturity status before allocation. The reporting of this study was guided by the CONSORT recommendations where applicable to improve methodological transparency. Following baseline assessments, participants were randomly allocated to either an experimental group performing a neuromuscular warm-up or an active control group performing a conventional warm-up. All warm-ups were conducted prior to regular table tennis-specific training sessions. Physical fitness tests were administered during the weeks immediately before and after the eight-week intervention. Pre- and post-intervention assessments evaluated upper and lower quarter YBT, CMJ height, and forehand/backhand topspin stroke velocity. Testing sessions were conducted at similar times of day in the same indoor sports hall to minimize circadian and environmental influence. Pre- and post-intervention assessments were conducted under comparable indoor testing conditions and at similar times of day for each participant. To control for confounding variables, participants were instructed to maintain their habitual lifestyle and dietary intake, refrain from exercise the day before testing, and avoid caffeine for at least 24 hours prior to testing.

Sample size estimation and justification

An a priori sample size estimation was performed using G*Power (version 3.1.9.6) for a repeated-measures ANOVA within-between interaction. The calculation was based on a two-group, two-measurement design, with the effect size informed by pilot observations ($f = 0.30$), $\alpha = 0.05$, statistical power of 0.80, a correlation among repeated measures of 0.50, and a nonsphericity correction of $\varepsilon = 1$. The analysis indicated that a minimum total sample of 24 participants was required. To account for a potential dropout rate of up to 20%, at least 30 participants were targeted for recruitment. This target sample size was also comparable to that used in a previous study [18].

Participants

Thirty adolescent male table tennis players were recruited from the junior training program of the China Table Tennis College. They were classified as Highly Trained/National Level (Tier 3) according to the Participant Classification Framework [24,25]. Participants were randomly allocated to either the experimental group or the control group using a computer-generated randomization sequence created in Microsoft Excel. The randomization sequence was generated by a researcher not involved in testing. The experimental group included 15 participants (age 13.93 ± 1.91 years, body mass 54.83 ± 13.00 kg, height 166.00 ± 11.06 cm, estimated age at peak height velocity [PHV] 13.83 ± 0.79 years, maturity offset 0.11 ± 1.32 years), and the control group included 15 participants (age 13.33 ± 1.72 years, body mass 50.56 ± 10.90 kg, height 164.07 ± 8.69 cm, estimated age at PHV 13.85 ± 0.81 years, maturity offset −0.52 ± 0.98 years). Inclusion criteria were: (i) no contraindications to exercise participation and (ii) age between 10 and 19 years. Exclusion criteria included cardiometabolic disease, neuromuscular or musculoskeletal disorders, and the use of medication that could influence the study outcomes. Written informed consent was obtained from all participants and their parents or legal guardians. The study was approved by the local institutional ethics committee (Approval No. 102772025RT103) and was conducted in accordance with the Declaration of Helsinki. The overall study flow is shown in Figure 1.

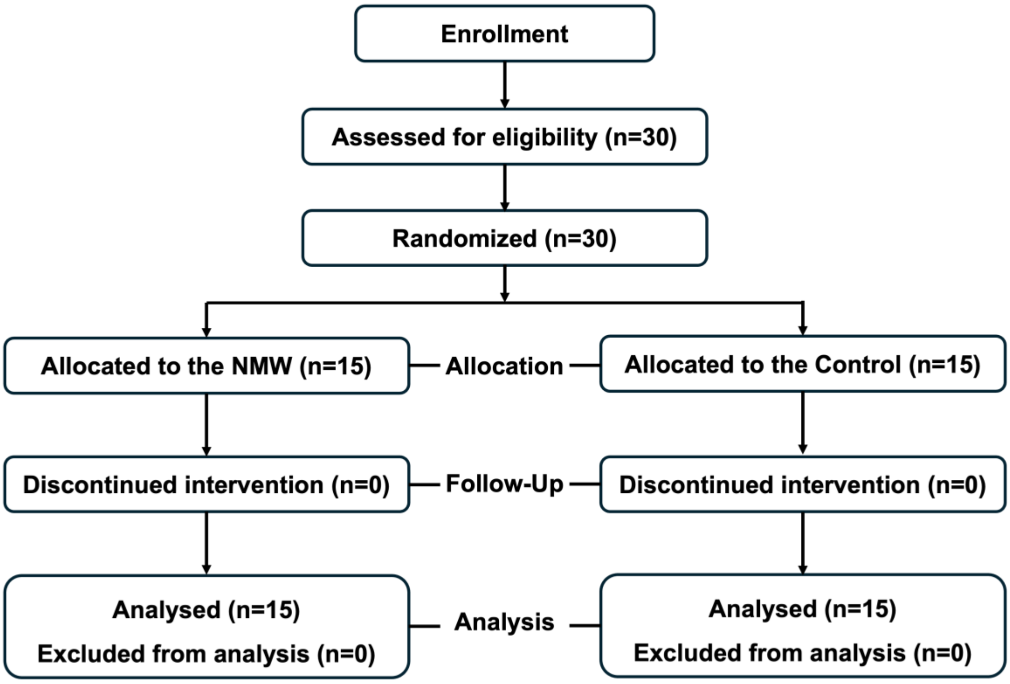

Figure 1. Experimental Flowchart

Abbreviation: NMW: neuromuscular warm-up

Maturity Status

Height was measured using a metal stadiometer with a minimum graduation of 1 mm, used in conjunction with a movable horizontal headboard. Seated height was measured using the same stadiometer, combined with an adjustable sitting stool to ensure the subject's thighs were parallel to the ground and feet were flat. All measurements were performed by uniformly trained assessors following standard anthropometric postures. Three measurements were taken for each parameter and averaged to minimize error. Leg length was calculated as standing height minus sitting height. The timing of puberty was estimated for each individual based on biological maturity using the prediction equation described by Mirwald et al. [19].

