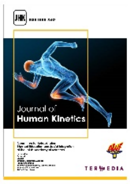

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Section II – Exercise Physiology and Sports Medicine

Integrating Footwork in Table Tennis Multi-Ball Practice Increases Physiological and Neuromuscular Demands without Affecting Energy Cost and Plantar Pressure

by
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This study assessed the physiological and neuromuscular consequences of using different footwork techniques during table tennis forehand loop multi-ball training. Ten male table tennis players executed forehand loops with no step, a chasse step, a side step, and a cross step at three different frequencies (12, 24 and 36 balls·min^{-1} for the cross step, and 24, 36 and 48 balls·min^{-1} for the others) on separated days. Cardiorespiratory variables along with total and per-stroke energy cost were determined. Plantar pressure data were collected using instrumented insoles. Countermovement jump tests were performed before and immediately after each stage. The heart rate, oxygen uptake, and total energy cost significantly increased with frequency for all footwork techniques (all $p < 0.05$). However, the energy cost per stroke decreased at higher frequencies ($p < 0.05$), as did the peak plantar pressure across the whole foot and specific foot regions ($p < 0.05$). Countermovement jump height decreased at moderate and high frequencies ($p < 0.05$), except for no step and the chasse step. In conclusion, integrating footwork into forehand loop multi-ball training increases physiological and neuromuscular demands in table tennis players. The reduced energy cost at higher frequencies likely reflects a reduction in movement amplitude, a strategy to cope with shorter time windows, which in turn leads to lower force production from the lower limbs. Coaches should adapt training interventions focusing on improving the power and strength of lower limbs to offset the reduction of force caused by the shortened time window at high frequency.

Keywords: *lower limb; energy metabolism; neuromuscular fatigue; racket sport; athletic training*

Introduction

Table tennis is a racket sport characterized by intermittent movements, including short rallies and relatively long rest intervals (Pradas et al., 2021; Zagatto et al., 2010). It primarily relies on the aerobic system, while the anaerobic alactic system plays a vital role in rallies (Zagatto et al., 2016). During matches, players execute nearly 400 footwork movements combined with different strokes, especially the forehand loop (Fuchs et al., 2018). Multi-ball training is a common practice involving variations in frequency, ball displacement, speed, and spin, which aims to improve stroke accuracy (Katsikadelis et al., 2014), dynamic posture control (Gu et al., 2019), and the formation and fixation of technical movements (Cao et al., 2020). Despite its popularity, the physiological and neuromuscular characteristics of table tennis training are not well described (Zagatto et al., 2018).

A previous study has investigated the energetic cost per stoke (E_s) during forehand loop practice, revealing a reduction in E_s, decreasing from ~10 to 6 J·kg^{-1}·stroke^{-1} with increasing

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frequency from 35 to 85 balls·min^{-1} (Li et al., 2020). However, that study focused specifically on forehand loop practice, excluding essential footwork techniques such as a chasse step, a side step, and a cross step commonly employed in matches (Yu and Huang, 2025). Given the crucial role of feet in transferring energy from lower to upper limbs (Reid et al., 2008; Seeley et al., 2011), mastering footwork is vital for achieving an optimal hitting position and enhancing hitting performance. Therefore, delving into the physiological characteristics of table tennis multi-ball drills can assist coaches in crafting more effective training designs.

In table tennis training and matches, players execute repetitions of fast starts and stops, which impose significant constraints on the lower limbs (Lees, 2003). Gathering data on the location and magnitude of foot pressures could advance our understanding of shoe-surface interaction and contribute to preventing overtraining injuries (Girard et al., 2007). Despite previous studies comparing plantar pressure distribution during different lower limb movements (Lam et al., 2019), these results, based on fixed frequency and a limited number of repetitions, i.e., 4 strokes (He et al., 2021), and 5 strokes (Lam et al., 2019), might not accurately represent real situations. In multi-ball training drills, a player could hit as many as 200 balls (Sperlich et al., 2011). Therefore, concurrently investigating lower limb movements during multi-ball training holds significance.

High-level table tennis requires players to repeatedly accelerate, decelerate, maintain balance, and execute effective strokes (Pradas et al., 2021). These demanding movements can lead to neuromuscular fatigue (NMF) which may impair performance (Girard and Millet, 2009). Given the high work-rest ratio (W:R ratio) in a table tennis match, NMF was detected only at the end of the first game and remained unchanged thereafter (Le Mansec et al., 2017). Contrastingly, training drill execution typically involves a relatively higher W:R ratio compared to actual competition (Katsikadelis et al., 2014), potentially subjecting players to increased neuromuscular demand. To date, no research has delved into NMF during table tennis training.

The aim of this study was to explore the physiological and neuromuscular responses to different footwork techniques during table tennis forehand loop multi-ball training across low, moderate, and high ball serving frequencies. Given its longer step length and more complex movement pattern, the cross step was expected to impose the highest physiological and neuromuscular demands, followed by the side step and the chasse step, relative to a control condition involving no stepping movement.

