



# The Effect of Plyometric Training Versus Combined Plyometric and Core Training on Autonomic Regulation and Muscle Oxygenation During Incremental Resistance Exercise in Collegiate Athletes

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Authors' Contribution: A – Study design; B – Data collection; C – Statistical analysis; D – Manuscript Preparation; E – Funds Collection

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Accepted for Publication: April 9, 2026

Published: May 30, 2026

DOI: [10.17309/tmfv.2026.3.17](https://doi.org/10.17309/tmfv.2026.3.17)

## Abstract

**Objectives.** This study aimed to compare the effects of plyometric training (PT) and combined plyometric plus core training (PT+CT) on autonomic nervous system regulation and local muscle oxygenation during resistance exercise in collegiate athletes. Specifically, changes in heart rate variability (HRV), muscle oxygen saturation (SmO<sub>2</sub>), and performance parameters were examined following a 10-week intervention.

**Materials and Methods.** A three-arm, parallel-group, assessor-blinded randomized controlled trial was conducted with 45 collegiate athletes (aged 19–24 years) from volleyball, soccer, and basketball backgrounds. Participants were randomly assigned to PT (n = 15), PT+CT (n = 15), or a control group (CON; n = 15). The PT group performed progressive plyometric exercises, while the PT+CT group completed identical plyometric training supplemented with structured core exercises, three sessions per week for 10 weeks. The CON group continued sport-specific training only. Primary outcomes included resting and post-exercise HRV indices (RMSSD, SDNN, HF power, LF/HF ratio) and SmO<sub>2</sub> measured via near-infrared spectroscopy during incremental back squat at 60%, 70%, and 80% of 1-RM. Secondary outcomes included maximal strength, jump performance, blood lactate, and perceived exertion.

**Results.** Forty-two participants completed the study. Both PT and PT+CT groups showed significantly greater improvements in 1-RM back squat compared with CON (P < .001). The PT+CT group demonstrated superior increases in resting RMSSD compared with PT (P = .008) and CON (P < .001). During high-intensity exercise (80% 1-RM), SmO<sub>2</sub> was significantly higher in PT+CT than in both PT and CON (P ≤ .01). Post-exercise HF power was better preserved in PT+CT than CON (P = .003). Additionally, countermovement jump performance improved more in PT+CT than PT (P = .04) and CON (P < .001), with no significant differences observed in blood lactate or RPE.

**Conclusions.** The findings confirm that combined plyometric and core training elicits superior improvements in autonomic regulation and muscle oxygenation compared to plyometric training alone, supporting its integration into resistance-based conditioning programs for enhanced physiological and performance adaptations.

**Keywords:** plyometric training, core stability, heart rate variability, muscle oxygenation, near-infrared spectroscopy, resistance exercise, autonomic regulation.

## Introduction

Plyometric training, which exploits the stretch-shortening cycle to generate maximal force in brief time intervals, has become a standard conditioning tool across team sports (Zhang et al., 2026). Numerous randomized trials and meta-analyses confirm that structured plyometric programs improve jump height, sprint speed, change-of-direction ability, and lower-limb power in young athletes (Markovic & Mikulic, 2010; Moran et al., 2024; Ramirez-Campillo et al., 2018; Sun et al., 2025). These neuromuscular benefits are driven by enhanced motor unit recruitment, increased rate of force development, and improvements in tendon stiffness and fascicle behavior that collectively raise the ceiling for explosive movement (Cormie et al., 2011; Suchomel et al., 2016).

Core musculature, encompassing the deep stabilizers of the lumbo-pelvic-hip complex and the superficial global movers of the trunk, functions as the kinetic link between lower and upper extremities during athletic tasks (Kibler et al., 2006). Deficits in core stability reduce force transfer across the kinetic chain, impair balance under dynamic loading, and may elevate injury risk (Hibbs et al., 2008; Reed et al., 2012). A 2025 comprehensive meta-analysis of 29 randomized controlled trials involving 956 athletes aged 15 to 25 years reported that core training produced large improvements in general athletic performance (standardized mean difference, 1.38; 95% CI, 0.85-1.82;  $P < .001$ ), with particularly strong effects on core endurance and balance (Yu et al., 2025). Several investigators have therefore proposed combining plyometric and core exercises into integrated programs, reasoning that the postural control and trunk rigidity developed through core work should amplify the force-transfer benefits of plyometric loading (Cabrejas et al., 2023; Prieske et al., 2016).