Maturity offset = −9.236 + 0.0002708 × (leg length × sitting height) − 0.001663 × (chronological age × leg length) + 0.007216 × (chronological age × sitting height) + 0.02292 × (body mass / standing height × 100).

In this equation, maturity offset represents the estimated number of years from PHV. Estimated age at PHV was calculated as chronological age minus maturity offset [20]. Consequently, a maturity offset of -1.0 indicates the athlete was measured one year before PHV; 0 indicates measurement at PHV; and +1.0 indicates measurement one year after PHV [20].

Experimental Protocol

One week before baseline data collection, all participants completed a familiarization session in which they were introduced to both the outcome assessments and the neuromuscular warm-up exercises. During this session, participants received standardized verbal instructions and demonstrations for the upper quarter Y-balance test (YBT-UQ), lower quarter Y-balance test (YBT-LQ), CMJ, and stroke velocity assessments, and they were allowed to practice each task to ensure that they understood the testing requirements. Participants were also familiarized with the neuromuscular warm-up exercises, and movement corrections were provided by the researchers.

Upon arrival at the testing venue for formal assessment, all participants underwent body composition assessment, followed by a standardized 15-minute warm-up. This warm-up consisted of 10 minutes of jogging, 2 repetitions of the "World's Greatest Stretch," 2 repetitions of shoulder and back stretches, and 10 slow bodyweight squats. After completing the standardized warm-up, a 3-minute rest period was provided. Subsequently, YBT-UQ, YBT-LQ, CMJ testing, and stroke velocity assessments were conducted in a fixed order. This order was selected to progress from lower-fatigue balance tasks to higher-intensity explosive and sport-specific maximal-effort tasks, thereby minimizing the potential influence of fatigue on subsequent assessments. The same testing order was maintained for all participants at both pre- and post-intervention assessments to reduce order effects and improve within-participant consistency. A 3-minute rest interval was provided between tests to reduce residual fatigue and allow adequate recovery before subsequent assessments, particularly before maximal-effort tasks such as CMJ and stroke velocity testing [21]. After a one-week washout period, the eight weeks training intervention commenced, consisting of two sessions per week, with at least 24 hours between consecutive sessions.

Participants performed the YBT for the upper quarter (YBT-UQ) and lower quarter (YBT-LQ) following a standardized protocol. Hand dominance was determined as the participant's preferred racket hand, and leg dominance was determined as the self-reported preferred kicking leg. The testing sequence was fixed and began with the right side rather than being determined by dominance. The same side order was maintained for all participants at both pre- and post-intervention assessments to reduce order effects and improve within-participant consistency. All tests were conducted barefoot after participants watched an instructional video. Two independent, blinded testers observed and scored all trials simultaneously.

YBT-UQ: Starting in a push-up position with one hand on the center platform, participants used the contralateral hand to push a reach indicator as far as possible in three directions (medial, inferolateral, superolateral). An attempt was deemed invalid if the participant: lost single-hand contact on the platform, lost continuous contact with the indicator, used the indicator for support, failed to return to the starting position under control, or lifted either foot. After one practice trial per side, three successful trials per direction per hand were recorded. The test sequence was fixed, beginning with the right stance hand. Reach distances were measured to the nearest 0.5 cm and normalized to upper limb length (measured from C7 to the tip of the middle finger with the arm abducted to 90°). The composite score was calculated as the average of the three normalized reach distances for each limb [22].

YBT-LQ: Standing on one leg on the center footplate, participants pushed the indicator with the free foot in three directions (anterior, posteromedial, posterolateral). Valid trials required the stance heel to maintain contact, hands to remain on hips, and a controlled return to the start. After two practice trials, three formal trials per direction per leg were collected. Reach distance was recorded to the nearest 0.5 cm and normalized to leg length (measured from the anterior superior iliac spine to the medial malleolus)[23]. The composite score was calculated using the formula: (Sum of the mean reach distances in all three directions for both legs) / (3 * Leg Length) * 100% [22].

During the CMJ test, participants performed a rapid descent until the thighs were approximately parallel to the ground, followed immediately by an explosive vertical jump [24]. Descent depth and velocity were self-selected and not externally controlled. Throughout the movement, hands remained on the hips, with arm swing prohibited. Participants were instructed to maintain full leg extension during the airborne phase, and any 'kipping' or flexion at the hips or knees to gain momentum was not permitted. The average of 3 trials was used for data analysis [25]. Jump height was measured using the smartphone application MyJump2, which has been demonstrated to be a valid and reliable tool for measuring CMJ height [26,27].

The stroke velocity test primarily measured ball velocity. Tests used D40+ 3-star seamless table tennis balls (D40+, Double Happiness Sports Co., Shanghai, China). Ball velocity was captured using a Pongbert Hawkeye system (SEEKER, Shanghai, China) mounted directly above the left side of the table. Balls were fed by a Pongbert ball machine (M-ONE, Shanghai, China) positioned outside the top right corner of the table. Each participant completed 5 forehand topspin and 5 backhand topspin stroke tests, instructed to hit the ball with maximum quality towards the smallest target area (50*50 cm) [28]. The average velocity from the five trials for each stroke type was used for analysis. All testing concluded with a 5-minute stretching session.