Methods

Participants

Ten collegiate male table tennis players (age: 20.8 ± 1.8 years, body height: 179.3 ± 4.6 cm, body mass: 70.65 ± 7.62 kg, maximal oxygen uptake: 46.9 ± 7.6 ml·kg^{-1}·min^{-1}) volunteered to participate in this study. All participants were classified as 'Tier 3: Highly Trained/National Level' (McKay et al., 2022), boasting an average of 11.6 ± 3.1 years of table tennis training experience, and engaging in ~10 h of weekly training. All participants were classified as right-hand dominant based on the hand used to hold the racket (Peters and Murphy, 1992). Participants were instructed to maintain their usual diet and avoid strenuous exercise, alcohol, and caffeine for 24 h before testing, as well as ensure adequate sleep to control for fatigue and nutritional status. During practice, all athletes used their own shake-hand grip racket with inverted rubbers on the forehand side. Participants were informed about the test procedures and potential risks before the research, and informed written consent was obtained. This study was conducted following the principles of the Declaration of Helsinki, and approved by the Shanghai University of Sport, Shanghai, China (approval code: 102772022RT101; approval date: 24 October 2023).

Design

This study employed a randomized crossover design, with footwork testing sequences generated using a randomization program. Participants underwent a familiarization session, followed by four randomized footwork tests on separated days with a washout period of at least 48 h. Upon arriving at the laboratory, all players performed a warm-up including stretching and jogging (5 min) and ball return practice (5 min), followed by a 5-min recovery period. After the short rest, a three-stage protocol was adapted. Each stage lasted for 3 min, with a 6-min interval between stages to simulate the real competition (Le Mansec et al., 2017). For the no-step (NS), chasse step (CS), and side step (SS) conditions, the ball serving machine's frequency (V-989H, TaiDe, Shenzhen, China) was set to 24 balls·min^{-1} (low frequency, LF), 36 balls·min^{-1} (moderate frequency, MF), and 48 balls·min^{-1} (high frequency, HF). For the cross step (CRS) condition, frequencies were set to 12, 24, and 36 balls·min^{-1} due to the larger step length and rapid lateral displacement. These settings were determined both theoretically, considering that players required at least 1.4 s to perform one footwork (Iino, 2018), and practically, based on the highest volume they could perform. Players were instructed to hit the ball diagonally to a target zone (30 × 30 cm) (Cao et al., 2020). Participants completed countermovement jumps (CMJ) after rest and each stage, and ratings of perceived exertion (RPEs) were collected using the 6–20 Borg scale (Williams, 2017). Blood samples, amounting 10 μL of capillary blood from the earlobe, were obtained before the test, at the 1st, the 3rd, and the 5th min after both LF and MF conditions, and also at the 1st, the 3rd, the 5th, and the 7th min after the HF condition. All balls used in this study were certified by the China Table Tennis Federation (plastic ball: 40 mm/white/three stars, DHS, China).

Measures

Physiological and Stroke Performance Measurements

A heart rate monitor (Polar Accurex Plus, Polar Electro Inc., Kempele, Finland) continuously recorded the heart rate. Blood samples were subsequently analyzed using a blood lactate analyzer (Biosen C_line, EKF Diagnostic, Magdeburg, Germany) to determine peak blood lactate concentration (BLC_{peak}). Respiratory variables were collected breath-by-breath using a portable spirometry system (MetaMax3BR2, Cortex, Germany). Continuous data acquisition occurred during the whole protocol and an additional six min after the HF condition. Standard calibration, following the manufacturer's recommendations, was performed for each testing day. Three components for each stage were used to calculate the energy cost of exercise, as detailed in a previous study (Li et al., 2020). The only difference was the use of the fast component of the VO_2 off-kinetics after each stage to more precisely calculate the anaerobic alactic energy contribution, considering the 6-min rest was sufficient. Total energy (E_{tot}, kJ) was computed as the sum of energy from the aerobic, anaerobic alactic, and anaerobic lactic energy systems. To determine the E_s (J·kg^{-1}·stroke^{-1}), the E_{tot} of one stage was divided by the corresponding stroke frequency in the same stage and the body mass of the player. Performance was measured by counting the number of balls that did not hit the target zone (i.e., out of the table, off the net, missed the zone).

Foot Pressure Measurements and Data Processing

Instrumented insoles (Pedar mobile system, Novel GmbH, Munich, Germany) were inserted between the midsole of participants' own sports shoes and the plantar surfaces of their dominant foot, determined based on their racket-holding hand. A telemetric data logger was attached to a belt worn around the player's waist, transmitting data to a computer for analysis at a sampling frequency of 100 Hz. The instrumented insoles were calibrated up to 700 kPa according to the manufacturer's standard procedure and a calibration device (Novel GmbH, Munich, Germany) to ensure measurement accuracy and prevent overloading during sport-specific movements. Foot pressure data were captured during the initial two steps of the second minute of every stage, with the subsequent two middle steps extracted for further analysis defined as the vertical ground reaction force first exceeded and reduced to 10 N (Lam et al., 2019). The second minute of each stage was selected for analysis to minimize variability from frequency adjustments during the first minute and avoid potential fatigue effects emerging in the third minute. Two clearly identifiable mid-stage steps were selected to ensure data completeness and consistency. Relative peak plantar pressure was calculated by dividing the recorded values by the player's body mass (Kpa·kg^{-1}).

Neuromuscular Measurement

Players performed three countermovement jumps (CMJs) with a 10-s rest interval between each jump. The CMJ procedure involved starting from a standing position, squatting down, and then extending the knees in one continuous movement, with hands kept on the hips to minimize the contribution of the upper limbs. CMJ tests were recorded by an iPhone 13 (Apple, Inc, USA) in slow-motion mode (1080 p, 240 fps) and analyzed using *My Jump* App, which has shown good reliability (CV = 3.8–7.6%) for the CMJ test (Gallardo-Fuentes et al., 2016). Jump height was averaged from the three trials for subsequent analysis (Claudino et al., 2017).

