

การปรับตัวเชิงแรง-เวลาเฉพาะเจาะจงต่อการฝึกแบบพลัยโอเมตริก และการฝึกแบบตรงกันข้ามในนักกีฬาวอลเลย์บอล

TRAINING-SPECIFIC FORCE-TIME ADAPTATIONS FOLLOWING PLYOMETRIC AND CONTRAST TRAINING IN VOLLEYBALL PLAYERS

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บทคัดย่อ

การศึกษานี้มีวัตถุประสงค์เพื่อตรวจสอบและเปรียบเทียบผลของการฝึกแบบพลัยโอเมตริก (PLY) และการฝึกแบบตรงกันข้าม (CT) ร่วมกับการฝึกซ้อมวอลเลย์บอลตามปกติกับกลุ่มควบคุม (CON) ในนักกีฬาวอลเลย์บอลชายระดับมหาวิทยาลัย จำนวน 45 คน เพื่อลดความแปรปรวนจากค่าเริ่มต้น ผู้เข้าร่วมการวิจัย (N = 45) ถูกจัดลำดับตามเวลาการวิ่งสปริง 0–5 เมตร จัดกลุ่มเป็นชุดสามคนที่มีความใกล้เคียงกัน และสุ่มแบ่งด้วยอัตราส่วน 1:1:1 เข้าสู่กลุ่มการฝึกแบบตรงกันข้าม (CT) กลุ่มการฝึกแบบพลัยโอเมตริก (PLY) หรือกลุ่มควบคุม (CON) (กลุ่มละ 15 คน) ตัวแปรทางชีวกลศาสตร์ของการกระโดดเคาน์เตอร์มูฟเมนต์ (CMJ) ได้แก่ พลังสูงสุด, พลังสูงสุดสัมพัทธ์, อัตราการสร้างแรง (RFD), แรงดล และความสูงในการกระโดด ได้รับการประเมินผ่านแผ่นรับแรง (force platform) และวิเคราะห์ด้วยสถิติ Multivariate และ Repeated-measures ANOVA ผลการศึกษา พบว่า ลักษณะเชิงแรง-เวลา (force-time characteristics) ของ CMJ ในกลุ่มทดลองทั้งสองกลุ่มมีการพัฒนาขึ้นอย่างมีนัยสำคัญทางสถิติเมื่อเทียบกับกลุ่ม CON ($p < .001$) โดยไม่มีความแตกต่างอย่างมีนัยสำคัญระหว่างกลุ่มที่จุดเริ่มต้นก่อนการแทรกแซง ($p > .05$) การเปรียบเทียบรายคู่เพิ่มเติมแสดงให้เห็นรูปแบบการปรับตัวทางกลไกที่แตกต่างกันระหว่างรูปแบบการฝึก โดยกลุ่ม CT แสดงผลลัพธ์ที่ดีกว่ากลุ่ม CON อย่างมีนัยสำคัญ และเหนือกว่ากลุ่ม PLY ในตัวแปรช่วงปลายบางตัว เช่น Peak RFD90, Relative Peak RFD90 และ Gross Impulse300 ($p < .05$) รวมถึงมีพลังสูงสุดสัมพัทธ์และความสูงในการกระโดดที่สูงกว่า ในทางกลับกัน ในช่วงเริ่มต้นของการสร้างแรง (0–30 มิลลิวินาที) ทั้งกลุ่ม PLY และ CT สามารถปรับปรุงการสร้างแรงอย่างรวดเร็วในช่วงต้น ซึ่งสะท้อนผ่าน Peak RFD30 และ Relative Peak RFD30 ได้ อย่างมีนัยสำคัญเมื่อเทียบกับกลุ่ม CON ($p < .05$) โดยไม่มีความแตกต่างอย่างมีนัยสำคัญทางสถิติระหว่างกลุ่มทดลองทั้งสองกลุ่ม ($p > .05$) สรุปได้ว่า ทั้งการฝึกแบบ PLY และ CT สามารถพัฒนาประสิทธิภาพการกระโดดได้อย่างมีประสิทธิภาพเมื่อเทียบกับการฝึกซ้อมวอลเลย์บอลตามปกติเพียงอย่างเดียว ผ่านรูปแบบการปรับตัวทางกลไกที่แตกต่างกันในแต่ละช่วงเวลา โดยการฝึกแบบ CT ส่งผลให้เกิดการพัฒนาในส่วน of อัตราการสร้างแรง (RFD) ช่วงปลายและความสูงในการกระโดดได้ดีกว่า ในขณะที่ทั้งสองวิธีช่วยพัฒนาการสร้างแรงอย่างรวดเร็วในช่วงต้นได้อย่างมีนัยสำคัญโดยไม่มีความแตกต่างกัน สิ่งนี้ตอกย้ำถึงการประยุกต์ใช้จริงของการวิเคราะห์ลักษณะเชิงแรง-เวลา (force-time profiling) เพื่อการกำหนดโปรแกรมการฝึกเฉพาะบุคคล

คำสำคัญ: การฝึกแบบพลัยโอเมตริก, การฝึกแบบตรงกันข้าม, การกระโดดเคาน์เตอร์มูฟเมนต์, อัตราการสร้างแรง, วอลเลย์บอล

Abstract

This study aimed to investigate and compare the effects of plyometric training (PLY) and contrast training (CT), combined with routine volleyball practice, against a control group (CON) in 45 male collegiate volleyball players. To minimize baseline variability, participants ($N = 45$) were ranked according to their 0–5 m sprint times, organized into matched triplets, and randomly allocated in a 1:1:1 ratio to the Contrast Training (CT), Plyometric Training (PLY), or Control (CON) group ($n = 15$ per group). Countermovement jump (CMJ) biomechanical variables, including peak power, relative peak power, rate of force development (RFD), impulse, and jump height, were assessed using a force platform and analyzed using multivariate and repeated-measures ANOVA. The results showed significant improvements in CMJ force–time characteristics in both experimental groups compared with CON ($p < .001$), with no significant between-group differences at baseline before the intervention ($p > .05$). Further pairwise comparisons revealed distinct mechanical adaptation profiles between the training modalities. CT demonstrated significantly better outcomes than CON and outperformed PLY in selected late-phase variables, such as Peak RFD90, Relative Peak RFD90, and Gross Impulse300 ($p < .05$), alongside greater relative peak power and jump height. In contrast, during the initial phase of force development (0–30 ms), both PLY and CT significantly improved early-phase rapid force development, as reflected in Peak RFD30 and Relative Peak RFD30, compared with CON ($p < .05$), with no statistically significant differences between the two experimental groups ($p > .05$). In conclusion, both PLY and CT effectively improved jumping performance compared with routine volleyball practice alone, through distinct mechanical adaptation profiles across temporal phases. CT produced greater improvements in late-phase RFD and jump height, whereas both methods significantly improved early-phase rapid force development, with no significant differences between them. These findings highlight the practical application of force–time profiling to individualized training prescription.

Keywords: Plyometric training, Contrast training, Countermovement jump, Rate of force development, Volleyball

Introduction

Volleyball is a high-intensity, intermittent team sport characterized by frequent explosive actions such as spiking, blocking, and rapid changes of direction that demand exceptional muscular strength, power, speed, agility, and vertical jump performance (Sheppard et al., 2009; Ziv & Lidor, 2010). Matches consist of short, high-intensity rallies primarily driven by the phosphagen system, supported by aerobic and glycolytic recovery (Gabbett & Georgieff, 2007; Rebelo et al., 2024), alongside elite anthropometric and physiological profiles favorable for power output (Sattler et al., 2015). Biomechanically, explosive performance relies on efficient kinetic-chain coordination (Wagner et al., 2009; Ziv & Lidor, 2010) and stretch–shortening cycle (SSC) utilization to minimize ground contact time and maximize reactive strength (Komi, 2000; Brughelli & Cronin, 2008). Moreover, rapid force generation is governed by neuromuscular efficiency including motor-unit recruitment, firing frequency, synchronization, and fast-twitch fiber activation establishing the rate of force development (RFD) as a critical index of explosive capacity in high-speed movements (Aagaard, 2003; Cormie et al., 2011).

Given these specific demands, training programs designed to enhance vertical jump performance and explosive power are essential for collegiate players transitioning to advanced competitive levels (Sheppard & Newton, 2012). Among various conditioning modalities, plyometric training (PLY) and contrast training (CT) are widely recognized as effective methods for developing lower-limb power. PLY leverages

the stretch–shortening cycle (SSC) through rapid eccentric-to-concentric transitions to store and release elastic energy, stimulate stretch reflexes, and enhance neural drive, motor unit recruitment, tendon stiffness, and reactive strength, thereby elevating explosive force and rate of force development (Markovic, 2007; Markovic & Mikulic, 2010; Stojanović et al., 2017), with systematic reviews confirming its efficacy in improving jumping ability and speed in volleyball players (Slimani et al., 2016; Milić et al., 2008). Conversely, CT alternates heavy resistance exercises with biomechanically similar explosive movements within the same training set, capitalizing on post-activation performance enhancement (PAPE) (Seitz & Haff, 2016; Tillin & Bishop, 2009) to heighten neural readiness, motor unit recruitment, and muscle calcium sensitivity for superior power output (Sale, 2002; Blazevich & Babault, 2019), a mechanism further supported by meta-analytic evidence in power-dependent athletes (Dobbs et al., 2019).

To monitor and evaluate these explosive adaptations, the countermovement jump (CMJ) assessed via a force platform has become a gold standard in sports science (Cormie et al., 2010). While traditional metrics like jump height and peak power provide a global assessment of performance, force–time characteristics including phase-specific rate of force development (e.g., RFD30 and RFD90) and impulse offer granular insights into the underlying mechanical and neuromuscular adaptation profiles of different training regimens (Rebello et al., 2024).

Although extensive research confirms that both PLY and CT improve general jumping ability and power output, comparative studies evaluating their specific effects on CMJ force–time characteristics among university volleyball players remain limited. Previous investigations have predominantly focused on global performance measures (e.g., jump height and peak power), leaving a critical knowledge gap regarding how PLY and CT distinctly influence phase-specific force production, such as early-phase rapid force generation versus late-phase impulse accumulation. Therefore, this study aimed to compare the effects of 8 weeks of PLY and CT combined with routine volleyball practice on the force–time characteristics of the CMJ in male collegiate volleyball players. The findings of this study are expected to clarify the distinct mechanical adaptation profiles associated with each training modality, providing coaches and practitioners with empirical evidence to inform individualized training prescriptions based on athletes' specific force–time profiles.