Measurement Reliability and Familiarization

All outcome measures were administered by trained assessors using standardized procedures, instructions, and demonstrations. Participants completed a familiarization session before baseline data collection, and task-specific practice trials were also provided before the recorded YBT assessments. Three successful trials were recorded for the YBT and CMJ assessments, and five trials were recorded for forehand and backhand topspin stroke velocity. The mean value of the recorded trials was used for statistical analysis to reduce random measurement error. The selected tests and devices have demonstrated acceptable reliability and validity in previous studies, and the stroke velocity protocol was adapted from previous table tennis research using standardized ball-feeding and target-hitting procedures.

Neuromuscular Warm-up

The neuromuscular warm-up protocol consisted of five training modules. This protocol served as a substitute for the conventional warm-up training and took approximately 20-25 minutes to complete. All 11 exercises in the protocol focused on four key training elements: core stability, neuromuscular control, eccentric strength, and agility (details in Table 1).

Table 1. Neuromuscular Warm-up Protocol

Warm-up Module	Exercise	Repetitions	Sets
Warm-up	1. Jogging + Shoulder Circles (Forward/Backward)	12 reps	1 set
	2. Jogging + Alternate Arm Lifts with Vibration	10 reps each arm	1 set
	3. Lateral Shuffling	10 reps each side	1 set
Core Activation	1. Standard Plank	25 seconds	2 sets
	2. Side Plank (Left/Right)	25 seconds/side	2 sets
	3. YTW Exercise	6 reps	2 sets
Plyometrics	1. Countermovement Jumps	8 reps	2 sets
	2. Multi-Directional Jumps	8 reps	2 sets
Strength	1. Forward Walking Lunges	4-6 reps/side	2 sets
	2. Lateral Lunges	4-6 reps/side	2 sets
Agility & Change of Direction	Acceleration-Deceleration-Reacceleration	6 reps/set	2 sets

Statistical Analysis

Descriptive statistics are presented as mean ± standard deviation (SD). Normality of baseline distributions and homogeneity of variances were assessed using the Shapiro–Wilk test and Levene's test, respectively. For baseline between-group comparisons, Welch's independent-samples t tests were used for normally distributed variables, whereas the Mann–Whitney U test was used when the assumption of normality was not met [29]. Baseline comparisons were performed for participant characteristics, biological maturity indicators, and all outcome variables.

To evaluate intervention effects, linear mixed-effects models were fitted separately for each outcome variable, including upper and lower quarter Y-balance test composite scores, countermovement jump height, and forehand and backhand topspin stroke velocities. In each model, group (neuromuscular warm-up vs. control), time (pre vs. post), and their interaction (group × time) were included as fixed effects, while participant was included as a random intercept to account for within-subject dependence arising from repeated measurements. A random-intercept model was selected because each participant contributed two repeated observations per outcome, allowing individual baseline differences to be modeled while avoiding overparameterization. Random-slope models including time as a participant-level random slope were explored; however, these models failed to converge because the random-effects structure was not identifiable given the two-time-point design. Therefore, the more parsimonious random-intercept model was retained. Fixed effects were evaluated using Type III analysis of variance with the Satterthwaite approximation for degrees of freedom and p values. Model assumptions were assessed by visual inspection of residual-versus-fitted plots and Q-Q plots of residuals. Standardized residuals were examined to identify potential outliers, and fitted models were checked for convergence or singularity issues. When a significant group × time interaction was observed, post hoc pairwise comparisons were performed using estimated marginal means with Tukey adjustment. Tukey adjustment was applied within each outcome variable for the relevant post hoc pairwise comparisons, rather than as a global adjustment across all outcome variables. Estimated marginal mean comparisons were reported with 95% confidence intervals where appropriate.

Effect sizes for fixed effects were expressed as partial eta squared (ηp^2), estimated from the corresponding F statistics and degrees of freedom, and interpreted as trivial (<0.01), small (0.01–0.059), moderate (0.06–0.139), and large (≥0.14). Within-group pre-to-post effect sizes were calculated using Hedges' g, reported with 95% confidence intervals, and interpreted as trivial (<0.20), small (0.20–0.59), moderate (0.60–1.19), large (1.20–1.99), and very large (≥2.00) [30]. Percentage changes were calculated as $\%\Delta = 100 \times (\text{post} - \text{pre}) / \text{pre}$ and are presented descriptively to aid interpretation; statistical inference for intervention effects was based primarily on the linear mixed-effects models.

An exploratory individual response analysis was performed using the smallest worthwhile change (SWC), calculated as 0.2 × the control group baseline SD for each outcome. Participants were classified as positive responders if their pre-to-post change exceeded the SWC, non-responders if their change was within ±SWC, and negative responders if their change was below −SWC. The proportion of participants in each response category was summarized by group and outcome.

Statistical significance was set at $p < 0.05$. All analyses were performed in R (version 4.5.2). The main packages used were readxl for data import; dplyr, tidyr, stringr, and purrr for data processing; lme4 and lmerTest for linear mixed-effects models; car for Levene's tests and Type III analyses; emmeans for estimated marginal means and post hoc comparisons; effectsize for effect size estimation; and ggplot2 for visualization.