Statistical Analysis

All statistical analyses were performed using the SPSS version 26.0 (SPSS, Inc., Chicago, IL, USA.) and presented as mean ± SD. Normality, homoscedasticity, and sphericity were initially checked. A two-way ANOVA with repeated measures (frequency × footwork) was performed to identify significant main effects and interactions for each of the tested variables. When significant effects were detected, post hoc multiple comparisons were conducted using Bonferroni correction to control for the increased risk of type I errors due to multiple testing. Effect size was calculated using partial eta squared (η_p^2) for the ANOVA and interpreted as *small* ($0.1 \le \eta_p^2 < 0.06$), *moderate* ($0.06 \le \eta_p^2 < 0.14$), or *large* ($\eta_p^2 \ge 0.14$). The magnitude of the difference was assessed by Hedge's g for dependent samples, with changes considered *small* (0.20 ≤ Hedge's g < 0.50), *moderate* (0.50 ≤ Hedge's g < 0.80), or *large* (Hedge's g ≥ 0.80) (Cohen, 2013). Statistical significance was considered at $p < 0.05$.

Results

Physiological and Stroke Performance Outcomes

As illustrated in Table 1, there were significant main effects for frequency, footwork and interactions (except for VO_2 and errors) in all physiological outcomes. Regarding the footwork effect, the HR, VO_2, E_{total}, and E_S of the CS, SS and CRS conditions were significantly higher compared to the NS condition at all three frequencies (all $p < 0.05$). The same trend was observed in the RPE and BLA_{peak} at MF and HF, but not at LF, where only the RPE in the CS condition was higher than for the NS ($p < 0.001$, $g = 1.68$) and CRS ($p = 0.01$, $g = 1.14$) conditions. BLA_{peak} did not differ between footwork conditions at LF. No difference in errors was observed at LF under any of the footwork conditions, but the CRS condition resulted in more errors than other conditions at MF and HF.

Regarding the frequency effect, the RPE and the HR of each footwork condition increased with frequency, except that the HR of the NS condition at MF was not different from HF, and BLA_{peak} at LF did not differ from baseline under SS and CRS conditions. The BLA_{peak} of the NS condition did not change at any frequency. The E_s for all footwork conditions peaked at LF and then drastically declined with increasing frequency. VO_2 for NS and CS conditions was not different among the three frequencies, while SS ($p = 0.04$, $g = 1.14$; $p = 0.02$, $g = 0.53$) and CRS ($p < 0.001$, $g = 1.29$; $p < 0.001$, $g = 0.62$) conditions led to higher VO_2 at HF and MF compared to LF. E_{tot} increased with frequency and showed differences at HF and MF, which were higher than at LF for all footwork conditions. Errors were higher at HF than at MF and LF under all footwork conditions.

Relative Peak Plantar Pressure

All numerical and statistical results for the relative peak pressure of the whole foot are shown in Figure 1. There were no significant interactions for peak plantar pressure of the whole foot ($p > 0.05$, $\eta_p^2 = 0.21$). The main effect of frequency was significant ($p < 0.01$, $\eta_p^2 = 0.71$), and a decreasing trend was evident in the whole foot. Notably, plantar pressure for the NS ($p = 0.02$, $g = 1.29$), CS ($p = 0.05$, $g = 1.16$), SS ($p = 0.04$, $g = 1.12$) and CRS ($p < 0.001$, $g = 1.06$) conditions was higher at LF than at HF. Additionally, whole foot peak pressure under the CRS condition at MF was also greater than at HF ($p < 0.001$, $g = 0.93$). Moreover, footwork effect of relative peak pressure was significant ($p < 0.001$, $\eta_p^2 = 0.82$). the CRS condition exerted higher peak pressure compared to the NS, CS, and SS conditions at all frequencies.

Neuromuscular Fatigue

Two-way ANOVA revealed a significant effect of frequency on jump height ($p = 0.001$, $\eta_p^2 = 0.39$), but no footwork effect ($p = 0.55$, $\eta_p^2 = 0.55$) or frequency x footwork interaction ($p = 0.25$, $\eta_p^2 = 0.09$). Jump height under the SS condition at HF was lower than at Pre ($p = 0.02$, $g = 0.35$), LF ($p = 0.003$, $g = 0.62$), and MF ($p = 0.02$, $g = 0.35$). Furthermore, jump height under the SS condition at MF was also lower than at LF ($p = 0.02$, $g = 0.28$). Jump height under the CRS condition at Pre and LF was significantly higher than at MF ($p = 0.03$, $g = 0.45$; $p < 0.001$, $g = 0.58$) and HF ($p = 0.01$, $g = 0.76$; $p = 0.002$, $g = 0.86$). These results are presented in Figure 2.

Discussion

The purpose of this study was to examine the physiological and neuromuscular responses to different footwork techniques during table tennis forehand loop multi-ball training across low, moderate, and high ball serving frequencies. The main finding was that incorporating footwork into table tennis multi-ball practice significantly increased physiological and neuromuscular demands, therefore validating our hypothesis. However, E_s and peak plantar pressure consistently decreased at high frequency, irrespective of the footwork condition, partially contradicting our hypothesis. Overall, the integration of the footwork into table tennis multi-ball forehand practice increased physiological demand but without affecting energy cost and plantar pressure.

Table 1. Physiological and performance variables of table multi-ball training with different frequency and footwork.