Research Methodology

This study employed a repeated-measures experimental design. Participants were allocated into three groups, with dependent variables evaluated pre- and post-8-week intervention. All testing sessions were conducted under standardized laboratory conditions (25–26°C, 09:00–12:00 h) to minimize circadian effects.

1. Participants and Allocation

Forty-five male collegiate volleyball players from Chandrakasem Rajabhat University were recruited via purposive sampling (age: 19–21 years; competitive experience: >5 years; no musculoskeletal injuries within the preceding 6 months). Sample size was calculated a priori using G*Power software (v. 3.1.9.7; Heinrich Heine University Düsseldorf, Germany) for a repeated-measures ANOVA (within–between interaction). Assuming a moderate-to-large effect size $f = 0.40$ (Cohen, 1988), $\alpha = 0.05$, and power $(1-\beta) = 0.95$, a correlation among repeated measures of 0.50, and a nonsphericity correction $\epsilon = 1.0$ for 3 groups across 2 time points, the analysis indicated a minimum requirement of 30 participants in total (10 participants per group). However, to account for potential dropouts during the intervention and to further enhance statistical power, a total of 45 participants ($n = 15$ per group) were recruited and completed the

study. To minimize baseline performance variability, a matched-triplet randomized design was implemented. Following baseline 0–5 m sprint testing (assessed using the Smart Speed Timing Gate System, Fusion Sport, Australia), participants (N = 45) were ranked by sprint times and categorized into matched triplets of equivalent performance. Within each triplet, participants were randomly allocated (1:1:1 ratio) via simple randomization to one of three groups (n = 15 per group): Contrast Training (CT), Plyometric Training (PLY), or Control (CON). The study protocol was approved by the Ethics Committee for Human Research of Chandrakasem Rajabhat University (Approval No. SWP.045/2567; October 2, 2024) and adhered to the Declaration of Helsinki. Data collection was conducted between October 2024 and October 2025. All participants received a comprehensive explanation of the study procedures and signed written informed consent prior to data collection.

2. Countermovement Jump Testing, Data Processing, and Measurement Reliability

2.1 Countermovement Jump (CMJ) Test Protocol

Lower-limb explosive power and jump height were assessed using the Countermovement Jump (CMJ) test on a force platform (Force Plate 400 Series Performance, Fitness Technology, Australia). Participants performed 3–5 practice trials prior to actual testing. During testing, participants stood with feet shoulder-width apart and kept their hands on their hips throughout the execution to eliminate arm-swing contribution. Upon signal, they rapidly squatted to a self-selected comfortable depth and executed a maximal vertical jump with maximum effort. Each participant completed two maximal trials (separated by a 2-minute rest interval), and the trial with the greatest jump height was selected for statistical analysis.

2.2 Data Acquisition and Calibration

Vertical ground reaction force (vGRF) data were acquired at a sampling frequency of 1,000 Hz via an XPV7 signal processing system interfaced with Ballistic Measurement System software (BMS, Fitness Technology). Prior to daily testing, the force platform was zero-calibrated (tared) under unloaded conditions and calibrated using a known standard reference mass. Signal consistency across all four channels (CH #1–CH #4 baseline: 5,900–6,000 counts) was verified via XPV7 Diagnostics prior to data collection.

2.3 Signal Filtering and Net Force Calculation Raw force–time data were filtered using a digital low-pass 4th-order Butterworth filter with a cut-off frequency of 50 Hz. System weight (W_{sys}) was determined while the participant stood motionless on the platform for 3 seconds prior to jump initiation. Net vertical force ($F_{net}(t)$) at any given time point t was calculated as: $F_{net}(t) = F_{total}(t) - W_{sys}$ (where $F_{total}(t)$ represents the instantaneous vertical force and W_{sys} represents the static system weight).

2.4 Phase Boundaries Detection Movement Onset: Defined as the point at which F_{total} decreased below W_{sys} by 5 standard deviations (5 SD) or 20 N of the quiet standing baseline for a minimum duration of 30 ms. Take-off: Defined as the threshold where vertical force dropped below 10 N or 5 SD. Landing: Defined as the instance when vertical force exceeded 10 N.

2.5 Jump Height and Peak Power Calculation Jump height (JH) was derived from take-off velocity calculated via the impulse–momentum relationship:

$$JH = \left[\frac{v_{takeoff}^2}{2g} \right] \quad \text{Where} \quad v_{takeoff} = \int_{t_{onset}}^{t_{takeoff}} \frac{F_{net}(t)}{m} dt \quad \dots\dots\dots (1)$$

(where $m = W_{sys}/g$ represents participant mass and $g = 9.81\text{m/s}^2$), Peak power (PP) was determined as the maximum product of instantaneous force and velocity ($P(t) = F_{total}(t) \times v(t)$) during the concentric phase prior to take-off.

2.6 Rate of force development (RFD) was defined as the time rate of change of net vertical force calculated from concentric phase onset:

2.6.1 Peak RFD (0–30 ms): Peak rate of force development calculated over a 30-ms moving window within the initial 30 ms following concentric phase onset.

$$\text{Peak RFD}_{30} = \max_{t_{\text{onset}} \leq t \leq t_{\text{onset}} + t_{\text{window}}} \left(\frac{F(t+0.030) - F(t)}{0.030} \right) \quad \dots\dots\dots (2)$$

2.6.2 Peak RFD (0–90 ms): Peak rate of force development calculated over a 90-ms moving window within the initial 90 ms following concentric phase onset.

$$\text{Peak RFD}_{90} = \max_{t_{\text{onset}} \leq t \leq t_{\text{onset}} + t_{\text{window}}} \left(\frac{F(t+0.090) - F(t)}{0.090} \right) \quad \dots\dots\dots (3)$$

Note: Relative Peak RFD, Relative Peak RFD (0–30 ms), and Relative Peak RFD (0–90 ms) were calculated by normalizing their respective absolute Peak RFD values to each participant's body mass ($\text{N} \cdot \text{s}^{-1} \cdot \text{kg}^{-1}$).

2.6.3 Gross Impulse₃₀₀ (0–300 ms): Gross Impulse₃₀₀ was calculated by integrating the total vertical ground reaction force–time curve from movement onset (t_{onset}) to $t_{\text{onset}} + 0.300$ s (300 ms):

$$\text{Gross Impulse}_{300} = \int_{t_{\text{onset}}}^{t_{\text{onset}}+0.300} F_{\text{total}}(t) dt \quad \dots\dots\dots (4)$$

(where t_{onset} is the time point of movement onset, and $F_{\text{total}}(t)$ is the total vertical ground reaction force).

2.7 Within-session reliability

The reliability of all 11 Countermovement Jump (CMJ) biomechanical variables ($N = 45$) was evaluated pre- and post-intervention using a two-way mixed-effects model for single measures with absolute agreement (ICC_{3,1}) alongside coefficients of variation (CV). Pre-training evaluation yielded ICC values ranging from 0.830 to 0.997 with CVs of 2.31% to 5.36%, while post-training evaluation showed ICC values ranging from 0.925 to 0.994 with CVs of 3.96% to 6.65%. Rate of force development (RFD) parameters displayed ICC values greater than 0.950 and $\text{CV} \leq 5.55\%$. Point estimates, 95% confidence intervals (95% CIs), and CV values for each individual variable are detailed in Supplementary Table S1 (interpreted using the criteria established by Koo & Li, 2016).

3. Training Programs & Safety Protocols

3.1 Training Programs and Adherence

The contrast training (CT) and plyometric training (PLY) groups completed an 8-week supplementary training program (conducted twice weekly: Tuesdays and Thursdays) alongside their standard volleyball training. All participants, including the control group (CON), engaged solely in the team's standard volleyball practice on Mondays, Wednesdays, Fridays, and Saturdays. Each 70–80 min training session comprised three distinct phases:

3.1.1 Warm-up (15–20 min): Included general light jogging/walking (5–7 min), dynamic stretching for joint and muscle mobility (5–7 min), and multi-directional skill-specific movements (5–7 min).

3.1.2 Main Training (40–45 min): Rest intervals were 2–3 min between sets and 3–5 min between exercises/pairs.

3.1.2.1 Plyometric Training (PLY): Followed a progressive overload model across 8 weeks: Weeks 1–2 (Low-to-moderate intensity): Basic exercises (Squat Jump, Single-leg Vertical Jump, Standing Long Jump, Power Skipping) at 4 sets $\times$ 8 repetitions (128 foot contacts/session; 40-cm hurdle height). Weeks 3–4: Increased volume to 5 sets $\times$ 8 repetitions (160 foot contacts/session; 40-cm hurdle

height). Weeks 5–6 (High intensity): Advanced exercises (Repeated Tuck Jump, Split Squat Jump, Front Hurdle Hop, Alternate-Leg Bounding) at 5 sets × 8 repetitions (160 foot contacts/session; 50-cm hurdle height). Weeks 7–8: Peak volume at 5 sets × 10 repetitions (200 foot contacts/session; 50-cm hurdle height).

3.1.2.2 Contrast Training (CT): Combined heavy resistance and high-velocity movements to elicit Post-Activation Performance Enhancement (PAPE). To ensure methodological explicability and coincide with the optimal window of peak PAPE, a standardized 3-minute intra-set rest period was strictly implemented between the heavy conditioning activity (e.g., Back Squat) and the subsequent explosive movement (e.g., CMJ). The training progression was structured as follows: Weeks 1–2: Back Squat (3 × 5 at 80% 1RM) paired with Countermovement Jump (CMJ) (3 × 5); Trap Bar Jump Squat (3 × 5 at 20% 1RM) paired with Band-assisted Vertical Jump (3 × 5). Weeks 3–4: Back Squat (3 × 5 at 85% 1RM) + CMJ (3 × 5); Trap Bar Jump Squat (4 × 5 at 20% 1RM) + Band-assisted Vertical Jump (4 × 5). Following Week 4, 1RM values were re-evaluated to adjust training loads for Weeks 5–8, ensuring load progression reflected actual strength adaptations while preventing excessive overloading. Weeks 5–6: Back Squat (3 × 5 at 85% adjusted 1RM) + CMJ (3 × 5); Trap Bar Jump Squat (5 × 5 at 25% adjusted 1RM) + Band-assisted Vertical Jump (5 × 5). Weeks 7–8: Back Squat (3 × 3 at 95% adjusted 1RM) + CMJ (3 × 5); Trap Bar Jump Squat (5 × 6 at 30% adjusted 1RM) + Band-assisted Vertical Jump (5 × 6).