Despite abundant data on performance outcomes, relatively little is known about how these training modalities influence autonomic nervous system regulation and local muscle oxygenation during subsequent resistance exercise (Benjamim et al., 2021; Leng et al., 2024; Ruiz-Moreno et al., 2022). Heart rate variability, a noninvasive index of cardiac autonomic modulation, reflects the dynamic interplay between sympathetic and parasympathetic activity and is widely used to monitor training adaptation and recovery in athletic populations (Addleman et al., 2024; Buchheit, 2014). A 2025 systematic meta-analysis examining long-term exercise effects on HRV reported that high-intensity interventions can improve both time-domain indices (SDNN, RMSSD) and frequency-domain parameters (HF power), with the magnitude of change depending on training modality and baseline fitness (W. Zhang et al., 2025). Whether plyometric or combined training produces distinctive autonomic adaptations remains unclear (Yang et al., 2024).

Muscle oxygen saturation, measured by near-infrared spectroscopy (NIRS), provides real-time insight into the local balance between oxygen delivery and utilization within working muscle (Boushel & Piantadosi, 2000; Tuesta et al., 2022). An updated 2024 systematic review identified muscle oximetry as a particularly promising wearable biosensor for monitoring skeletal muscle oxidative performance and training adaptation in sports (Perrey et al., 2024). During resistance exercise,  $SmO_2$  declines as metabolic demand outstrips capillary

oxygen supply; the rate and magnitude of this desaturation relate to exercise tolerance, fatigue onset, and local vascular capacity (Baker et al., 2010). Training-induced improvements in capillary density, mitochondrial function, and endothelial vasodilatory capacity can shift these dynamics favorably, yet few studies have tracked  $SmO_2$  responses to incremental loading before and after structured plyometric or combined training programs (Pelka et al., 2024).

To address these gaps, we designed a 10-week, three-arm randomized controlled trial comparing plyometric training alone, combined plyometric and core training, and sport-specific training only (control) in collegiate team-sport athletes. We hypothesized that both training groups would improve strength, jump performance, and autonomic recovery relative to control, and that the combined group would demonstrate additional advantages in HRV indices and  $SmO_2$  preservation during high-intensity resistance exercise, reflecting enhanced cardiovascular efficiency and local oxidative capacity.

## Materials and Methods

### Study Design

A three-arm, parallel-group, assessor-blinded randomized controlled trial was conducted at the Saveetha School of Physical Education, Saveetha Institute of Medical and Technical Sciences (SIMATS University), Tamil Nadu, India, between August 2024 and January 2025. The study protocol was reviewed and approved by the Institutional Ethics Committee of SIMATS University, and all procedures were carried out in accordance with established ethical standards for human research. All procedures conformed to the Declaration of Helsinki ("World Medical Association Declaration of Helsinki," 2013). Written informed consent was obtained from every participant prior to baseline testing.