Outcomes	Footwork	Pre	LF	MF	HF
RPE	NS	8 ± 1	9 ± 1*	10 ± 1*†	12 ± 1*†‡
	CS	9 ± 1	12 ± 1*§	13 ± 1*†§	17 ± 1*†‡§
	SS	8 ± 1	10 ± 1*§	13 ± 1*†§	15 ± 1*†‡§‖
	CRS	7 ± 1	10 ± 1*‖	14 ± 1*†§	16 ± 1*†‡§
	NS	1.19 ± 0.31	1.63 ± 0.54	2.10 ± 0.97	2.91 ± 1.8
BLa_{peak}	CS	1.38 ± 0.29	3.28 ± 2.41*	5.32 ± 3.59 *†§	7.45 ± 4.06*†‡§
($mmol·L^{-1}$)	SS	1.37 ± 0.36	3.26 ± 1.42*	5.51 ± 2.83*†§	7.46 ± 3.15*†‡§
	CRS	1.02 ± 0.16	1.96 ± 0.91	5.87 ± 2.44†§	8.17 ± 2.11†‡§
	NS		18.35 ± 5.39	21.80 ± 7.64	21.80 ± 8.42
VO_2	CS		34.80 ± 6.86§	38.10 ± 6.67§	39.50 ± 8.68§
($ml.kg^{-1}·min^{-1}$)	SS		39.50 ± 6.67§	39.50 ± 9.74†§	43.00 ± 6.87†§
	CRS		28.74 ± 7.81§	34.83 ± 10.67†§	41.85 ± 11.32†§
	NS		78.55 ± 24.50	87.65 ± 25.63	94.02 ± 26.13
E_{TOT}	CS		157.00 ± 31.13§	182.16 ± 19.81†§	190.97 ± 32.31†‡§
(Kj)	SS		182.13 ± 32.30§	181.89 ± 30.38§	207.83 ± 24.58†‡§
	CRS		204.58 ± 33.71§	140.09 ± 26.50 †§	197.63 ± 46.11†§
	NS		15.26 ± 5.03	11.22 ± 3.37†	9.12 ± 2.67†
E_s	CS		31.94 ± 6.79§	23.94 ± 3.25†§	19.44 ± 4.00†‡§
($J.kg^{-1}·Stroke^{-1}$)	SS		35.77 ± 6.69§	23.79 ± 3.62†§	20.52 ± 3.07†‡§
	CRS		27.94 ± 5.81§¶	21.38 ± 6.96†§	19.94 ± 4.65†§
	NS		3.4 ± 0.92	5.30 ± 1.38	7.40 ± 1.73*
Errors	CS		5.4 ± 1.36	8.90 ± 1.76*	11.20 ± 2.04*
(Balls)	SS		8.8 ± 1.39	7.80 ± 1.51	11.1 ± 1.62†
	CRS		7.8 ± 1.85§	13.7 ± 1.70*§‖¶	16.4 ± 1.93*§‖¶
	NS		116 ± 16	128 ± 3†	132 ± 16†
HR	CS		158 ± 19§	174 ± 15†§	183 ± 10†‡§
(bpm)	SS		161 ± 20§	174 ± 16†§	183 ± 8†‡§
	CRS		153 ± 24§	180 ± 12†§	192 ± 9†‡§

HR: heart rate; BLa_{peak}: peak blood lactate; VO_2: oxygen uptake; E_{tot}: total energy cost; E_s: energy cost per stroke; RPE: rating of perceived exertion; Pre: pre-test measures; LF: low frequency; MF: moderate frequency; HF: high frequency; NS: No Step; CS: Chasse Step; SS: Side Step; CRS: Cross Step., † and ‡ denote significant difference compared to Pre, LF and MF, respectively ($p < 0.05$); §, ‖ and ¶ denote significant difference compared to NS, CS and SS, respectively ($p < 0.05$)*

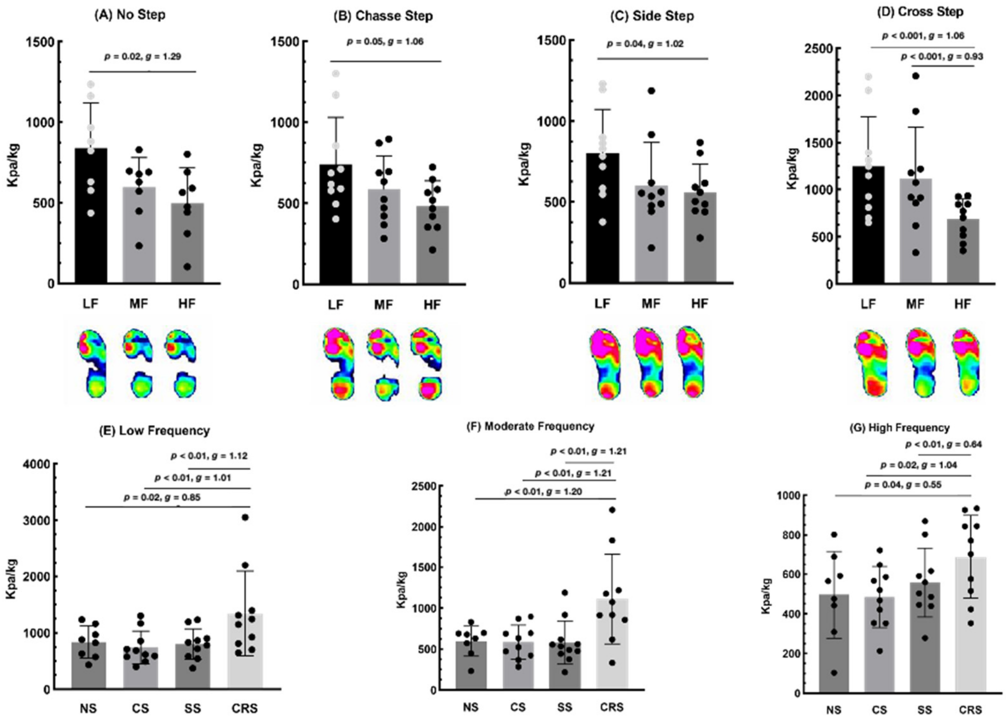

Figure 1. Relative peak plantar pressure of the whole foot and the heat map of one representative player.