3.1.2.3 Control Group (CON): Participated exclusively in standard volleyball training without additional resistance or power interventions.

3.1.3 Cool-down (10–15 min): Static stretching targeting major muscle groups to alleviate neuromuscular fatigue and facilitate recovery.

4. Program Adherence: Participants were required to maintain a minimum adherence rate of 90% across all scheduled sessions, tracked via attendance logs. Any missed session due to valid reasons was fulfilled through a make-up session within the same week to ensure training volume consistency.

5. Safety Control Measures & Adverse Event Tracking

All testing and training (e.g., Back Squat) were supervised by at least two sports scientists at all times. Participants completed a Back Squat technique assessment prior to the study and were evaluated for fatigue before each session. Smith Machine safety catches were individually adjusted according to squat depth to prevent injury during momentary muscle failure. An adverse event logging system was implemented after every session, with immediate training suspension and physical therapy referral upon injury detection. Over the 8-week period, no severe injuries or dropouts occurred, with only standard Delayed Onset Muscle Soreness (DOMS) reported.

6. 1RM Testing and Load Determination

Prior to the intervention and at week 4 (mid-intervention re-evaluation), participants' one-repetition maximum (1RM) for the Back Squat was determined. To ensure participant safety and avoid the risks associated with maximal 1RM lifting in collegiate athletes, a submaximal estimation protocol (repetition-to-fatigue method) was utilized. Participants performed a standardized warm-up followed by a set to volitional fatigue using a submaximal load ($r < 10$ repetitions). The predicted 1RM was subsequently calculated using the prediction equation established by Brzycki (1993):

$$1RM = \frac{\text{Weight}}{1.0278 - 0.0278 \times r} \quad \dots\dots\dots (5)$$

where Weight is the resistance lifted and r is the number of repetitions completed to fatigue. This estimated 1RM was then used to prescribe the training intensities (e.g., 80% to 90% 1RM) across the 8-week intervention phases.

7. Data Collection Procedures and Statistical Analysis

All participants underwent countermovement jump (CMJ) testing at two time points: baseline (pre-test) and immediately following the completion of the training intervention (post-test). To minimize potential confounding effects, all testing sessions were conducted under standardized environmental conditions, maintaining constant ambient temperature and identical time-of-day for each individual session. Mechanical variables derived from the CMJ specifically peak power, jump performance, rate of force development (RFD), and impulse were processed using standard statistical software packages. All descriptive data are presented as mean $\pm$ standard deviation (SD). Prior to inferential analysis, data normality and homogeneity of variance were verified using the Shapiro–Wilk test and Levene’s test, respectively. The homogeneity of covariance matrices was evaluated using Box’s M test; when this assumption was violated ($p < .05$), Pillai’s Trace was reported for multivariate analysis. To examine the training effects over time across the predefined cluster of CMJ mechanical variables, a 3×2 mixed-model repeated-measures MANOVA was performed, with group (3 levels) as the between-subject factor and time (2 levels: pre- vs. post-test) as the within-subject factor. In the presence of a statistically significant time-by-group interaction, follow-up univariate repeated-measures ANOVAs accompanied by Bonferroni-adjusted post hoc tests were executed for pairwise comparisons. The statistical significance threshold for all inferential tests was set at $p < .05$.

Results

The presentation of the research results is divided into two parts: participant baseline characteristics and baseline equivalence, and the adaptations of mechanical performance in the countermovement jump (CMJ).

1. Baseline Characteristics of the participants

Table 1 presents the baseline analysis of the contrast training (CT) group, the plyometric training (PLY) group, and the control group (CON). The results indicate that participants across all three groups possessed similar fundamental physical characteristics in terms of age, body weight, and height prior to the commencement of the training program.

Table 1. Physical characteristics of the participants

Group	Age (years)	Body mass (kg)	Height (cm)
Contrast training (n = 15)	20.4 $\pm$ 1.10	69.81 $\pm$ 7.56	179.47 $\pm$ 5.82
Plyometric training (n = 15)	19.9 $\pm$ 1.20	69.40 $\pm$ 9.09	179.00 $\pm$ 5.44
Control (n = 15)	19.9 $\pm$ 1.30	69.17 $\pm$ 9.62	178.73 $\pm$ 6.62

Table 2. Mean and standard deviation, and percentage change of variables in power, rate of force development, impulse, and jump height from the Countermovement Jump (CMJ) test pre- and post-training of each group.

Variable	Group	Pre-test (Mean ± SD)	Post-test (Mean ± SD)	% Change
Power & Jump Performance				
Peak power (W)	CT	3347.73±408.04	4314.97±480.93	+28.9
	PLY	3378.59±532.02	3874.39±485.24	+14.7
	CON	3358.39±542.34	3314.26±562.02	-1.3
Relative peak power (W·kg ⁻¹)	CT	48.24±5.94	62.60±9.13	+29.8
	PLY	48.72±4.85	55.91±5.31	+14.8
	CON	48.72±6.11	47.77±6.07	-1.9
Jump height (cm)	CT	29.61±4.17	40.07±5.01	+35.3
	PLY	28.67±5.74	35.01±5.47	+22.1
	CON	29.30±4.84	29.58±4.88	+1.0
Rate of Force Development				
Peak RFD (N·s ⁻¹)	CT	6312.53±1767.82	8214.07±1770.17	+30.1
	PLY	6431.33±1578.44	7577.78±1540.49	+17.8
	CON	5890.20±1266.29	5939.27±1290.84	+0.8
Relative Peak RFD (N·s ⁻¹ ·kg ⁻¹)	CT	91.17±26.54	119.14±27.83	+30.7
	PLY	95.40±30.47	111.63±31.54	+17.0
	CON	86.65±23.03	86.96±23.83	+0.4
Peak RFD ₃₀ (N·s ⁻¹)	CT	3627.53±2202.08	5443.20±1952.62	+50.1
	PLY	4331.93±2255.68	6403.33±2191.37	+47.8
	CON	3385.80±1048.89	3449.73±990.58	+1.9
Relative Peak RFD ₃₀ (N·s ⁻¹ ·kg ⁻¹)	CT	52.71±34.59	79.34±31.45	+50.5
	PLY	64.78±37.09	95.78±40.01	+47.8
	CON	50.19±17.54	50.91±16.73	+1.4
Peak RFD ₉₀ (N·s ⁻¹)	CT	2914.87±919.80	5973.60±1458.35	+104.9
	PLY	3217.07±1805.64	4385.07±1595.72	+36.3
	CON	2659.87±843.95	2719.85±857.55	+2.3
Relative Peak RFD ₉₀ (N·s ⁻¹ ·kg ⁻¹)	CT	42.77±16.64	87.15±25.29	+103.8
	PLY	47.65±26.93	65.08±27.31	+36.6
	CON	38.93±13.75	39.60±13.88	+1.7
Impulse Characteristics				
Gross Impulse ₃₀₀ (N·s)	CT	262.22±46.18	386.26±46.33	+47.3
	PLY	264.45±57.46	339.35±50.11	+28.3
	CON	263.80±47.36	261.60±43.65	-0.8
Relative Impulse ₃₀₀ (N·s·kg ⁻¹)	CT	3.77±0.59	5.59±0.82	+48.3
	PLY	3.81±0.71	4.91±0.77	+28.9
	CON	3.86±0.80	3.80±0.69	-1.6

Note: Data are presented as mean ± standard deviation (Mean ± SD); CT = Contrast Training group; PLY = Plyometric Training group; and CON = Control Group.

2. Descriptive Statistics and Percentage Changes

Descriptive statistics (Mean ± SD) and percentage changes (%Δ) for all mechanical and kinematic variables across the Contrast Training (CT), Plyometric Training (PLY), and Control (CON) groups are presented in Table 2. Following the 8-week intervention, both experimental groups (CT and PLY) exhibited substantial performance enhancements across all variables compared to the control group. The CT group demonstrated the highest percentage improvements in late-phase kinetics and overall jump performance,

including jump height (+35.3%), Peak RFD90 (+104.9%), Relative Peak RFD90 (+103.8%), Gross Impulse300 (+47.3%), and Relative Impulse300 (+48.3%). Furthermore, CT recorded the highest relative percentage gains in early-phase force production, with an increase of +50.1% in Peak RFD30 and +50.5% in Relative Peak RFD30. Meanwhile, the PLY group also showed substantial development in early-phase force production (Peak RFD30 increase of +47.8%). Owing to a higher pre-intervention baseline, the PLY group ultimately attained the highest absolute and relative mean values among all groups post-intervention for Peak RFD30 ($6403.33 \pm 2191.37 \text{ N}\cdot\text{s}^{-1}$, +47.8%) and Relative Peak RFD30 ($95.78 \pm 40.01 \text{ N}\cdot\text{s}^{-1}\cdot\text{kg}^{-1}$, +47.8%). In contrast, the CON group exhibited minimal fluctuations across all parameters, with percentage changes remaining within a narrow range of -1.9% to +2.3%. The descriptive changes presented above serve solely as an initial trend analysis of the data and do not represent formal hypothesis testing. The inferential statistical analyses and interaction effects of the training interventions are detailed in the subsequent section.