Results

All participants completed the assigned intervention and were included in the final analysis. Baseline between-group comparisons showed no significant differences in participant characteristics or biological maturity indicators reported in the Participants section, and no significant differences were observed for any outcome variable at baseline (all $p > 0.05$; Table 2).

Table 2. Descriptive statistics for all outcome measures (mean ± SD)

Outcome	Control Pre	Control Post	NMW Pre	NMW Post	Baseline p value
YBT-UQ	0.98 ± 0.12	0.99 ± 0.11	0.92 ± 0.06	1.04 ± 0.10	$p > 0.05$
YBT-LQ	1.07 ± 0.15	1.06 ± 0.14	1.02 ± 0.07	1.08 ± 0.11	$p > 0.05$
CMJ	29.75 ± 7.07	29.14 ± 6.06	32.69 ± 6.48	37.11 ± 7.66	$p > 0.05$
Forehand topspin velocity	13.01 ± 1.58	13.16 ± 1.26	12.83 ± 1.03	14.67 ± 1.74	$p > 0.05$
Backhand topspin velocity	11.89 ± 1.45	12.05 ± 1.65	11.48 ± 1.63	14.00 ± 2.42	$p > 0.05$

Note. Values are presented as mean ± standard deviation. NMW = neuromuscular warm-up; YBT-UQ = upper quarter Y-balance test composite score; YBT-LQ = lower quarter Y-balance test composite score; CMJ = countermovement jump.

Linear mixed-effects model analyses revealed significant group × time interactions for YBT-UQ, YBT-LQ, CMJ, forehand topspin velocity, and backhand topspin velocity (all $p < 0.01$; Figure 2), indicating that the magnitude of improvement over time differed between the neuromuscular warm-up and control groups across all outcome measures. All group × time interaction effects were interpreted as large based on partial eta squared values. Specifically, significant group × time interactions were observed for YBT-UQ ($F = 13.98$, $p < 0.001$, $\eta_p^2 = 0.32$), YBT-LQ ($F = 10.09$, $p = 0.003$, $\eta_p^2 = 0.25$), CMJ ($F = 35.49$, $p < 0.001$, $\eta_p^2 = 0.54$), forehand topspin velocity ($F = 12.59$, $p = 0.001$, $\eta_p^2 = 0.30$), and backhand topspin velocity ($F = 15.95$, $p < 0.001$, $\eta_p^2 = 0.35$). Post hoc comparisons were conducted using estimated marginal means with Tukey adjustment within each outcome variable.

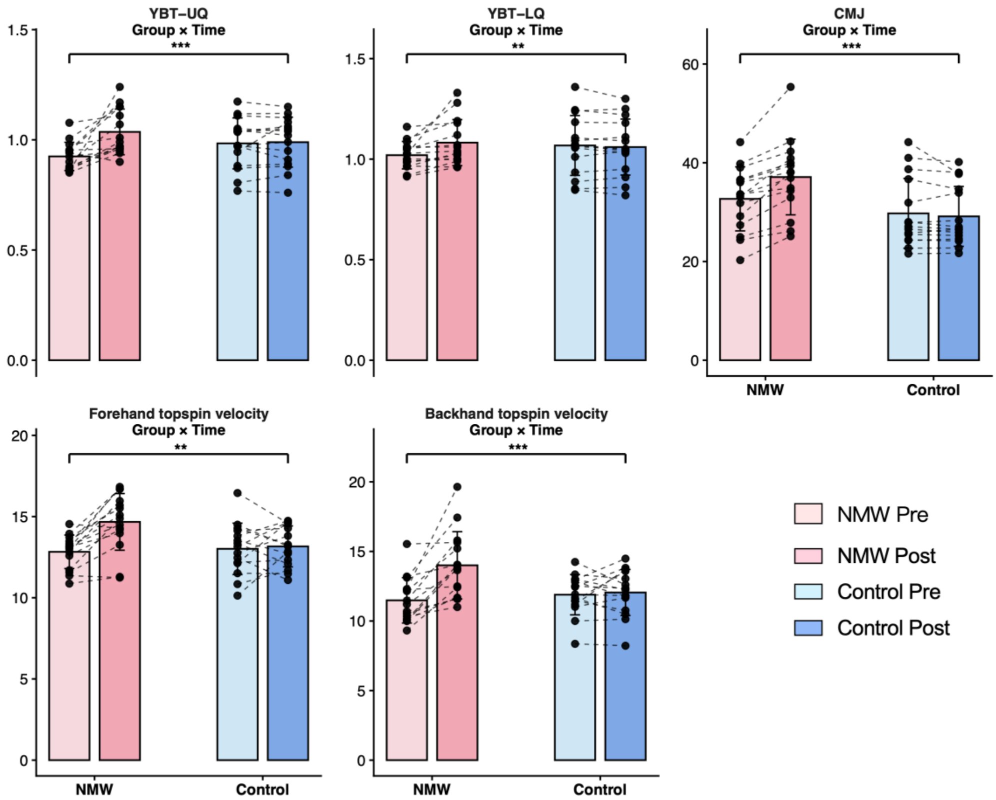

Figure 2. Changes in performance outcomes before and after the intervention in the neuromuscular warm-up (NMW) and control groups.