Note: The top panels represent relative peak plantar pressure data for the no-step (A), chasse step (B), side step (C), and cross step (D) conditions for three frequencies. The bottom panels represent RPP data for the low frequency (E), middle frequency (F), and high frequency (G) for four footwork conditions

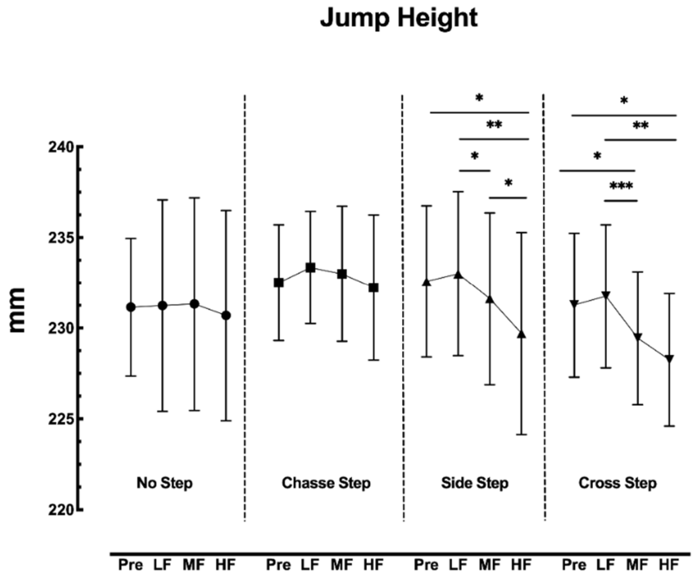

Figure 2. Countermovement jump height measured before (Pre) and immediately after Low, moderate and high frequency workouts (LF, MF and HF, respectively).

Pre: pretest measures; LF: low frequency; MF: moderate frequency; HF: high frequency;
**: p < 0.05; **: p < 0.01; ***: p < 0.001*

Including footwork into multi-ball drills significantly increased physiological metrics (e.g., HR, blood lactate, and VO_2) compared to the without movement condition (NS). The rather modest differences among CS, SS, and CRS conditions may be due to the limited space on a standard table tennis court, constraining movement and resulting in comparable physiological responses across different footwork techniques. However, E_s exhibited a decrease for all footwork techniques at high frequency. Giles and Reid (2021) found that a high ball speed (4.0–4.3 $m \cdot s^{-1}$) resulted in more flexed hip and ankle joints, which restricted the contribution of the lower body to stroke production and racquet speed at impact compared to the low ball speed (1.4–2.0 $m \cdot s^{-1}$) in eighteen professional tennis players. Similarly, Choi et al. (2026) found that tennis players reduced stroke angular displacement when responding to faster incoming balls. Moreover, Iino and Kojima (2016) observed that the maximum pelvis axial rotational velocity and the upper trunk axial rotational velocity tended to be larger for low ball frequency (35 $balls \cdot min^{-1}$) compared to high frequency (75 $balls \cdot min^{-1}$) in ten table tennis players. In the present study, relative peak pressure of the whole foot and specific regions decreased at high frequency compared to low frequency. As frequency increased, players likely reduced the movement amplitude to compensate for the shorter time window (Iino and Kojima, 2016), reducing the available range and time for force production and consequently decreasing E_s. This reduction in force at high frequencies may hinder player's ability to maintain optimal stroke technique during training (Deghaies et al., 2026).

Among all footwork techniques, the CRS produced the highest relative peak pressure across the whole foot and specific areas. Likewise, He et al. (2022) reported that the CRS induced significantly greater peak forces in the *rectus femoris* (+36%), *gastrocnemius* (+28%), and *soleus* (+25%) during the stance phase. This could be explained by the relatively large motion of the CRS. Previous research has indicated that maximal horizontal (+38%) and vertical (+11%) ground reaction forces, along with the maximal knee flexion angle (+20%) and maximum ankle inversion velocity (+148%) were significantly greater than for the chasse step (Lam et al., 2019). The excessive vertical and/or horizontal forces exerted during the CRS may impose significant joint torques or shear stress on the ligaments and other soft tissues of the lower limbs, potentially leading to higher plantar and neuromuscular constraints (Rajabi et al., 2012). However, Lam et al. (2019) reported no significant differences in the pressure-time integral, which reflects both the pressure magnitude and duration, among the SS, the CRS, and one-step footwork ($p = 0.02$), for the whole foot or specific regions. This may be due to increased stance time during one-step footwork to compensate for its lower biomechanical demands and maintain sufficient cumulative load despite reduced instantaneous plantar pressure (Lam et al., 2019). Therefore, caution should be exercised when interpreting the current findings, as only peak pressure was analyzed due to technical limitations.