3. Assumptions Testing and Statistical Selection

Prior to conducting statistical analyses for hypothesis testing, the researcher evaluated the underlying assumptions of Repeated Measures Multivariate Analysis of Variance (Repeated Measures MANOVA). The testing began with assessing the homogeneity of covariance matrices using Box's M test. The results indicated that all dependent variable sets statistically violated this assumption ($p \leq .001$), specifically: Power & Jump Performance: Box's $M = 100.108$, $F(42, 5236.942) = 1.883$, $p = .001$, Rate of Force Development: Box's $M = 585.728$, $F(156, 4700.258) = 2.149$, $p < .001$, Impulse: Box's $M = 53.204$, $F(20, 6331.980) = 2.289$, $p = .001$. Consequently, the researcher selected Pillai's Trace test statistic instead of Wilks' Lambda to evaluate the main effects and interaction effects in the multivariate analysis, as Pillai's Trace demonstrates the highest robustness against the violation of covariance matrix homogeneity. For the homogeneity of variance assumption, Levene's Test revealed that most dependent variables at both pre- and post-training exhibited no statistically significant differences in variance ($p > .05$), satisfying the assumption. However, minor violations ($p < .05$) were observed in specific dependent variables, including: Post-training Peak Rate of Force Development at 0–30 ms [$F(2, 42) = 4.882$, $p = .012$], Post-training Relative Peak Rate of Force Development at 0–30 ms [$F(2, 42) = 4.454$, $p = .018$], Pre-training Peak Rate of Force Development at 0–90 ms [$F(2, 42) = 4.000$, $p = .026$], Pre-training Relative Peak Rate of Force Development at 0–90 ms [$F(2, 42) = 5.472$, $p = .008$], Post-training Relative Peak Rate of Force Development at 0–90 ms [$F(2, 42) = 3.289$, $p = .047$]. Because the sample sizes were equal across all groups ($n = 15$ per group, total $N = 45$), the F -test remains robust against these violations. Furthermore, the researcher applied the Bonferroni adjustment method for subsequent pairwise comparisons to control and prevent Type I error inflation. Following the completion of assumption testing, inferential statistical analyses were conducted to evaluate group main effects (training method), time main effects, and Time x Group interaction effects across the descriptive variables, as detailed in the subsequent table.

Table 3. Multivariate Tests of Main and Interaction Effects

Effect	Test Statistic	Value	F	df1,df2	p-value	Partial η^2
Power & Jump Performance						
Group	Pillai's Trace	.253	1.981	6,82	.078	.127
Time	Pillai's Trace	.933	184.283	3,40	< .001*	.933
Time × Group	Pillai's Trace	.908	11.375	6,82	< .001*	.454
Rate of Force Development						
Group	Pillai's Trace	.447	1.824	12, 76	.059	.224
Time	Pillai's Trace	.943	102.549	6, 37	< .001*	.943
Time × Group	Pillai's Trace	1.255	10.669	12, 76	< .001*	.628
Impulse						
Group	Pillai's Trace	.263	3.182	4, 82	.017*	.132
Time	Pillai's Trace	.854	120.323	2, 41	< .001*	.854
Time × Group	Pillai's Trace	.783	13.521	4, 82	< .001*	.392

Note: Pillai's Trace was reported due to the violation of the assumption of homogeneity of covariance matrices (Box's *M* test). * Statistically significant at the .05 level ($p < .05$).

4. Multivariate Analysis of Main and Interaction Effects

A repeated-measures multivariate analysis of variance (RM-MANOVA) was conducted to evaluate the effects of the training interventions and time on three domains of dependent variables: Power & Jump Performance, Rate of Force Development (RFD), and Impulse (Table 3). Due to the violation of the homogeneity of covariance matrices assumption (Box's *M* test), Pillai's Trace statistic was reported in accordance with established statistical standards. For Power & Jump Performance, the multivariate test revealed a statistically significant main effect for Time (Pillai's Trace = .933, $F(3, 40) = 184.283$, $p < .001$, partial $\eta^2 = .933$), indicating overall performance changes across time points. Although the main effect for Group was not statistically significant (Pillai's Trace = .253, $F(6, 82) = 1.981$, $p = .078$, partial $\eta^2 = .127$), a statistically significant Time × Group interaction effect was observed (Pillai's Trace = .908, $F(6, 82) = 11.375$, $p < .001$, partial $\eta^2 = .454$). This demonstrates that the trajectory of change in power and jump performance across time was dependent on the specific training intervention received. Regarding Rate of Force Development (RFD), a significant main effect for Time was also found (Pillai's Trace = .943, $F(6, 37) = 102.549$, $p < .001$, partial $\eta^2 = .943$), while the main effect for Group did not reach statistical significance (Pillai's Trace = .447, $F(12, 76) = 1.824$, $p = .059$, partial $\eta^2 = .224$). However, a highly significant Time × Group interaction effect was detected (Pillai's Trace = 1.255, $F(12, 76) = 10.669$, $p < .001$, partial $\eta^2 = .628$), indicating distinct, group-specific adaptations in explosive force production over the training period. For Impulse, statistically significant main effects were found for both Group (Pillai's Trace = .263, $F(4, 82) = 3.182$, $p = .017$, partial $\eta^2 = .132$) and Time (Pillai's Trace = .854, $F(2, 41) = 120.323$, $p < .001$, partial $\eta^2 = .854$). Furthermore, a statistically significant Time × Group interaction effect was present (Pillai's Trace = .783, $F(4, 82) = 13.521$, $p < .001$, partial $\eta^2 = .392$), confirming that changes in impulse were jointly influenced by the training modality and time. Given the statistically significant Time × Group interaction effects across all variable domains ($p < .001$), further statistical decomposition via simple main effects analysis and subsequent pairwise comparisons was warranted.

Table 4. Univariate tests of Time effect and Time × Group interaction effect for Power & Jump Performance (P&JP), Rate of Force Development (RFD), and Impulse variables

Factor / Dependent Variable	Source	SS	df1,df2	MS	F	p-value	Partial η^2
Power & Jump Performance (P&JP)							
Time							
Peak power (W)	Sphericity Assumed	5033287.62	1, 42	5033287.62	244.329	< .001*	.853
Relative peak power (W.kg ⁻¹)	Sphericity Assumed	1061.59	1, 42	1061.59	159.762	< .001*	.792
Jump height (cm)	Sphericity Assumed	729.32	1, 42	729.32	403.372	< .001*	.906
Time × Group							
Peak power (W)	Sphericity Assumed	3841698.67	2, 42	1920849.34	93.243	< .001*	.816
Relative peak power (W.kg ⁻¹)	Sphericity Assumed	879.79	2, 42	439.89	66.201	< .001*	.759
Jump height (cm)	Sphericity Assumed	393.33	2, 42	196.66	108.771	< .001*	.838
Rate of Force Development (RFD)							
Time							
Peak RFD (N.s ⁻¹)	Sphericity Assumed	23979245.139	1, 42	23979245.139	158.416	< .001*	.790
Relative Peak RFD (N.s ⁻¹ .kg ⁻¹)	Sphericity Assumed	4952.108	1, 42	4952.108	147.346	< .001*	.778
Peak RFD ₃₀ (N.s ⁻¹)	Sphericity Assumed	39026002.500	1, 42	39026002.500	72.578	< .001*	.633
Relative Peak RFD ₃₀ (N.s ⁻¹ .kg ⁻¹)	Sphericity Assumed	8512.779	1, 42	8512.779	63.902	< .001*	.603
Peak RFD ₉₀ (N.s ⁻¹)	Sphericity Assumed	45939778.005	1, 42	45939778.005	229.887	< .001*	.846
Relative Peak RFD ₉₀ (N.s ⁻¹ .kg ⁻¹)	Sphericity Assumed	9761.459	1, 42	9761.459	246.226	< .001*	.854
Time × Group							
Peak RFD (N.s ⁻¹)	Sphericity Assumed	13015078.724	2, 42	6507539.362	42.991	< .001*	.672
Relative Peak RFD (N.s ⁻¹ .kg ⁻¹)	Sphericity Assumed	2889.422	2, 42	1444.711	42.986	< .001*	.672
Peak RFD ₃₀ (N.s ⁻¹)	Sphericity Assumed	17909729.067	2, 42	8954864.533	16.654	< .001*	.442
Relative Peak RFD ₃₀ (N.s ⁻¹ .kg ⁻¹)	Sphericity Assumed	4016.027	2, 42	2008.013	15.073	< .001*	.418
Peak RFD ₉₀ (N.s ⁻¹)	Sphericity Assumed	34487756.031	2, 42	17243878.015	86.290	< .001*	.804
Relative Peak RFD ₉₀ (N.s ⁻¹ .kg ⁻¹)	Sphericity Assumed	7295.928	2, 42	3647.964	92.018	< .001*	.814
Impulse							
Time							
Gross Impulse ₃₀₀ (N.s)	Sphericity Assumed	96766.569	1, 42	96766.569	236.186	< .001*	.849
Relative Impulse ₃₀₀ (N.s.kg ⁻¹)	Sphericity Assumed	20.544	1, 42	20.544	172.481	< .001*	.804
Time × Group							
Gross Impulse ₃₀₀ (N.s)	Sphericity Assumed	60739.218	2, 42	30369.609	74.125	< .001*	.779
Relative Impulse ₃₀₀ (N.s.kg ⁻¹)	Sphericity Assumed	13.583	2, 42	6.791	57.018	< .001*	.731

Note: SS = Sum of Squares; df = Degrees of Freedom; MS = Mean Square; F = F-statistic; p = p-value; Partial η^2 = Partial Eta Squared; * Statistically significant at the .05 level ($p < .05$)

5. Univariate Tests of Main and Interaction Effects

Follow-up univariate ANOVA tests were examined to evaluate the main effects of Time and the Time × Group interaction effects across all dependent variables within the three performance domains (Table 4).

5.1 Power & Jump Performance (P&JP): Statistically significant main effects for Time were observed across all parameters ($p < .001$): Peak Power [$F(1, 42) = 244.329, p < .001$, partial $\eta^2 = .853$], Relative Peak Power [$F(1, 42) = 159.762, p < .001$, partial $\eta^2 = .792$], and Jump Height [$F(1, 42) = 403.372, p < .001$, partial $\eta^2 = .906$]. Furthermore, statistically significant Time × Group interaction effects were detected for all variables ($p < .001$): Peak Power [$F(2, 42) = 93.243, p < .001$, partial $\eta^2 = .816$], Relative Peak Power [$F(2, 42) = 66.201, p < .001$, partial $\eta^2 = .759$], and Jump Height [$F(2, 42) = 108.771, p < .001$, partial $\eta^2 = .838$].