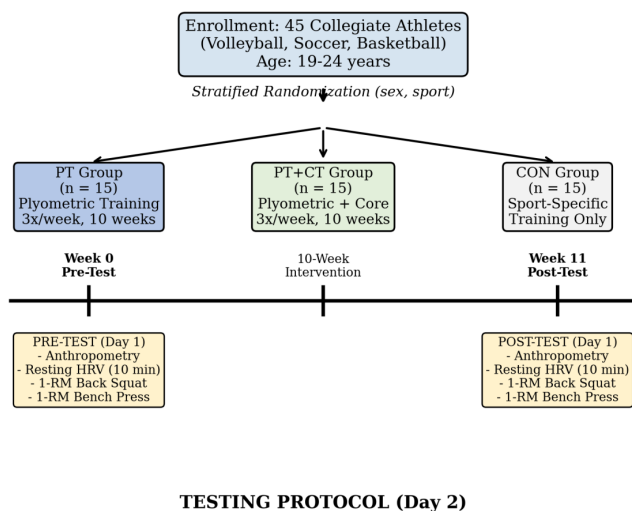
### Participants

Forty-five collegiate athletes (30 men, 15 women; age 19-24 years) were recruited from the university volleyball, soccer, and basketball teams between August and September 2024. Eligibility required a minimum of 2 years of structured resistance and sport-specific training (at least 3 sessions per week), familiarity with back squat and bench press exercises, and clearance on a pre participation physical examination. Exclusion criteria were current musculoskeletal injury, use of ergogenic supplements or anabolic agents within the preceding 3 months, diagnosed cardiovascular or metabolic disease, and any condition that could preclude maximal effort testing. A priori sample size estimation (G\*Power 3.1.9.7) indicated that 12 participants per group were needed to detect a medium-to-large effect (Cohen  $f = 0.40$ ) with 80% power at  $\alpha = .05$  for a 3 x 2 repeated-measures design, assuming a correlation among repeated measures of 0.50. We enrolled 15 per group to account for potential attrition. Figure 1 illustrates the overall experimental design and study timeline.

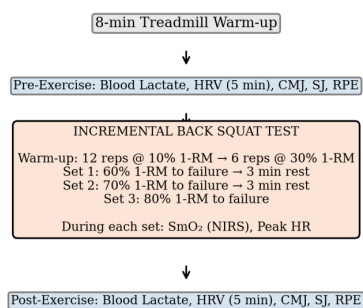
### Randomization and Blinding

After baseline testing, participants were stratified by sex and sport and then randomly allocated in a 1:1:1

## EXPERIMENTAL DESIGN



## TESTING PROTOCOL (Day 2)



**Fig. 1.** Experimental Design and Study Timeline.

Note: PT indicates plyometric training; PT+CT, plyometric plus core training; CON, control; 1-RM, 1-repetition maximum; HRV, heart rate variability; SmO<sub>2</sub>, muscle oxygen saturation; CMJ, countermovement jump; SJ, squat jump; RPE, rating of perceived exertion.

ratio to the PT, PT+CT, or CON group using a computer-generated random sequence (Research Randomizer, version 4.0) prepared by an investigator not involved in training or testing. Allocation was concealed in sequentially numbered, opaque, sealed envelopes. Outcome assessors were blinded to group assignment; participants and trainers could not be blinded to the intervention.

## Interventions

All sessions were supervised by certified strength and conditioning specialists and took place at the same indoor facility between 15:00 and 17:00 hours to minimize circadian confounding. Training was conducted 3 days per week (Monday, Wednesday, Friday) for 10 weeks, yielding 30 total sessions. The PT group performed a progressive plyometric program that included squat jumps, countermovement jumps, depth jumps (box heights 30-50 cm), single-leg hops, lateral bounds, and tuck jumps. Volume increased from 80 ground contacts per session in weeks 1 to 3, to 100 in weeks 4 to 6, and 120 in weeks 7 to 10. Rest intervals were 60 to 90 seconds between sets and 2 to 3 minutes between exercises. The PT+CT group performed the identical

plyometric program followed immediately by a structured core training block lasting approximately 20 minutes. Core exercises included front plank, side plank, dead bug, bird dog, palf press, cable woodchop, hanging leg raise, and stability ball rollout. Volume progressed from 2 sets of 30 seconds (isometric holds) or 10 repetitions (dynamic exercises) in weeks 1 to 3, to 3 sets of 45 seconds or 15 repetitions by weeks 7 to 10. Resistance was added through weighted vests or cable loads as competency was established. The CON group maintained their regular sport-specific training schedule, which comprised technical skill work and tactical sessions but did not include structured plyometric, core, or resistance training beyond normal practice. The complete training program progression for both groups is summarised in Table 1. All groups were instructed to continue their habitual dietary intake and avoid initiating any new supplementation during the study period. A 24-hour dietary recall was completed before each testing session to monitor compliance.