Note: This figure illustrates pre- to post-intervention changes in performance outcomes in the two groups, including upper quarter Y-balance test composite score (YBT-UQ), lower quarter Y-balance test composite score (YBT-LQ), countermovement jump height (CMJ), forehand topspin velocity, and backhand topspin velocity. Bars represent group means at pre- and post-intervention, and error bars indicate standard deviations. Dots represent individual participant values, and dashed lines indicate within-subject changes from pre- to post-intervention. Asterisks above brackets indicate significant group × time interactions (*p < 0.05, **p < 0.01, ***p < 0.001). Significant group × time interactions were observed for YBT-UQ, YBT-LQ, CMJ, forehand topspin velocity, and backhand topspin velocity.

Countermovement Jump

For CMJ, a significant group × time interaction was observed ($F = 35.49$, $p < 0.001$, $\eta p^2 = 0.54$, large). Post hoc comparisons based on estimated marginal means showed that CMJ significantly increased in the neuromuscular warm-up group ($p < 0.001$), whereas no significant change was found in the control group ($p = 0.33$). The corresponding within-group effect sizes were small in the neuromuscular warm-up group (Hedges' g = 0.54, 95% CI: 0.35 to 0.73) and trivial in the control group (Hedges' g = −0.07, 95% CI: −0.19 to 0.04) (Figure 3). No between-group difference was found at baseline ($p = 0.25$), whereas the neuromuscular warm-up group showed significantly greater CMJ than the control group at post-test ($p = 0.003$). Percentage changes were interpreted descriptively and were 13.80 ± 8.42% in the neuromuscular warm-up group and −1.43 ± 4.61% in the control group.

Upper Quarter Composite Balance Score

For YBT-UQ, the group × time interaction was significant ($F = 13.98$, $p < 0.001$, $\eta p^2 = 0.32$, large). Post hoc comparisons based on estimated marginal means showed that the neuromuscular warm-up group significantly improved from pre- to post-intervention ($p < 0.001$), whereas the control group showed no significant change ($p = 0.80$). The corresponding within-group effect sizes were moderate in the neuromuscular warm-up group (Hedges' g = 1.19, 95% CI: 0.43 to 1.96) and trivial in the control group (Hedges' g = 0.04, 95% CI: −0.13 to 0.22) (Figure 3). No significant between-group differences were detected at either baseline ($p = 0.12$) or post-test ($p = 0.21$). Percentage changes were interpreted descriptively and were 12.31 ± 11.93% in the neuromuscular warm-up group and 0.66 ± 4.51% in the control group.

Lower Quarter Composite Balance Score

For YBT-LQ, the group × time interaction was significant ($F = 10.09$, $p = 0.003$, $\eta p^2 = 0.25$, large). Post hoc comparisons based on estimated marginal means showed that the neuromuscular warm-up group significantly improved from pre- to post-intervention ($p < 0.001$), whereas the control group showed no significant change ($p = 0.63$). The corresponding within-group effect sizes were small in the neuromuscular warm-up group (Hedges' g = 0.56, 95% CI: 0.14 to 0.97) and trivial in the control group

(Hedges' g = −0.05, 95% CI: −0.12 to 0.03) (Figure 3). No significant between-group differences were detected at either baseline (p = 0.29) or post-test (p = 0.62). Percentage changes were interpreted descriptively and were 6.06 ± 8.18% in the neuromuscular warm-up group and −0.61 ± 2.25% in the control group.

Forehand Topspin Velocity

For forehand topspin velocity, a significant group × time interaction was found (F = 12.59, p = 0.001, ηp^2 = 0.30, large). Post hoc comparisons based on estimated marginal means showed that the neuromuscular warm-up group significantly improved after the intervention (p < 0.001), whereas the control group did not (p = 0.67). The corresponding within-group effect sizes were moderate in the neuromuscular warm-up group (Hedges' g = 1.07, 95% CI: 0.60 to 1.55) and trivial in the control group (Hedges' g = 0.10, 95% CI: −0.38 to 0.57) (Figure 3). No baseline between-group difference was observed (p = 0.73), but the neuromuscular warm-up group demonstrated significantly greater forehand topspin velocity than the control group at post-test (p = 0.006). Percentage changes were interpreted descriptively and were 14.32 ± 9.78% in the neuromuscular warm-up group and 2.02 ± 11.69% in the control group.

Backhand Topspin Velocity

For backhand topspin velocity, the group × time interaction was also significant (F = 15.95, p < 0.001, ηp^2 = 0.35, large). Post hoc comparisons based on estimated marginal means showed that the neuromuscular warm-up group showed a significant increase from pre- to post-intervention (p < 0.001), whereas the control group showed no significant change (p = 0.72). The corresponding within-group effect sizes were moderate in the neuromuscular warm-up group (Hedges' g = 1.10, 95% CI: 0.52 to 1.68) and trivial in the control group (Hedges' g = 0.10, 95% CI: −0.28 to 0.47) (Figure 3). No between-group difference was found at baseline (p = 0.55), whereas the neuromuscular warm-up group was significantly higher than the control group at post-test (p = 0.005). Percentage changes were interpreted descriptively and were 22.50 ± 17.28% in the neuromuscular warm-up group and 1.60 ± 10.35% in the control group.