5.2 Rate of Force Development (RFD): Significant main effects for Time were confirmed for all RFD variables ($p < .001$): Peak RFD [$F(1, 42) = 158.416, p < .001$, partial $\eta^2 = .790$], Relative Peak RFD [$F(1, 42) = 147.346, p < .001$, partial $\eta^2 = .778$], Peak RFD₃₀ [$F(1, 42) = 72.578, p < .001$, partial $\eta^2 = .633$], Relative Peak RFD₃₀ [$F(1, 42) = 63.902, p < .001$, partial $\eta^2 = .603$], Peak RFD₉₀ [$F(1, 42) = 229.887, p < .001$, partial $\eta^2 = .846$], and Relative Peak RFD₉₀ [$F(1, 42) = 246.226, p < .001$, partial $\eta^2 = .854$]. Similarly, significant Time × Group interaction effects were demonstrated across all RFD metrics ($p < .001$): Peak RFD [$F(2, 42) = 42.991$,

$p < .001$, partial $\eta^2 = .672$], Relative Peak RFD [$F(2, 42) = 42.986$, $p < .001$, partial $\eta^2 = .672$], Peak RFD30 [$F(2, 42) = 16.654$, $p < .001$, partial $\eta^2 = .442$], Relative Peak RFD30 [$F(2, 42) = 15.073$, $p < .001$, partial $\eta^2 = .418$], Peak RFD90 [$F(2, 42) = 86.290$, $p < .001$, partial $\eta^2 = .804$], and Relative Peak RFD90 [$F(2, 42) = 92.018$, $p < .001$, partial $\eta^2 = .814$].

5.3 Impulse: Statistically significant main effects for Time were found for both Impulse variables ($p < .001$): Gross Impulse300 [$F(1, 42) = 236.186$, $p < .001$, partial $\eta^2 = .849$] and Relative Impulse300 [$F(1, 42) = 172.481$, $p < .001$, partial $\eta^2 = .804$]. Additionally, statistically significant Time $\times$ Group interaction effects were observed ($p < .001$): Impulse300 [$F(2, 42) = 74.125$, $p < .001$, partial $\eta^2 = .779$] and Relative Impulse300 [$F(2, 42) = 57.018$, $p < .001$, partial $\eta^2 = .731$].

The presence of significant Time $\times$ Group interaction effects across all dependent variables confirms that performance changes over time were moderated by the specific training intervention. Consequently, simple main effect analyses were conducted to further examine group differences at each time point and changes over time within each group.

Table 5. Comparison of Differences Between Experimental Groups at Baseline (Time 1) and Post-training (Time 2) for Power & Jump Performance (P&JP), Rate of Force Development (RFD), and Impulse variables

Variable	Period	(I) Group	(J) Group	Mean Difference (I-J)	SE	p-value	95% CI
Power & Jump Performance (P&JP)							
Peak Power (W)	Baseline (Time 1)	CT	PLY	-30.860	181.802	1.000	[-484.214, 422.494]
		CT	CON	-10.667	181.802	1.000	[-464.021, 442.687]
		PLY	CON	20.193	181.802	1.000	[-433.161, 473.547]
	Post-training (Time 2)	CT	PLY	440.580	186.501	.069	[-24.485, 905.659]
		CT	CON	1000.710	186.501	<.001*	[535.641, 1465.785]
		PLY	CON	560.130	186.501	.013*	[95.055, 1025.199]
Relative Peak Power (W·kg ⁻¹)	Baseline (Time 1)	CT	PLY	-.480	2.067	1.000	[-5.635, 4.675]
		CT	CON	-.480	2.067	1.000	[-5.635, 4.675]
		PLY	CON	.000	2.067	1.000	[-5.155, 5.155]
	Post-training (Time 2)	CT	PLY	6.687	2.569	.038*	[.281, 13.092]
		CT	CON	14.827	2.569	<.001*	[8.421, 21.232]
		PLY	CON	8.140	2.569	.009*	[1.735, 14.545]
Jump Height (cm)	Baseline (Time 1)	CT	PLY	.940	1.811	1.000	[-3.570, 5.463]
		CT	CON	.310	1.811	1.000	[-4.203, 4.830]
		PLY	CON	-.630	1.811	1.000	[-5.150, 3.883]
	Post-training (Time 2)	CT	PLY	5.067	1.871	.029*	[.400, 9.733]
		CT	CON	10.493	1.871	<.001*	[5.827, 15.160]
		PLY	CON	5.427	1.871	.018*	[.760, 10.093]
Rate of Force Development (RFD)							
Peak RFD (N·s ⁻¹)	Baseline (Time 1)	CT	PLY	-118.800	566.476	1.000	[-1531.403, 1293.803]
		CT	CON	422.333	566.476	1.000	[-990.270, 1834.936]
		PLY	CON	541.133	566.476	1.000	[-871.470, 1953.736]
	Post-training (Time 2)	CT	PLY	636.287	564.620	.799	[-771.687, 2044.260]
		CT	CON	2274.800	564.620	.001*	[866.826, 3682.774]
		PLY	CON	1638.513	564.620	.018*	[230.540, 3046.487]
Relative Peak RFD (N·s ⁻¹ ·kg ⁻¹)	Baseline (Time 1)	CT	PLY	-4.227	9.805	1.000	[-28.676, 20.223]
		CT	CON	4.527	9.805	1.000	[-19.923, 28.976]
		PLY	CON	8.753	9.805	1.000	[-15.696, 33.203]
	Post-training (Time 2)	CT	PLY	7.513	10.192	1.000	[-17.903, 32.930]
		CT	CON	32.180	10.192	.009*	[6.764, 57.596]
		PLY	CON	24.667	10.192	.060	[-0.750, 50.083]

Table 5. (continued)

Variable	Period	(I) Group	(J) Group	Mean Difference (I-J)	SE	p-value	95% CI
Relative Peak RFD (N·s ⁻¹ ·kg ⁻¹)	Baseline	CT	PLY	-4.227	9.805	1.000	[-28.676, 20.223]
	(Time 1)	CT	CON	4.527	9.805	1.000	[-19.923, 28.976]
		PLY	CON	8.753	9.805	1.000	[-15.696, 33.203]
	Post-training (Time 2)	CT	PLY	7.513	10.192	1.000	[-17.903, 32.930]
		CT	CON	32.180	10.192	.009*	[6.764, 57.596]
		PLY	CON	24.667	10.192	.060	[-0.750, 50.083]
Peak RFD ₃₀ (N·s ⁻¹)	Baseline	CT	PLY	-704.400	700.395	.961	[-2450.951, 1042.151]
	(Time 1)	CT	CON	241.733	700.395	1.000	[-1504.818, 1988.284]
		PLY	CON	946.133	700.395	.552	[-800.418, 2692.684]
	Post-training (Time 2)	CT	PLY	-960.133	653.064	.447	[-2588.658, 668.391]
		CT	CON	1993.467	653.064	.012*	[364.942, 3621.991]
		PLY	CON	2953.600	653.064	<.001*	[1325.075, 4582.125]
Relative Peak RFD ₉₀ (N·s ⁻¹ ·kg ⁻¹)	Baseline	CT	PLY	-12.067	11.313	.877	[-40.278, 16.145]
	(Time 1)	CT	CON	2.527	11.313	1.000	[-25.685, 30.738]
		PLY	CON	14.593	11.313	.612	[-13.618, 42.805]
	Post-training (Time 2)	CT	PLY	-16.440	11.294	.459	[-44.603, 11.723]
		CT	CON	28.427	11.294	.047*	[0.264, 56.589]
		PLY	CON	44.867	11.294	.001*	[16.704, 73.029]
Peak RFD ₉₀ (N·s ⁻¹)	Baseline	CT	PLY	-302.200	462.775	1.000	[-1456.206, 851.806]
	(Time 1)	CT	CON	255.000	462.775	1.000	[-899.006, 1409.006]
		PLY	CON	557.200	462.775	.706	[-596.806, 1711.206]
	Post-training (Time 2)	CT	PLY	1,588.533	490.283	.007*	[365.931, 2811.136]
		CT	CON	3,253.753	490.283	<.001*	[2031.151, 4476.356]
		PLY	CON	1,665.220	490.283	.005*	[442.617, 2887.823]
Relative Peak RFD ₉₀ (N·s ⁻¹ ·kg ⁻¹)	Baseline	CT	PLY	-4.887	7.277	1.000	[-23.032, 13.259]
	(Time 1)	CT	CON	3.840	7.277	1.000	[-14.305, 21.985]
		PLY	CON	8.727	7.277	.711	[-9.419, 26.872]
	Post-training (Time 2)	CT	PLY	22.073	8.375	.035*	[1.188, 42.958]
		CT	CON	47.553	8.375	<.001*	[26.668, 68.438]
		PLY	CON	25.480	8.375	.012*	[4.595, 46.365]
Impulse							
Gross Impulse ₃₀₀ (N·s)	Baseline	CT	PLY	-2.227	18.472	1.000	[-48.289, 43.836]
	(Time 1)	CT	CON	-1.580	18.472	1.000	[-47.643, 44.483]
		PLY	CON	0.647	18.472	1.000	[-45.416, 46.709]
	Post-training (Time 2)	CT	PLY	46.913	17.079	.026*	[4.324, 89.503]
		CT	CON	124.660	17.079	<.001*	[82.071, 167.249]
		PLY	CON	77.747	17.079	<.001*	[35.157, 120.336]
Relative Impulse ₃₀₀ (N·s·kg ⁻¹)	Baseline	CT	PLY	-0.040	0.257	1.000	[-0.681, 0.601]
	(Time 1)	CT	CON	-0.093	0.257	1.000	[-0.735, 0.548]
		PLY	CON	-0.053	0.257	1.000	[-0.695, 0.588]
	Post-training (Time 2)	CT	PLY	0.687	0.278	.053	[-0.008, 1.381]
		CT	CON	1.793	0.278	<.001*	[1.099, 2.488]
		PLY	CON	1.107	0.278	.001*	[0.412, 1.801]

Note. SE = Standard Error; CI = Confidence Interval; * The mean difference is significant at the .05 level. Adjustments for multiple comparisons (e.g., Bonferroni) were applied as specified in the statistical model.