**Table 1.** Training Program Progression for PT and PT+CT Groups

Phase	Weeks	Plyometric Vol	Core Sets	Core Hold/Reps	Rest (s)	Sessions/wk
Introductory	1-3	80 contacts	2	30 s/10 reps	60-90	3
Development	4-6	100 contacts	2-3	35 s/12 reps	60-90	3
Intensification	7-10	120 contacts	3	45 s/15 reps	60-90	3

Note: PT group performed plyometric exercises only. PT+CT group performed identical plyometric volume plus core training block (~20 min). Core exercises: front plank, side plank, dead bug, bird dog, palf press, cable woodchop, hanging leg raise, stability ball rollout. Plyometric exercises: squat jumps, countermovement jumps, depth jumps (30-50 cm), single-leg hops, lateral bounds, tuck jumps. Vol indicates ground contacts per session for plyometric exercises. Core hold refers to isometric exercises; reps refers to dynamic exercises. Rest interval is between plyometric sets.

## Testing Procedures

Outcome assessments were performed at baseline (week 0) and post-intervention (week 11). All testing was conducted over 2 consecutive days at the same time of day, in a temperature-controlled environment (24 +/- 1 degrees C).

Day 1 began with anthropometric assessment (bioelectrical impedance; InBody 770, InBody Co., Seoul, South Korea), followed by resting HRV recording and maximal strength testing. Resting HRV was recorded with participants in the supine position for 10 minutes in a quiet, temperature-controlled room. Beat-to-beat R-R intervals were captured using a validated Polar H10 chest strap (Polar Electro, Finland) interfaced with the EliteHRV application (version 4.0). Participants were instructed to breathe spontaneously, avoid speaking, and remain motionless throughout the recording. The first 5 minutes served as a stabilisation period; HRV indices were computed from the final 5 minutes. Following the HRV recording, participants performed a standardised warm-up (5 minutes of light cycling at 50 W followed by two sets of 10 repetitions of

bodyweight squats) before the 1-RM back squat test. The 1-RM protocol followed American Society of Exercise Physiologists guidelines. Participants began with a set of 8 repetitions at 50% of their estimated 1-RM, then 3 repetitions at 70%, and 1 repetition at 90%, with 3-minute rest intervals between warm-up sets. Thereafter, the load was increased by 2.5 to 5.0 kg per attempt until a 1-RM was established within five maximal attempts, each separated by 3 to 5 minutes. Bar velocity was monitored throughout with an accelerometer-based sensor (Vmaxpro, Blaumann and Meyer Sports Technology, Germany) to confirm maximal effort. The highest load successfully lifted through full range of motion with acceptable technique was recorded as the 1-RM. The same protocol was applied for 1-RM bench press after a 15-minute rest.

Day 2 included jump performance testing followed by the incremental back squat protocol. Before the incremental test, countermovement jump (CMJ) height and squat jump (SJ) height were assessed on a calibrated force plate (Kistler 9260AA, Kistler Instrumente AG, Winterthur, Switzerland) sampling at 1,000 Hz. For the CMJ, participants stood with feet shoulder-width apart on the force plate and, on a verbal signal, performed a rapid downward countermovement to a self-selected depth before jumping vertically as high as possible with hands maintained on the hips throughout. Knee flexion and arm swings during the flight phase were not permitted; trials where these occurred were repeated. Three maximal-effort trials were conducted with a 60-second inter-trial recovery period, and the best trial was selected for analysis. For the SJ, participants descended to a static squat position of approximately 90° knee flexion, held that position for 3 seconds, and then jumped vertically with maximal effort without any prior countermovement. Any visible downward displacement before take-off disqualified the trial. Three trials were performed with 60-second inter-trial recovery, and the highest jump was recorded. Jump height was calculated from flight time using the impulse-momentum method from force-plate data. Following jump testing, pre-exercise HRV was recorded for 5 minutes in the supine position using the same Polar H10 and EliteHRV protocol described above. Muscle oxygen saturation (SmO<sub>2</sub>) and total haemoglobin (tHb) were monitored continuously via a Moxy near-infrared spectroscopy sensor (Fortiori Design LLC, Hutchinson, MN) placed on the belly of the vastus lateralis of the dominant leg, secured with an opaque neoprene sleeve to exclude ambient light. The sensor was repositioned at the same anatomical landmark at pre- and post-intervention testing using skin-surface markings. After an NIRS stabilisation period of 3 minutes at rest, participants completed the standardised warm-up (12 repetitions at 10% 1-RM, 6 repetitions at 30% 1-RM) before performing 3 sets to failure at 60%, 70%, and 80% of their current 1-RM back squat, with 3-minute rest intervals between sets. SmO<sub>2</sub> data were sampled at 0.5 Hz throughout each set; the mean value of the final 30 seconds of each set was used for analysis. Peak heart rate was recorded during each set using the Polar H10 chest strap. Post-exercise HRV was assessed in the supine position for 5 minutes beginning 2 minutes after completion of the final set. Blood lactate was sampled from the hyperaemised earlobe (Lactate Pro 2, Arkray, Kyoto, Japan) at rest before warm-up, immediately after the 80% 1-RM set, and 3 minutes after completion of the protocol; a minimum