Our results indicate that increasing frequency induced NMF, as evidenced by reduced CMJ jump height at MF and HF only under SS and CRS conditions, while NS and CS conditions did not show any significant change. Importantly, the degree of NMF was not influenced by the footwork condition. In table tennis daily training and matches, players engage in repetitions of fast starts and stops, alternating between brief periods of maximal or near maximal intensity and longer periods of lower intensity (Lees, 2003). No previous study has investigated NMF in daily training, which precludes the comparison of our results with existing literature. The occurrence of NMF only under SS and CRS conditions could be explained by the larger biomechanical demand associated with the execution of these two footwork techniques. Similarly, one recent research demonstrated that shorter-distance lateral shuffle movements (2.5 m) induced greater physiological and neuromuscular fatigue, likely due to the higher frequency of changes of direction (Lyu et al., 2025). In the present study, SS and CRS may have similarly required more frequent and demanding lateral displacement, rapid braking, and re-acceleration, thereby increasing lower-limb neuromuscular loading and leading to greater NMF. Overall, when conducting multi-ball drills with the SS or the CRS, shorter duration of practice and longer rest time might be recommended.

Another observation was the significant increase in the number of errors with the rising frequency, which was particularly evident when performing the CRS, where the number of errors was noticeably higher compared to the other conditions. This increase in the number of errors may be attributed to the combination of a shortened time window for movement execution and a greater movement volume at higher frequencies, both of which likely contributed to the accumulation of fatigue. Previous studies have indicated that in badminton, shuttlecock speed and precision, in terms of the number of faults and accuracy, were negatively affected by lower limb fatigue (Le Mansec et al., 2020). Similarly, the tennis players' error rate and ball velocity deteriorated with fatigue development (Vergauwen et al., 1998). However, ball speed, spin, arc, placement, and power are key indicators of table tennis performance (Yu and Huang, 2025). Le Mansec et al. (2018) investigated the effects of quadriceps fatigue on French regional and national table tennis players' performance, finding no impact on accuracy, ball speed, and total scores, but an increase in the number of committed errors. Similarly, Zagatto et al. (2014) found that increasing frequency did not affect ball speed (p = 0.32), with mean speeds ranging from 51.6 ± 1.8 $km \cdot h^{-1}$ to 58.7 ± 4.8 $km \cdot h^{-1}$ across stages. These unchanged performance outcomes may be because all existing protocols, including the present study, use anticipated conditions. In contrast, actual play requires reacting to opponents' returns under unanticipated conditions (Zhu et al., 2022). Therefore, future research should investigate performance indicators under unanticipated training conditions to better reflect real competitive settings.

The present study has several limitations to be acknowledged. Firstly, the sample size was relatively small (n = 10), slightly below the recommended 14 from our power analysis. However, all participants were male athletes from the China Table Tennis Academy, known for high training and selection standards. Due to COVID-19 restrictions, only male athletes were available, which ensured consistency but limits generalizability, particularly as female athletes may differ in physical profiles (Pradas et al., 2022) and movement strategies (Giles and Reid, 2021). Future studies should include larger, sex-diverse samples to validate and extend these findings. Secondly, we utilized a mobile application to quantify NMF during training, but recent studies suggest that time-based metrics (e.g., reactive strength index modified, time to peak power, and time to take-off) may better detect subtle changes after intense exercise (Bishop et al., 2023). Using a force plate to capture these time-based metrics could provide deeper insights (Bishop et al., 2023). Finally, the high volume of footwork (36–144 balls) in a single session required a high-speed camera to identify the start and the end of each footwork technique. Future studies might benefit from advanced equipment, such as marker-less 3D systems combined with artificial intelligence algorithms (Moran et al., 2021), for more accurate joint kinetic and kinematic measurement.

In conclusion, adding footwork to table tennis multi ball drills significantly increased the physiological, neuromuscular, and biomechanical responses in highly trained/national level male table tennis players. However, the energy cost per stroke decreased at high frequency, irrespective of the footwork. This reduction may be associated with the force generated by lower limbs, as indicated by reduced peak pressure at moderate and high frequencies. Future research endeavors should delve into the kinematics and kinetics of the trunk and upper limbs to gain a more comprehensive understanding of whole-body movement during higher frequency ball strokes.

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References

Bishop, C., Jordan, M., Torres-Ronda, L., Loturco, I., Harry, J., Virgile, A., Mundy, P., Turner, A., & Comfort, P. (2023). Selecting metrics that matter: Comparing the use of the countermovement jump for performance profiling, neuromuscular fatigue monitoring, and injury rehabilitation testing. *Strength and Conditioning Journal*, *45*(5), 545–553. https://doi.org/10.1519/SSC.0000000000000772

Cao, Z., Xiao, Y., Lu, M., Ren, X., & Zhang, P. (2020). The impact of eye-closed and weighted multi-ball training on the improvement of the stroke effect of adolescent table tennis players. *Journal of Sports Science & Medicine, 19*(1), 43–51.

Claudino, J. G., Cronin, J., Mezêncio, B., McMaster, D. T., McGuigan, M., Tricoli, V., Amadio, A. C., & Serrão, J. C. (2017). The countermovement jump to monitor neuromuscular status: A meta-analysis. *Journal of Science and Medicine in Sport*, *20*(4), 397–402. https://doi.org/10.1016/j.jsams.2016.08.011

Cohen, J. (2013). *Statistical power analysis for the behavioral sciences*. Routledge.