6. Post-Hoc Pairwise Comparisons

The results of the pairwise comparisons between the experimental groups prior to training (Time 1) and after training (Time 2), with p -values adjusted using the Bonferroni method as shown in Table 5, are categorized by biomechanical movement variable groups as follows:

6.1 Power & Jump Performance (P&JP) Prior to training (Time 1), no statistically significant differences were found among all three experimental groups across all variables (all $p = 1.000$), confirming that participants in all groups had equal baseline physical performance. However, after training (Time 2), statistically significant changes were observed. For Peak Power, both the CT group and the PLY group were significantly higher than the CON group ($MD = 1000.710$, $p < .001$ and $MD = 560.130$, $p = .013$, respectively), whereas no significant difference was found between the CT and PLY groups ($MD = 440.580$, $p = .069$). Regarding Relative Peak Power and Jump Height, statistically significant differences were found across all pairwise comparisons ($p < .05$), with a clear order of development demonstrating that Contrast Training yielded the highest adaptations, followed by Plyometric Training, and Control groups, respectively (CT > PLY > CON). Specifically: Relative Peak Power: CT vs. PLY ($MD = 6.687$, $p = .038$), CT vs. CON ($MD = 14.827$, $p < .001$), PLY vs. CON ($MD = 8.140$, $p = .009$). Jump Height: CT vs. PLY ($MD = 5.067$, $p = .029$), CT vs. CON ($MD = 10.493$, $p < .001$), PLY vs. CON ($MD = 5.427$, $p = .018$).

6.2 Rate of Force Development (RFD) Prior to training (Time 1), no statistically significant differences were observed among the groups across any variables (all $p > .05$). After training (Time 2), distinct mechanical adaptations were identified based on the force production time window as follows: Absolute Peak RFD: Both the CT and PLY groups were significantly higher than the CON group ($MD = 2274.800$, $p = .001$ and $MD = 1638.513$, $p = .018$, respectively), with no significant difference between CT and PLY ($MD = 636.287$, $p = .799$). Relative Peak RFD: Only the CT group was significantly higher than the CON group ($MD = 32.180$, $p = .009$), whereas the PLY group showed no significant difference compared to CON ($MD = 24.667$, $p = .060$) or CT ($MD = 7.513$, $p = 1.000$). When examining force development across time intervals: Early Phase (Peak RFD30 and Relative Peak RFD30 at 0–30 ms): Both the CT and PLY groups were significantly higher than the CON group ($p < .05$), while no significant difference was observed between the two experimental groups ($p > .05$). Notably, the PLY group exhibited the highest mean difference compared to the CON group ($MD = 2953.600$, $p < .001$ for Peak RFD30; $MD = 44.867$, $p = .001$ for Relative Peak RFD30). Subsequent Phase (Peak RFD90 and Relative Peak RFD90 at 0–90 ms): Statistically significant differences were found across all pairwise comparisons ($p < .05$), following the developmental hierarchy of CT group > PLY group > CON group. Peak RFD90: CT vs. PLY ($MD = 1588.533$, $p = .007$), CT vs. CON ($MD = 3253.753$, $p < .001$), PLY vs. CON ($MD = 1665.220$, $p = .005$). Relative Peak RFD90: CT vs. PLY ($MD = 22.073$, $p = .035$), CT vs. CON ($MD = 47.553$, $p < .001$), PLY vs. CON ($MD = 25.480$, $p = .012$).

6.3 Impulse Prior to training (Time 1), no significant differences were observed among groups for both absolute and relative values (all $p = 1.000$). However, after training (Time 2): Gross Impulse300: Showed statistically significant differences across all pairwise comparisons ($p < .05$), following the hierarchy of CT group > PLY group > CON group (CT vs. PLY: $MD = 46.913$, $p = .026$; CT vs. CON: $MD = 124.660$, $p < .001$; PLY vs. CON: $MD = 77.747$, $p < .001$). Relative Impulse300: Both the CT and PLY groups were significantly higher than the CON group ($MD = 1.793$, $p < .001$ and $MD = 1.107$, $p = .001$, respectively), with no statistically significant difference between the CT and PLY groups ($MD = 0.687$, $p = .053$).

Discussion

The primary empirical findings demonstrate that 8 weeks of Contrast Training (CT) and Plyometric Training (PLY) led to significant overall improvements in Countermovement Jump (CMJ) force–time characteristics compared to the control group ($p < .001$), with no significant baseline differences prior to the intervention ($p > .05$). Specifically, pairwise comparisons revealed distinct mechanical adaptation profiles: the CT group achieved significantly greater relative peak power, jump height, Peak RFD90, Relative Peak RFD90, and Gross Impulse300 compared to both PLY and CON ($p < .05$). Conversely, within the initial phase of force production (0–30 ms), both experimental groups significantly enhanced early-phase rapid force generation (Peak RFD30 and relative Peak RFD30) relative to CON ($p < .05$), with PLY displaying the highest numerical values, although not statistically differing from CT ($p > .05$). Building upon these empirical outcomes, the physiological and biomechanical mechanisms driving these distinct adaptation pathways between CT and PLY are elaborated below.

1. Adaptations in Early-Phase Rate of Force Development (Early-Phase RFD: 0–30 ms)

The present study found that, following the training intervention, both absolute Peak RFD30 and relative Peak RFD30 during the initial 0–30 ms of muscle contraction were significantly higher in the Contrast Training (CT) and Plyometric Training (PLY) groups than in the Control (CON) group ($p < .05$). No statistically significant difference was observed between the CT and PLY groups ($p > .05$). When the mean differences (*MD*) relative to the CON group were considered, the PLY group demonstrated the largest numerical differences in both Peak RFD30 ($MD = 2953.60$, $p < .001$) and Relative Peak RFD30 ($MD = 44.87$, $p = .001$). However, because the difference between the CT and PLY groups did not reach statistical significance, it cannot be concluded that PLY was directly superior to CT for improving RFD30. These findings should therefore be interpreted as indicating that both CT and PLY enhanced the ability to rapidly produce force during the 0–30 ms interval compared with regular training, while PLY showed a numerical tendency toward a greater magnitude of difference than CT when compared with CON.

The improvement in Early-Phase RFD can be explained, in part, by the important role of neural adaptations, which contribute substantially to the development of force during the early phase of muscle contraction. These adaptations include enhanced efferent neural drive, motor unit recruitment, and motor unit discharge rate (Aagaard et al., 2002; Folland et al., 2014; Del Vecchio et al., 2019). During the very early phase of force production, particularly within approximately the first 50 ms, neural mechanisms play an important role in determining the rate at which force increases, as the muscle is still in the early stages of force generation and tension development. Accordingly, rapid increases in neural drive and the ability to recruit motor units efficiently are important for enhancing RFD within this restricted time period. The characteristics of the PLY program, which emphasized high-velocity movements combined with rapid and maximal force-production intent (high-velocity movement with explosive intent), may have promoted neural adaptations that improved the ability of the nervous system to transmit neural drive and recruit motor units in response to the demand for rapid force production within a limited time frame. Such adaptations may have enhanced the efficiency of force production during the initial phase of contraction and may therefore help explain the increases in Peak RFD30 and Relative Peak RFD30 observed in the PLY group. At the physiological level, increased neural drive may support the excitation–contraction coupling process, which links electrical activation of the muscle to the release of calcium ions (Ca^{2+}) from the sarcoplasmic reticulum and subsequently facilitates interactions between actin and myosin, forming the fundamental basis of muscle force production. However, because Ca^{2+} dynamics, cross-bridge kinetics, and motor unit activity were not directly measured in the present study, these mechanisms should be regarded

as potential mechanisms that may help explain the observed findings rather than as mechanisms directly demonstrated to have resulted from the training intervention. Furthermore, the high-velocity movements performed during PLY may be associated with adaptations in the processes involved in translating neural activation into mechanical force and may potentially influence Electromechanical Delay (EMD). From a theoretical perspective, such adaptations could facilitate more rapid development of mechanical force. However, because EMD was not directly measured in the present study, it should be interpreted as a potential contributing mechanism rather than as a direct effect of PLY training. With regard to motor unit recruitment, rapid force production and the intent to generate force quickly may enhance the capacity of the nervous system to recruit high-threshold motor units more rapidly when a high rate of force production is required. However, this phenomenon should not be interpreted as a violation or bypassing of Henneman's Size Principle. Rather, it should be understood as an improvement in the speed and efficiency with which the nervous system can recruit high-threshold motor units under conditions requiring a high rate of force production, while remaining broadly consistent with the normal hierarchical organization of motor unit recruitment.

In summary, the findings indicate that both CT and PLY improved the ability to develop force within the 0–30 ms interval compared with regular training in the CON group. Although the PLY group demonstrated the largest numerical differences relative to CON, it did not differ significantly from the CT group. Therefore, PLY should not be considered directly superior to CT based on the RFD30 findings alone. Instead, the results support the concept that training characterized by rapid force production and high-velocity movement may promote neural adaptations associated with Early-Phase RFD. These early adaptations may provide an important foundation for the subsequent development of force over longer time intervals, such as Late-Phase RFD (0–90 ms), and may potentially contribute to subsequent force accumulation as reflected by Impulse300.

2. Transition and Adaptations in RFD Over 0–90 ms and Their Effects on Impulse

Prior to the intervention (Time 1), no statistically significant differences were observed among the three groups in Power & Jump Performance (P&JP), Rate of Force Development (RFD), and Impulse variables ($p > .05$ for all variables). This finding indicates that the participants in all three groups had comparable baseline physical capacities before receiving their respective training programs. Following the intervention (Time 2), statistically significant between-group differences were observed. For Peak Power, the Contrast Training (CT) and Plyometric Training (PLY) groups demonstrated significantly higher values than the Control (CON) group ($MD = 1000.71$, $p < .001$ and $MD = 560.13$, $p = .013$, respectively), whereas no statistically significant difference was found between the CT and PLY groups ($MD = 440.59$, $p = .069$). These findings indicate that both training modalities were effective in improving maximal power production compared with regular volleyball training. However, when considering body-mass-normalized and mechanical performance variables, namely Relative Peak Power and Jump Height, a clear pattern of adaptation emerged in the order of $CT > PLY > CON$ ($p < .05$ for all pairwise comparisons). The CT group demonstrated significantly greater Relative Peak Power than both the PLY group ($MD = 6.69$, $p = .038$) and the CON group ($MD = 14.83$, $p < .001$). Similarly, the CT group achieved significantly greater Jump Height than the PLY group ($MD = 5.07$ cm, $p = .029$) and the CON group ($MD = 10.49$ cm, $p < .001$). These findings indicate that CT was more effective than PLY in improving body-mass-relative power output and jumping performance. This finding is consistent with systematic reviews by Cormier et al. (2020), which reported that complex or contrast training can produce greater improvements in power output and jump performance than unimodal training approaches.