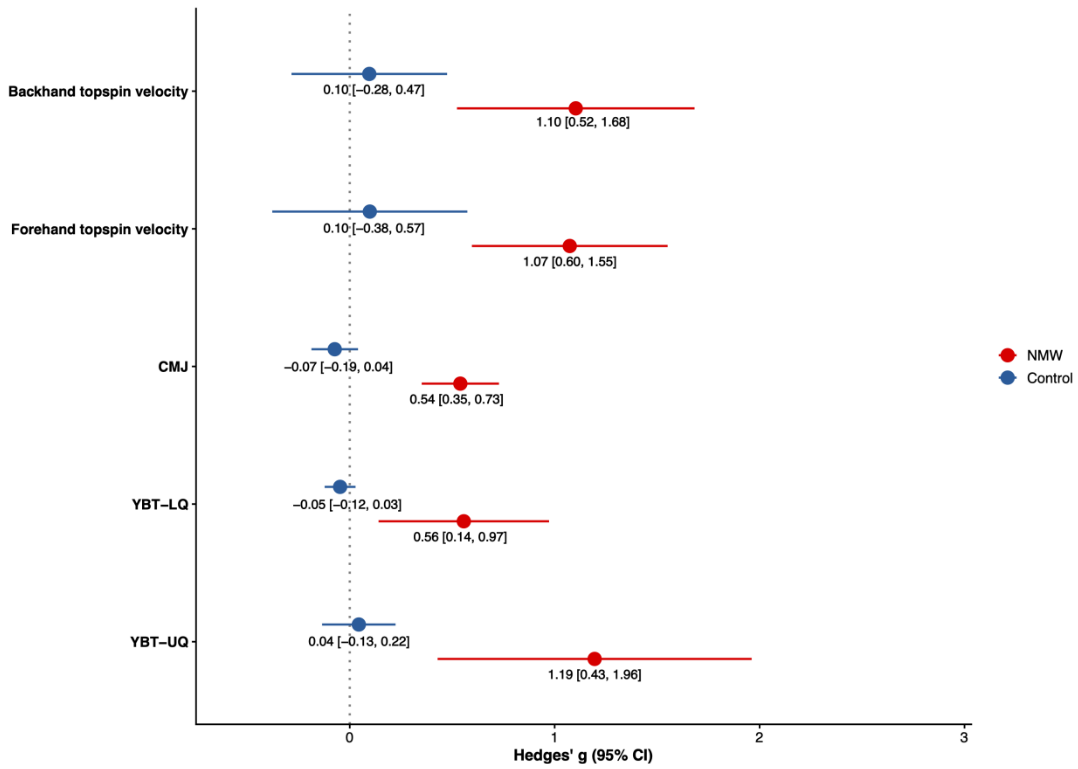

Figure 3. Forest plot of within-group effect sizes for performance outcomes in the neuromuscular warm-up (NMW) and control groups.

Note: This figure presents within-group effect sizes for performance outcomes before and after the intervention, including upper quarter Y-balance test composite score (YBT-UQ), lower quarter Y-balance test composite score (YBT-LQ), countermovement jump height (CMJ), forehand topspin velocity, and backhand topspin velocity. Dots indicate Hedges' g estimates, and horizontal lines represent the corresponding 95% confidence intervals (95% CI). The vertical dashed line indicates the null effect reference line (Hedges' g = 0). According to the predefined thresholds, the NMW group showed moderate effects for YBT-UQ, forehand topspin velocity, and backhand topspin velocity, and small effects for YBT-LQ and CMJ, whereas the control group showed trivial effects across all outcomes.

Exploratory individual response analysis based on the smallest worthwhile change showed that a greater proportion of participants in the neuromuscular warm-up group were classified as positive responders across all outcomes (Figure 4). In the neuromuscular warm-up group, positive responder proportions were 86.7% for YBT-UQ, 53.3% for YBT-LQ, 93.3% for CMJ, 86.7% for forehand topspin velocity, and 86.7% for backhand topspin velocity. In the control group, the corresponding positive responder proportions were 13.3%, 0.0%, 6.7%, 40.0%, and 33.3%, respectively.

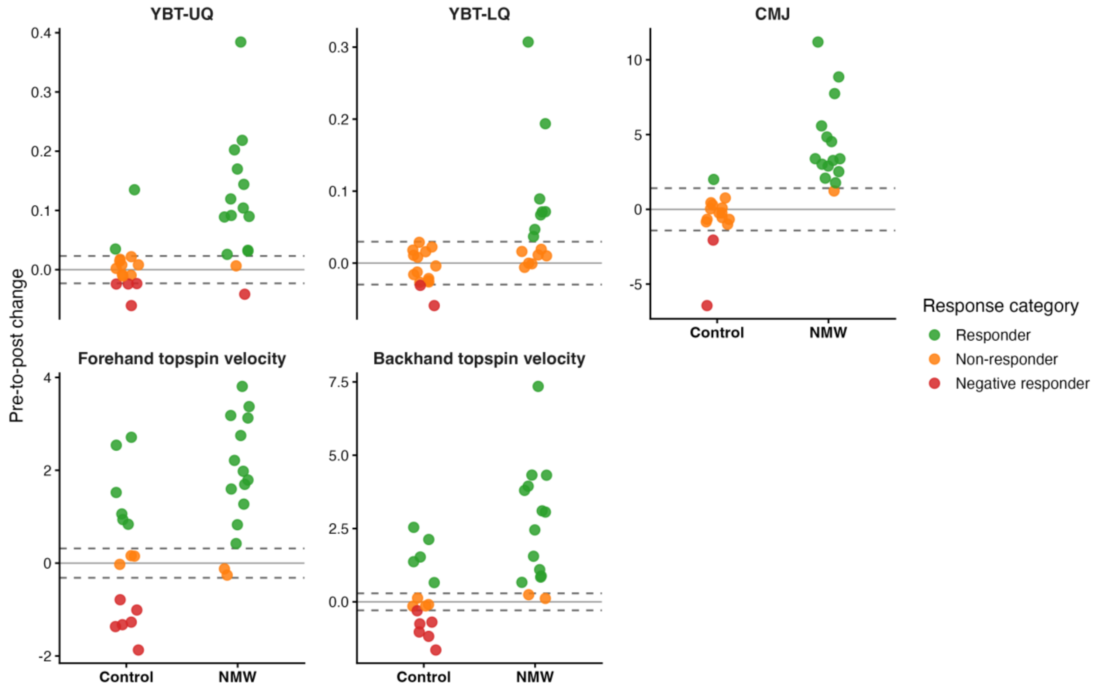

Figure 4. Individual response analysis based on the SWC.