Choi, Y., Song, J., Park, D., Park, J., & Park, J. (2026). Adaptive Forehand Stroke Strategies for Varying Ball Speed in Tennis Performance. *Journal of Human Kinetics*, Advance online publication. https://doi.org/10.5114/jhk/208391

Deghaies, K., Lussiana, T., Touzard, P., Fourel, L., Ozan, S., Brechbuhl, C., Gindre, C., Bideau, B., & Martin, C. (2026). Tennis Serve Constraints Delimit but Do Not Prohibit Individual Movement Strategies among Professional Players. *Journal of Human Kinetics*, *102*, 44–55. https://doi.org/10.5114/jhk/203795

Fuchs, M., Liu, R., Malagoli Lanzoni, I., Munivrana, G., Straub, G., Tamaki, S., Yoshida, K., Zhang, H., & Lames, M. (2018). Table tennis match analysis: A review. *Journal of Sports Sciences*, *36*(23), 2653–2662. https://doi.org/10.1080/02640414.2018.1450073

Gallardo-Fuentes, F., Gallardo-Fuentes, J., Ramírez-Campillo, R., Balsalobre-Fernández, C., Martínez, C., Caniuqueo, A., Cañas, R., Banzer, W., Loturco, I., Nakamura, F. Y., & Izquierdo, M. (2016). Intersession and intrasession reliability and validity of the *My* Jump App for measuring different jump actions in trained male and female athletes. *Journal of Strength and Conditioning Research*, *30*(7), 2049–2056. https://doi.org/10.1519/JSC.0000000000001304

Giles, B., & Reid, M. (2021). Applying the brakes in tennis: How entry speed affects the movement and hitting kinematics of professional tennis players. *Journal of Sports Sciences*, *39*(3), 259–266. https://doi.org/10.1080/02640414.2020.1816287

Girard, O., Eicher, F., Fourchet, F., Micallef, J. P., & Millet, G. P. (2007). Effects of the playing surface on plantar pressures and potential injuries in tennis. *British Journal of Sports Medicine*, *41*(11), 733–738. https://doi.org/10.1136/bjsm.2007.036707

Girard, O., & Millet, G. P. (2009). Neuromuscular Fatigue in Racquet Sports. *Physical Medicine and Rehabilitation Clinics of North America*, *20*(1), 161–173. https://doi.org/10.1016/j.pmr.2008.10.008

Gu, Y., Yu, C., Shao, S., & Baker, J. S. (2019). Effects of table tennis multi-ball training on dynamic posture control. *PeerJ*, *6*, e6262. https://doi.org/10.7717/peerj.6262

He, Y., Shao, S., Fekete, G., Yang, X., Cen, X., Song, Y., Sun, D., & Gu, Y. (2022). Lower limb muscle forces in table tennis footwork during topspin forehand stroke based on the OpenSim musculoskeletal model: A Pilot Study. *Molecular & Cellular Biomechanics*, *19*(4), 221–235. https://doi.org/10.32604/mcb.2022.027285

He, Y., Sun, D., Yang, X., Fekete, G., Baker, J. S., & Gu, Y. (2021). Lower limb kinetic comparisons between the chasse step and one step footwork during stroke play in table tennis. *PeerJ*, *9*, e12481. https://doi.org/10.7717/peerj.12481

Iino, Y. (2018). Hip joint kinetics in the table tennis topspin forehand: Relationship to racket velocity. *Journal of Sports Sciences*, *36*(7), 834–842. https://doi.org/10.1080/02640414.2017.1344777

Iino, Y., & Kojima, T. (2016). Effect of the racket mass and the rate of strokes on kinematics and kinetics in the table tennis topspin backhand. *Journal of Sports Sciences*, *34*(8), 721–729. https://doi.org/10.1080/02640414.2015.1069377

Katsikadelis, M., Pilianidis, T., Mantzouranis, N., Fatouros, I., & Agelousis, N. (2014). Heart rate variability of young table tennis players with the use of the multiball training. *Journal of Biology of Exercise, 10*, 25-35. https://doi.org/10.4127/jbe.2014.0076

Lam, W.-K., Fan, J.-X., Zheng, Y., & Lee, W. C.-C. (2019). Joint and plantar loading in table tennis topspin forehand with different footwork. *European Journal of Sport Science*, *19*(4), 471–479. https://doi.org/10.1080/17461391.2018.1534993

Le Mansec, Y., Pageaux, B., Nordez, A., Dorel, S., & Jubeau, M. (2018). Mental fatigue alters the speed and the accuracy of the ball in table tennis. *Journal of Sports Sciences*, *36*(23), 2751–2759. https://doi.org/10.1080/02640414.2017.1418647

Le Mansec, Y., Perez, J., Rouault, Q., Doron, J., & Jubeau, M. (2020). Impaired performance of the smash stroke in badminton induced by muscle fatigue. *International Journal of Sports Physiology and Performance*, *15*(1), 52–59. https://doi.org/10.1123/ijspp.2018-0697

Le Mansec, Y., Seve, C., & Jubeau, M. (2017). Neuromuscular fatigue and time motion analysis during a table tennis competition. *Journal of Sports Medicine and Physical Fitness*, *57*(4). https://doi.org/10.23736/S0022-4707.16.06129-6

Lees, A. (2003). Science and the major racket sports: a review. *Journal of Sports Sciences*, *21*(9), 707–732. https://doi.org/10.1080/0264041031000140275.