These performance adaptations were accompanied by corresponding changes in the RFD and Impulse variables. Following the intervention, the CT group demonstrated significantly greater Peak RFD90, Relative Peak RFD90, Gross Impulse300, and Relative Impulse300 than both the PLY and CON groups ($p < .05$). This pattern can be interpreted in terms of neuromuscular adaptations across different phases of force production. During the very early phase of muscle contraction (<50 ms), the rate of force development is strongly influenced by neural mechanisms, including motor unit recruitment and motor unit discharge rate. As force production progresses toward approximately 75–90 ms, the contribution of maximal force-generating capacity and muscle architectural properties becomes increasingly important (Maffiuletti et al., 2016; Rodriguez-Rosell et al., 2018). Therefore, the greater RFD90 observed in the CT group may reflect a synergistic adaptation involving enhanced neural function together with an increased maximal force-generating capacity of the skeletal muscle (Suchomel et al., 2018).

From physiological and biomechanical perspectives, CT may promote favorable adaptations in muscle structure, including increases in physiological cross-sectional area (PCSA) and alterations in pennation angle, which may contribute to an increased capacity for maximal force production (Andersen & Aagaard, 2006; Suchomel et al., 2016). At the same time, force transmission through the musculotendinous system represents another important component of neuromuscular performance. Adaptations in tendon mechanical properties, particularly increased tendon stiffness resulting from resistance training combined with high-velocity movements, may enhance the efficiency of force transmission from muscle to the skeletal system and reduce mechanical energy dissipation during rapid force production (Bohm et al., 2015; Kubo et al., 2017). However, because tissue- and cellular-level variables were not directly measured in the present study, mechanisms involving tendon slack and cross-bridge kinetics should be regarded as theoretical explanations and interpreted with caution.

The ability to increase force rapidly during the 0–90 ms interval is mechanically related to early force accumulation and contributes to the subsequent development of Gross Impulse300. In the present study, Gross Impulse300 represents the total area under the vertical ground reaction force–time curve over the first 300 ms of movement, including the gravitational force component (W_{sys}), expressed as:

$$\text{Gross Impulse}_{300} = \int_{t_{\text{onset}}}^{t_{\text{onset}}+0.300} F_{\text{total}}(t) dt \quad \dots\dots\dots (6)$$

The higher early rate of force production (RFD90) observed in the CT group elevated the force–time curve during the initial phase of contraction. Maintaining this elevated force profile throughout the 300-ms interval naturally expanded the overall area under the total force–time curve, resulting in a significantly greater Gross Impulse300 (Cormie, et al., 2011). Importantly, RFD90 should not be interpreted as a direct determinant of impulse, nor should Gross Impulse300 be conflated with net propulsive impulse. While net impulse governs take-off velocity and jump height according to the impulse–momentum theorem, Gross Impulse300 serves as an index of total force accumulation and force-holding capacity within the constrained 300-ms timeframe.

In summary, the superiority of the CT group was not attributable solely to improvements in Peak Power. Rather, it reflected a systematic adaptation of the neuromuscular system that enhanced rapid force production (Peak RFD90) together with total force accumulation (Gross Impulse300) within a constrained time frame, alongside enhanced body-mass-normalized mechanical outputs (Relative Power and Jump Performance).

3. Adaptations in Gross Impulse₃₀₀

Following the training period, Gross Impulse₃₀₀ demonstrated statistically significant differences among all three groups ($p < .05$), following an order of mean values of $CT > PLY > CON$. Specifically, the CT group exhibited significantly higher Gross Impulse₃₀₀ values than both the PLY group ($MD = 46.913$, $p = .026$) and the CON group ($MD = 124.660$, $p < .001$). Meanwhile, the PLY group showed significantly higher values compared to the CON group ($MD = 77.747$, $p < .001$). These findings indicate that contrast training (CT) enhances the capacity for force accumulation within a 300-ms timeframe to a greater extent than plyometric training (PLY) and conventional volleyball training (CON). Mechanically, Gross Impulse₃₀₀ represents the total area under the unadjusted force–time curve over the first 300 ms of contraction, encompassing both active muscle force production and system body weight (W_{sys}). Consequently, an increase in Gross Impulse₃₀₀ is driven by a heightened capacity for rapid initial force production coupled with the ability to maintain elevated force levels throughout the designated timeframe. When interpreted alongside the superior Peak RFD₉₀ and Relative Peak RFD₉₀ observed in the CT group compared to PLY and CON, these results suggest that CT facilitates both rapid force development and greater overall force accumulation within 300 ms. The superiority of CT may be attributed to the unique structure of contrast training, which integrates high-load resistance exercises with high-velocity explosive movements. The resistance component enhances maximal force capacity (F_{max}), whereas the high-velocity component promotes rapid early-phase force production. These dual mechanisms likely act synergistically to augment the total force–time integral (Gross Impulse₃₀₀). At the physiological and biomechanical levels, high-load and high-velocity modalities elicit adaptations in both neural and muscular systems. These include enhanced efferent neural drive, superior motor unit recruitment, increased muscular force-generating capacity, and structural modifications within the musculotendinous unit. However, as tissue-level and physiological parameters such as neural drive, motor-unit activity, physiological cross-sectional area (PCSA), or tendon stiffness were not directly measured in the present study, these mechanisms should be interpreted as potential mechanisms supporting the discussion rather than definitively confirmed outcomes of the training intervention. Regarding Relative Impulse₃₀₀ (impulse normalized to body mass), both the CT and PLY groups achieved significantly higher values than the CON group ($MD = 1.793$, $p < .001$ and $MD = 1.107$, $p = .001$, respectively), with no statistically significant difference between CT and PLY ($MD = 0.687$, $p = .053$). These results demonstrate that when accounting for body mass, both CT and PLY effectively enhance force accumulation per unit of body weight compared to habitual training. Although the CT group maintained a numerically higher mean than the PLY group, this difference did not reach statistical significance ($p = .053$), represents a marginal trend favoring CT, likely attributable to greater gains in muscle mass and maximal strength conducive to force accumulation. It is important to clarify from a biomechanical perspective that Gross Impulse₃₀₀ reflects total force accumulation within a fixed 300-ms time window rather than the net propulsive impulse. According to the impulse–momentum theorem, center-of-mass acceleration and takeoff velocity are governed strictly by net impulse (force integrated above body weight over the entire movement duration). Therefore, the observed improvements in Gross Impulse₃₀₀ should be interpreted as an enhanced capacity to generate and sustain high total force during the early phase of movement, rather than a direct mathematical determinant of takeoff velocity or jump height.

In summary, the present findings demonstrate that CT induces the greatest enhancement in Gross Impulse₃₀₀, followed by PLY and CON, respectively. When normalized to body mass, both CT and PLY are superior to CON, with no significant difference between CT and PLY. These results indicate that the advantage of CT in Gross Impulse₃₀₀ stems from the integration of rapid force development and sustained

high force output over time, reflecting an overall neuromuscular adaptation in early-phase force accumulation capacity.

4. Links to Countermovement Jump (CMJ) Performance

The findings of the present study revealed that the CT group exhibited the greatest improvements in jump height and peak power. From a biomechanical perspective, jumping performance is fundamentally governed by the impulse–momentum theorem, where relative net vertical impulse serves as the primary determinant of takeoff velocity (v_{to}) and subsequent jump height, as expressed by:

$$\text{Net Vertical Impulse} = m \cdot v_{to} \rightarrow \text{Jump Height} = \frac{v_{to}^2}{2g} \quad \dots\dots\dots (7)$$

Although the PLY group displayed a numerical trend toward superior improvements in early-phase RFD (Peak RFD30) likely driven by initial neural adaptations the active concentric phase of a CMJ typically spans approximately 200–300 ms or longer, which substantially exceeds the initial 30 ms window. Consequently, achieving high force levels later in the contraction phase plays a crucial role in overall propulsive force generation. The superior adaptations observed in late-phase RFD (RFD90) and Gross Impulse300 in the CT group reflect an enhanced capacity for rapid force development and sustained force accumulation within the first 300 ms of movement (Andersen & Aagaard, 2006; Cormie et al., 2011). While Gross Impulse300 includes system body weight and should not be mathematically equated with net propulsive impulse, the ability to rapidly accumulate and maintain high total force during this early timeframe provides a superior mechanical foundation. This enhanced force-generating capability during the initial 300 ms likely facilitated greater overall work and net impulse generation throughout the entire propulsion phase, ultimately contributing to the observed superior gains in Peak Power and CMJ Height in the CT group.

Limitations of the Study

1. Inability to Isolate Training Volume and Exposure Effects

A notable limitation of the present study is the difference in total training exposure between the experimental and control groups. The Contrast Training (CT) and Plyometric Training (PLY) groups completed two additional training sessions per week dedicated to the interventions, whereas the control (CON) group participated solely in routine volleyball practice. Consequently, the observed performance enhancements cannot be completely isolated from the effects of increased overall training volume and exposure time.

2. Task-Specific Practice and Testing Familiarity

The inclusion of the countermovement jump (CMJ) as a core training exercise within the CT program, coupled with its use as the primary performance outcome measure, introduces the possibility of task-specific practice effects. Greater familiarity with the testing movement mechanics among the CT participants may have contributed to their performance improvements, independent of the training adaptations alone.

3. Mechanical Loading Disparities and Internal Load Inconsistencies

Although the training programs for the CT and PLY groups were structured with comparable structural volume (e.g., sets, repetitions, and foot contacts), achieving absolute equivalence in comprehensive mechanical workload was inherently challenging due to disparate loading profiles (i.e., heavy external resistance in CT versus bodyweight in PLY). Furthermore, session rating of perceived exertion (sRPE) data were incomplete and excluded from analysis due to field log inconsistencies. Therefore,

the manuscript must avoid implying that total internal training load or cumulative mechanical stress were perfectly equated between the two experimental modalities.