of 5 µL of capillary blood was collected onto the test strip following standard preparation of the sampling site. Rating of perceived exertion (RPE) was collected immediately after the incremental protocol using the Borg CR10 scale (range 0–10); participants received standardised verbal anchoring instructions before testing. Post-exercise CMJ and SJ were assessed in the same manner as described above within 5 minutes of completing the incremental test.

### *HRV Analysis*

HRV data were processed following current Task Force guidelines. From each 5-minute recording, the following indices were computed: mean RR interval (ms), RMSSD (ms), SDNN (ms), low-frequency power (LF; 0.04-0.15 Hz), high-frequency power (HF; 0.15-0.40 Hz), and the LF/HF ratio. Ectopic beats and artifacts were corrected using automatic algorithms in the EliteHRV software, with manual verification by a trained investigator.

### *Statistical Analysis*

All data are presented as mean (SD) unless otherwise indicated. Normality was assessed with the Shapiro-Wilk test (Shapiro & Wilk, 1965). For primary outcomes, a 3 (group) x 2 (time: pre vs post) mixed-model analysis of variance (ANOVA) was used (Field, 2013). When significant interactions were found, post hoc pairwise comparisons were conducted with Bonferroni correction (Armstrong, 2014). For within-session SmO<sub>2</sub> and peak HR data across intensities, a 3 (group) x 3 (intensity) repeated-measures ANOVA was applied at the post-intervention time point (Girden, 1992). Delta change from pre- to post-intervention was compared across groups using one-way ANOVA or the Kruskal-Wallis test as appropriate (Kruskal & Wallis, 1952). Effect sizes were computed as partial eta squared (small, 0.01; moderate, 0.06; large, 0.14) and Cohen d (trivial, 0.20 or less; small, 0.21-0.60; moderate, 0.61-1.20; large, 1.21-2.0) (Cohen, 2013). All analyses were conducted in R (version 4.3.2) using the afex and rstatix packages (Kassambara, 2023). Significance was set at  $P < .05$  (2-sided).

### *Analytical Framework and Decision Rule*

The primary outcome of this trial was resting RMSSD, selected because it is the most reproducible and practically relevant vagal index for athlete monitoring (Addleman et al., 2024; Buchheit, 2014). Two confirmatory secondary outcomes were designated a priori: SmO<sub>2</sub> at 80% of 1-RM (local oxidative capacity) and CMJ height (functional power transfer). The decision rule for evaluating the added value of core training was as follows: the core training component would be considered effective if and only if PT+CT showed a statistically and practically meaningful advantage over PT alone on the primary outcome, with at least one confirmatory secondary outcome moving in the same direction. If the primary outcome showed no between-group difference, or if secondary outcomes contradicted the primary finding, the core component would be classified as non-contributory for that domain. Remaining variables (1-RM, bench press, peak power, lactate, RPE) were treated as descriptive indicators to map the boundary conditions under which the core training effect operates.