Li, Y., Li, B., Wang, X., Fu, W., Dai, B., Nassis, G. P., & Ainsworth, B. E. (2020). Energetic profile in forehand loop drive practice with well-trained, young table tennis players. *International Journal of Environmental Research and Public Health*, *17*(10), 3681. https://doi.org/10.3390/ijerph17103681

Lyu, M., Yin, M., Ding, L., Tang, R., Chen, Z., Deng, S., Zhong, Y., Li, Z., Nassis, G., & Li, Y. (2025). Physiological and Neuromuscular Fatigue after 3-Minute Lateral Shuffle Movement at Different Speeds and Distances. *Journal of Human Kinetics*, *95*, 151–159. https://doi.org/10.5114/jhk/190145

Moran, M. F., Rogler, I. C., & Wager, J. C. (2023). Inter-Session Repeatability of Marker-Less Motion Capture of Treadmill Running Gait. *Applied Sciences*, *13*(3), 1702. https://doi.org/10.3390/app13031702

McKay, A. K. A., Stellingwerff, T., Smith, E. S., Martin, D. T., Mujika, I., Goosey-Tolfrey, V. L., Sheppard, J., & Burke, L. M. (2022). Defining training and performance caliber: A participant classification framework. *International Journal of Sports Physiology and Performance*, *17*(2), 317–331. https://doi.org/10.1123/ijspp.2021-0451

Peters, M., & Murphy, K. (1992). Cluster analysis reveals at least three, and possibly five distinct handedness groups. *Neuropsychologia*, *30*(4), 373–380. https://doi.org/10.1016/0028-3932(92)90110-8

Pradas, F., de la Torre, A., Castellar, C., & Toro-Román, V. (2021). Physiological profile, metabolic response and temporal structure in elite individual table tennis: differences according to gender. *International Journal of Environmental Research and Public Health*, *18*(22), 11898. https://doi.org/10.3390/ijerph182211898

Pradas, F., Toro-Román, V., de la Torre, A., Moreno-Azze, A., Gutiérrez-Betancur, J. F., & Ortega-Zayas, M. Á. (2022). Analysis of specific physical fitness in high-level table tennis players: Sex differences. *International Journal of Environmental Research and Public Health*, *19*(9), 5119. https://doi.org/10.3390/ijerph19095119

Rajabi, R., Johnson, G. M., Alizadeh, M. H., & Meghdadi, N. (2012). Radiographic knee osteoarthritis in ex-elite table tennis players. *BMC Musculoskeletal Disorders*, *13*(1), 12. https://doi.org/10.1186/1471-2474-13-12

Reid, M., Elliott, B., & Alderson, J. (2008). Lower-limb coordination and shoulder joint mechanics in the tennis serve. *Medicine & Science in Sports & Exercise*, *40*(2), 308–315. https://doi.org/10.1249/mss.0b013e31815c6d61

Seeley, M. K., Funk, M. D., Denning, W. M., Hager, R. L., & Hopkins, J. T. (2011). Tennis forehand kinematics change as post-impact ball speed is altered. *Sports Biomechanics*, *10*(4), 415–426. https://doi.org/10.1080/14763141.2011.629305

Sperlich, B., Koehler, K., Holmberg, H.-C., Zinner, C., & Mester, J. (2011). Table tennis: cardiorespiratory and metabolic analysis of match and exercise in elite junior national players. *International Journal of Sports Physiology and Performance*, *6*(2), 234–242. https://doi.org/10.1123/ijspp.6.2.234

Yu, J., & Huang, Z. (2025). The Indirect Influence of Stroke Performances on Point Scoring and Conceding in the Four Primary Table Tennis Match Formats. *Journal of Human Kinetics*, *99*, 223–237. https://doi.org/10.5114/jhk/196651

Vergauwen, L., Spaepen, A. J., Lefevre, J., & Hespel, P. (1998). Evaluation of stroke performance in tennis. *Medicine and Science in Sports and Exercise*, *30*(8), 1281–1288. https://doi.org/10.1097/00005768-199808000-00016

Williams, N. (2017). The Borg rating of perceived exertion (RPE) scale. *Occupational Medicine*, *67*(5), 404–405. https://doi.org/10.1093/occmed/kqx063

Zagatto, A. M., Kondric, M., Knechtle, B., Nikolaidis, P. T., & Sperlich, B. (2018). Energetic demand and physical conditioning of table tennis players. A study review. *Journal of Sports Sciences*, *36*(7), 724–731. https://doi.org/10.1080/02640414.2017.1335957

Zagatto, A. M., Leite, J. V. de M., Papoti, M., & Beneke, R. (2016). Energetics of table tennis and table tennis–specific exercise testing. *International Journal of Sports Physiology and Performance*, *11*(8), 1012–1017. https://doi.org/10.1123/ijspp.2015-0746

Zagatto, A. M., Morel, E. A., & Gobatto, C. A. (2010). Physiological responses and characteristics of table tennis matches determined in official tournaments. *Journal of Strength and Conditioning Research*, *24*(4), 942–949. https://doi.org/10.1519/JSC.0b013e3181cb7003

Zagatto, A. M., Papoti, M., Dos Reis, I. G. M., Beck, W. R., & Gobatto, C. A. (2014). Analysis of cardiopulmonary and metabolic variables measured during laboratory and sport-specific incremental tests for table tennis performance prediction. *Science & Sports*, *29*(2), 62–70. https://doi.org/10.1016/j.scispo.2013.08.001

Zhu, M., Pi, Y., Zhang, J., & Gu, N. (2022). The superior response speed of table tennis players is associated with proactive inhibitory control. *PeerJ*, *10*, e13493. https://doi.org/10.7717/peerj.13493