4. Statistical Power Constraints in Head-to-Head Comparisons

While the total sample size ($N = 45$) provided robust statistical power to detect overall interaction effects, it possessed inherent limitations for detecting smaller effect sizes in direct head-to-head comparisons between the CT and PLY groups (e.g., Early-phase RFD at $p > .05$, absolute Peak Power at $p = .069$, and Relative Impulse₃₀₀ at $p = .053$). These non-significant comparisons should not be interpreted as definitive equivalence between modalities, but rather as a statistical limitation in detecting phase-specific variations.

5. Absence of Direct Neuromuscular and Structural Diagnostics

Direct physiological and structural mechanisms such as efferent neural drive, motor unit recruitment via surface electromyography (sEMG), and musculotendinous architectural changes (e.g., tendon stiffness or fascicle length via ultrasonography) were not empirically measured. Consequently, proposed physiological explanations remain theoretical inferences rather than confirmed direct outcomes.

Conclusion

The present study demonstrates that both Contrast Training (CT) and Plyometric Training (PLY) effectively enhance power performance, rate of force development (RFD), and impulse compared to conventional training (CON). However, the mechanical adaptation profiles differ across the temporal phases of force production:

1. Early-Phase Rate of Force Development (0–30 ms)

Both the PLY and CT groups achieved significant improvements in Peak RFD₃₀ and Relative Peak RFD₃₀ compared to the CON group ($p < .05$). Although the PLY group displayed higher numerical mean values, the two experimental modalities did not differ significantly from each other ($p > .05$), indicating that both training methods significantly improved rapid initial force production compared to control, with no statistically significant difference between them.

2. Late-Phase Rate of Force Development (0–90 ms) and Impulse

The CT group demonstrated significantly higher Peak RFD₉₀, Relative Peak RFD₉₀, and absolute Gross Impulse₃₀₀ compared to both the PLY and CON groups ($p < .05$). For Relative Impulse₃₀₀, while the CT group exhibited a higher numerical value, the comparison between CT and PLY yielded a non-significant difference ($p = .053$), indicating that statistical superiority cannot be confirmed between the two experimental modalities for this specific variable. This reflects CT's greater capacity to sustain force production over extended contraction windows.

3. Jump Performance and Peak Power

The adaptations in Late-Phase RFD and early-phase force accumulation provided a mechanical foundation that enabled the CT group to achieve greater enhancements in Relative Peak Power and Countermovement Jump (CMJ) height compared to CON, with PLY also showing significant improvements over CON. In contrast, absolute Peak Power showed no statistically significant difference between the CT and PLY groups ($p = .069$), indicating that neither modality established statistical superiority over the other in absolute terms. This aligns with the understanding that the active concentric push-off duration during jumping relies heavily on sustained high force generation, where greater early force accumulation facilitates the subsequent generation of total work and net propulsive impulse required to maximize takeoff velocity.

Practical Applications

Sports coaches and strength and conditioning specialists can translate these empirical findings into professional training designs through three evidence-informed strategies:

1. Time-Specific Training Targets

Match intervention modalities to the specific time constraints of force production: use Plyometric Training (PLY) for athletic tasks requiring rapid early-phase RFD (< 50 ms) like initial acceleration and quick directional changes, as it significantly enhances early-phase force generation compared to control. Conversely, use Contrast Training (CT) for disciplines requiring prolonged force accumulation and high vertical jumps (> 75 ms), as it bridges maximal strength with high-velocity movements to maximize late-phase RFD, absolute impulse, and peak power. (Note: While PLY's early-phase effectiveness is theoretically attributable to potential adaptations in rapid force transfer and stretch-shortening cycle utilization, these underlying neuromuscular mechanisms should be viewed as plausible theoretical rationales rather than directly measured outcomes).

2. Sequential Periodization

Although the present study evaluated PLY and CT as independent parallel interventions, coaches can strategically synthesize these complementary adaptations into a sequential (block) periodization model: initiate training during the Accumulation Phase with PLY to establish a foundational neural base; transition during the Transmutation Phase to CT to fuse maximal strength with rapid neural drive for peak late-phase RFD and jump performance; and maintain these adaptations during the In-Season Phase using low-volume, high-quality explosive sessions.

3. Quality Control and Execution

Ensure intended neuromuscular adaptations by enforcing strict execution standards: require maximal volitional intent on every repetition to recruit high-threshold motor units, and provide 2–5 minutes of inter-set rest while strictly avoiding muscular failure to prevent fatigue-induced decrements in motor neuron function.

4. Sport-Specific Kinematic Integration (Volleyball Context)

Recognize that sport-specific movements such as volleyball spiking and blocking typically rely on an active arm swing and operate under a fast stretch-shortening cycle (Fast SSC) characterized by exceptionally short take-off durations. Consequently, coaches should extend these general training applications into specialized drills that emphasize upper-body force transfer via an efficient kinetic chain and incorporate multi-directional jumping to bridge controlled training adaptations with dynamic competition demands.

Recommendations for Future Research

1. Head-to-Head Power Optimization and Population Expansion

To definitively discern phase-specific mechanical variations between active interventions (e.g., CT vs. PLY), future trials should conduct a priori power calculations specifically powered ($f < 0.20$) to detect subtle, small-to-moderate effect sizes during early force production (0–30 ms, such as Peak RFD₃₀). Additionally, expanding study cohorts to include female athletes, elite-level competitors, and multidirectional sports requiring rapid change of direction (COD) will enhance the ecological validity and generalizability of training transfer across athletic populations.

2. Direct Neuromuscular and Structural Diagnostics

To empirically validate the theoretical biological adaptation pathways proposed in this study, future research should integrate force platform kinetics with direct biological diagnostics. Specifically,

surface electromyography (sEMG) or high-density EMG should be incorporated to analyze the rate of EMG rise (RER) and neural drive during early RFD. Furthermore, B-mode ultrasonography should be utilized to track musculotendinous architectural properties such as muscle pennation angle, fascicle length, and tendon stiffness to elucidate the underlying structural mechanisms governing late-phase impulse accumulation (Impulse300).

3. SSC Spectrum Mechanics and Multi-Dimensional Load Quantification

Future investigations should expand biomechanical profiles beyond slow stretch-shortening cycle (SSC) tasks (e.g., CMJ) by incorporating fast SSC evaluations, such as the Drop Jump (DJ) and reactive agility assessments. Concurrently, while maintaining strictly standardized external loading, future protocols should implement continuous, objective internal strain monitoring (e.g., daily Heart Rate Variability [HRV] or wearable sensors) to account for individual physiological stress and fatigue dynamics during high-intensity conditioning.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this manuscript, the authors utilized artificial intelligence tools, specifically Gemini and ChatGPT, throughout the entire manuscript for the purposes of improving grammatical structure, correcting spelling, translating text, and refining academic phrasing. Following the use of these tools, the authors thoroughly reviewed, edited, and verified the accuracy of all content, data analyses, scientific interpretations, and references in the final manuscript. The authors retain full responsibility for the content, accuracy, scientific integrity, and originality of the final work.

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Supplementary Table S1 . Test-Retest Reliability of Power, Jump Performance, Rate of Force Development, and Impulse Variables during the CMJ Test (N = 45) Before and After Training

Variable	Testing Phase	CV	Single Measures ICC	95% Confidence Interval (Lower – Upper)	F-value	p-value	Rating (Koo & Li, 2016)
Power & Jump Performance: P&JP							
Peak Power (W)	Pre	3.76	0.934	0.883 – 0.963	28.672	<.001	Excellent
	Post	4.37	0.931	0.798 – 0.970	38.673	<.001	Excellent
Relative Peak Power (W·kg ⁻¹)	Pre	4.63	0.886	0.801 – 0.935	16.163	<.001	Good
	Post	3.96	0.939	0.489 – 0.981	71.947	<.001	Excellent
Jump Height (cm)	Pre	4.81	0.884	0.800 – 0.935	16.300	<.001	Good
	Post	4.23	0.950	0.192 – 0.988	146.038	<.001	Excellent
Rate of Force Development (RFD)							
Peak RFD (N·s ⁻¹)	Pre	2.64	0.978	0.958 – 0.988	99.273	<.001	Excellent
	Post	5.55	0.960	0.693 – 0.987	100.851	<.001	Excellent
Relative Peak RFD (N·s ⁻¹ ·kg ⁻¹)	Pre	2.31	0.987	0.977 – 0.993	161.989	<.001	Excellent
	Post	4.91	0.970	0.313 – 0.993	247.000	<.001	Excellent
Peak RFD ₃₀ (N·s ⁻¹)	Pre	4.25	0.994	0.989 – 0.997	338.596	<.001	Excellent
	Post	4.94	0.987	0.481 – 0.997	629.810	<.001	Excellent
Relative Peak RFD ₃₀ (N·s ⁻¹ ·kg ⁻¹)	Pre	2.90	0.997	0.994 – 0.998	604.474	<.001	Excellent
	Post	4.86	0.986	0.615 – 0.997	483.593	<.001	Excellent
Peak RFD ₉₀ (N·s ⁻¹)	Pre	4.04	0.990	0.980 – 0.995	234.928	<.001	Excellent
	Post	5.23	0.994	0.946 – 0.998	611.501	<.001	Excellent
Relative Peak RFD ₉₀ (N·s ⁻¹ ·kg ⁻¹)	Pre	3.77	0.951	0.912 – 0.973	38.980	<.001	Excellent
	Post	5.49	0.984	0.769 – 0.996	314.245	<.001	Excellent
Impulse							
Impulse ₃₀₀ (N·s)	Pre	3.23	0.960	0.929 – 0.978	48.039	<.001	Excellent
	Post	6.65	0.925	0.038 – 0.982	119.602	<.001	Excellent
Relative Impulse ₃₀₀ (N·s·kg ⁻¹)	Pre	5.36	0.830	0.711 – 0.903	10.553	<.001	Good
	Post	6.55	0.930	0.139 – 0.982	95.998	<.001	Excellent

Note: Reliability was assessed using the Intraclass Correlation Coefficient (ICC Model: Two-Way Mixed, Absolute Agreement, Single Measures) and Coefficient of Variation (CV%). The wider 95% confidence intervals observed in the post-test phase reflect increased between-subject variability resulting from individual adaptations to the training interventions. However, combined with acceptable CV% values (< 6.65%) and significant F-test results ($p < .001$), these metrics confirm that all variables maintained high reliability across both testing time points.