Note: Dots represent individual pre-to-post changes for each outcome. The solid horizontal line indicates no change, and the dashed horizontal lines indicate the positive and negative SWC thresholds. The SWC was calculated as 0.2 × the between-subject SD of the control group at baseline for each outcome. Participants were classified as responders, non-responders, or negative responders according to whether their pre-to-post change exceeded +SWC, remained within ±SWC, or was below −SWC, respectively. NMW = neuromuscular warm-up; YBT-UQ = upper quarter Y-balance test composite score; YBT-LQ = lower quarter Y-balance test composite score; CMJ = countermovement jump.

Discussion

This study aimed to investigate the effects of a neuromuscular warm-up intervention on balance capacity (including both lower and upper quarter composite balance), CMJ performance, and table tennis stroke velocity (forehand and backhand topspin velocity) in adolescent male table tennis players. Our results demonstrated that, compared to a conventional warm-up, an eight-week neuromuscular warm-up significantly improved the athletes' YBT-UQ, YBT-LQ, CMJ height, and stroke velocity.

Balance refers to the ability to maintain the body's center of gravity vertically within the base of support and to perform smooth, coordinated neuromuscular actions, relying on rapid, continuous feedback from the visual, vestibular, and proprioceptive systems [31]. Improving balance capacity is crucial for optimizing sports performance [32], as it helps athletes maintain stability, control body position, and coordinate movement during rapid sport-specific actions [33,34]. The YBT, a standardized version of the Star Excursion Balance Test, includes protocols for both the upper and lower quarters [35,36]. The YBT-UQ primarily assesses upper quarter dynamic stability and proprioceptive function [35]. Our finding of a significant improvement in the YBT-UQ composite score following an eight-week neuromuscular warm-up may reflect improved upper-quarter dynamic stability and movement-control capacity [37]. This improvement can likely be attributed to the neuromuscular warm-up, which enhances nerve conduction velocity, improves muscle contraction, refines sensory feedback, and consequently improves dynamic joint stability, optimizes movement patterns and skills, enhances neuromuscular control, and increases strength [38–40]. Schwiertz et al. [41] provided empirical support for the functional relevance of upper-quarter balance, reporting that youth athletes demonstrated significantly better YBT-UQ performance compared to untrained controls, with large effect sizes (Cohen's $d = 0.88–1.48$) and an area under the curve (AUC) of ≥71% for discriminating between the groups [41]. This indicates that superior performance in this metric is associated with a higher level of athletic training and proficiency, suggesting that the improvements observed in our study may contribute directly to enhanced athletic performance capacity in adolescent table tennis players. In addition to YBT-UQ, the present study also demonstrated a significant group × time interaction for YBT-LQ, indicating that the neuromuscular warm-up produced greater improvements in lower-quarter dynamic balance than the conventional warm-up. The neuromuscular warm-up group showed a significant pre-to-post improvement in YBT-LQ, whereas the control group did not. This finding suggests that the intervention enhanced lower-limb dynamic stability and postural control, which may be attributable to the balance, strength, and movement-coordination components incorporated into the neuromuscular warm-up. Because lower-quarter balance is closely related to lower-extremity control during sport-specific movement, improved YBT-LQ performance may also be relevant to both performance enhancement and injury-risk management in adolescent table tennis players. According to relevant research, each 1-point increase in the YBT composite score is associated with a 6% reduction in injury probability [$OR = 0.94$, 95% CI: 0.88–0.99, $p = 0.047$] [42]. Furthermore, combining YBT scores, competition frequency, and physical activity time might provide a more comprehensive assessment of lower limb injury risk than a single metric alone [42].

CMJ performance is an important tool for talent identification [43], fatigue monitoring [44,45], and sports performance prediction [46] in specific sports. Our study found a significant improvement in CMJ height after eight weeks of neuromuscular warm-up. This improvement may stem from the plyometric and strength components integrated into the neuromuscular warm-up, which may have enhanced lower-limb force-production capacity and neuromuscular readiness. This heightened neuromuscular and strength capacity may, in turn, promote increased torque production at the hip joint [47]. Consequently, the efficiency of power transfer through the kinetic chain could be optimized [48]. It is noteworthy that the hip joint is highly involved during table tennis strokes, and the axial rotation torque of the stance-side hip pelvis plays a crucial role in achieving high racket horizontal velocity at impact [49]. Therefore, the improvement in jumping ability may also indirectly contribute to stroke performance.

We found significant improvements in both forehand and backhand topspin velocities after the eight-week neuromuscular warm-up. The forehand topspin is considered the most common stroke in table tennis [50] and is executed in a proximal-to-distal sequence, involving multiple muscles working in different phases within a coordinated kinetic chain [51]. The significant increase in forehand topspin velocity following the intervention may be partly explained by improved coordination and efficiency of the kinetic chain after the neuromuscular warm-up. Such warm-ups may enhance dynamic activation and stretch-shortening cycle function, thereby supporting more coordinated force transfer from the lower limbs and trunk to the upper limb during stroke execution [52]. The "small and fast" hip movements effectively transfer energy to the upper limbs, increasing the movement speed of the elbow and wrist joints, thereby enhancing stroke velocity [53]. Furthermore, the improvement in the upper quarter YBT composite score, leading to enhanced dynamic joint stability and optimized movement patterns [38–40], may further explain the increase in stroke velocity [50]. Regarding backhand topspin velocity, Bańkosz et al. [54] found that the speed of arm abduction and shoulder girdle rotation towards the active side is closely related to stroke velocity during the backhand. The neuromuscular warm-up intervention included upper limb exercises in both the warm-up and core activation modules, potentially enhancing the activation and coordination of the shoulder girdle muscles, thereby enabling greater angular displacement and torque generation [55,56]. In addition, by improving multi-joint coordination, the neuromuscular warm-up may have optimized the synergistic efficiency of the elbow and wrist joints during the stroke, allowing athletes to generate more effective velocity output at similar angular velocities [54].

Practical Applications

Based on the findings of this study, coaches may consider incorporating this 20- to 25-minute neuromuscular warm-up into regular training sessions, either as a structured supplement to or replacement for conventional warm-up routines, which integrates dynamic activation, core, jumping, strength, and agility exercises to simultaneously elevate body temperature and prime the neuromuscular system. To ensure effectiveness, this warm-up should be implemented at least twice weekly and maintained as a permanent component of the long-term training plan. During execution, coaches should prioritize movement quality over the mere completion of repetitions. Finally, the effectiveness of the warm-up can be monitored regularly (e.g., monthly) using simple, quantifiable metrics such as YBT-UQ, YBT-LQ, countermovement jump height, and stroke velocity.

Limitations

Several limitations should be acknowledged. First, due to resource limitations, standing height and sitting height were measured using a high-precision metal stadiometer rather than dedicated scientific anthropometric instruments. Although measurement error was minimized through standardized procedures, assessor training, and averaging of three repeated measurements, minor systematic error may still have occurred when estimating biological maturity status.

Second, a separate test-retest reliability session was not conducted before baseline testing; therefore, study-specific ICC, SEM, or CV values were not available. However, the outcome measures used in this study were based on previously validated and reliable testing procedures or devices, including standardized YBT protocols, the MyJump2 application for CMJ height, and a previously published table tennis stroke velocity testing procedure. In addition, all assessments were administered by trained assessors using standardized protocols, and the mean value of multiple recorded trials was used for statistical analysis to reduce random measurement error. Future studies should include separate reliability assessments to quantify the reproducibility of the YBT-UQ, YBT-LQ, CMJ, and stroke velocity measures specifically in adolescent table tennis players.

Third, this study examined the effects of a relatively short-term eight-week neuromuscular warm-up intervention. Although significant improvements were observed immediately after the intervention, the absence of long-term follow-up means that we cannot determine whether these effects would be maintained over a longer training period or competitive season. Future studies with longer intervention periods, follow-up assessments, and seasonal monitoring are needed to evaluate the durability and practical relevance of neuromuscular warm-up adaptations in youth table tennis players.

In addition, although all testing sessions were conducted in the same indoor sports hall and at similar times of day, indoor temperature and relative humidity were not continuously recorded. Future studies should report these environmental conditions more precisely to further improve methodological transparency.

Conclusion

An eight-week neuromuscular warm-up significantly improved the upper and lower quarter YBT composite scores, CMJ height, and forehand and backhand stroke velocities in adolescent male table tennis players. These findings support the integration of neuromuscular warm-up into regular youth table tennis training to enhance dynamic balance, explosive performance, and stroke execution.

Declarations

Ethical considerations

This study was approved by the Ethics Committee of Shanghai University of Sport (approval number: 102772025RT103) and was conducted in accordance with the Declaration of Helsinki.

Consent to participate

Written informed consent was obtained from all participants and their parents or legal guardians prior to participation.

Consent for publication

Not applicable, as no identifiable individual participant data are included in the manuscript.

Declaration of conflicting interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request, subject to ethical and privacy considerations.

Authors' contributions

Chenwen Zhu: research concept and study design, literature review, data collection, data analysis and interpretation, writing of the manuscript, and reviewing/editing drafts of the manuscript.

Lina Wang: data collection and reviewing drafts of the manuscript.

Meiling Tao: data collection and reviewing drafts of the manuscript.

Lingling Gu: data collection and reviewing drafts of the manuscript.

Xulan He: data collection and reviewing drafts of the manuscript.

Tianyue Yin: data collection and reviewing drafts of the manuscript.

Jiuzhang Li: data collection and reviewing drafts of the manuscript.

Steve Thompson: data analysis and interpretation, statistical analyses, reviewing drafts of the manuscript, and editing drafts of the manuscript.

Ziemowit Bańkosz: data analysis and interpretation, statistical analyses, reviewing drafts of the manuscript, and editing drafts of the manuscript.

Nan Gu: research concept and study design, supervision, writing of the manuscript, reviewing drafts of the manuscript, and editing drafts of the manuscript.

All authors read and approved the final manuscript.

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