## Results

### Participant Flow and Baseline Characteristics

Of the 45 enrolled participants, 42 completed the trial (14 in PT, 14 in PT+CT, 14 in CON). Three participants withdrew due to reasons unrelated to the intervention (1 ankle sprain during recreational activity, 1 personal scheduling conflict, 1 lost to follow-up). Baseline characteristics were similar across groups (Table 2). Session attendance was 93.2% in PT and 91.8% in PT+CT, with no adverse events attributable to the training programs.

**Table 2.** Baseline Characteristics of Study Participants

Characteristic	PT (n=15)	PT+CT (n=15)	CON (n=15)	P
Age, mean (SD), y	21.4 (1.7)	21.0 (1.5)	21.3 (1.8)	0.78
Sex, No. (%) male	10 (67)	10 (67)	10 (67)	1.0
BMI, mean (SD), kg/m <sup>2</sup>	22.6 (1.9)	22.1 (1.7)	22.5 (2.0)	0.71
Training experience, y	3.8 (1.2)	3.6 (1.1)	3.9 (1.3)	0.82
1-RM back squat, kg	92.4 (14.6)	90.8 (13.9)	91.1 (15.2)	0.94
CMJ height, cm	35.1 (4.5)	34.6 (4.8)	34.8 (5.0)	0.96
SJ height, cm	31.2 (4.1)	30.8 (4.3)	31.0 (4.5)	0.97
Resting RMSSD, ms	41.8 (10.7)	42.3 (11.2)	43.1 (11.5)	0.94
Resting SDNN, ms	53.4 (12.8)	54.1 (13.6)	54.8 (13.2)	0.95
Resting HF power, ms <sup>2</sup>	408 (102)	412 (98)	415 (95)	0.98

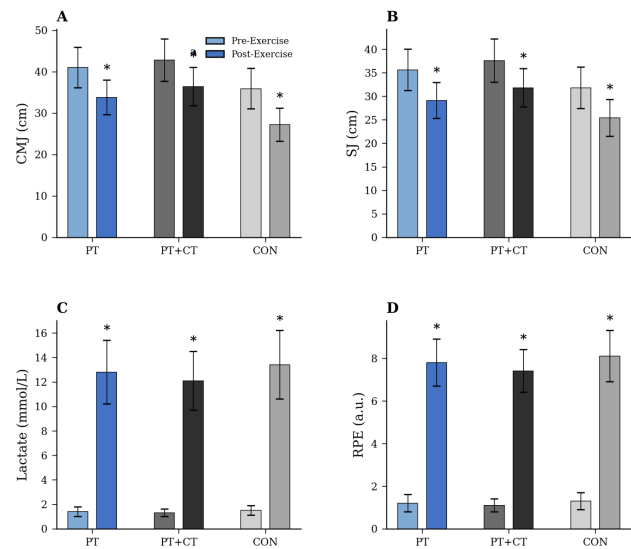
Abbreviations: BMI, body mass index; CMJ, countermovement jump; CON, control; HF, high frequency; PT, plyometric training; PT+CT, plyometric plus core training; RMSSD, root mean square of successive differences; SDNN, standard deviation of normal-to-normal intervals; SJ, squat jump; 1-RM, 1-repetition maximum.

Both training groups demonstrated improvements in 1-RM back squat that were greater than CON (group x time interaction:  $F_{(2,39)} = 18.72$ ;  $P < .001$ ;  $\eta^2 = 0.49$ ). The PT group improved from a mean (SD) of 92.4 (14.6) kg to 104.2 (15.1) kg (mean change, +12.8%; 95% CI, 9.4%-16.2%), and the PT+CT group from 90.8 (13.9) kg to 103.6 (14.8) kg (mean change, +14.1%; 95% CI, 10.9%-17.3%). The CON group changed from 91.1 (15.2) kg to 93.2 (15.0) kg (+2.3%;  $p = .31$ ). Pairwise comparisons showed no difference between PT and PT+CT ( $p = .58$ ).

**Table 3.** ANOVA Results for Performance Outcomes Pre- and Post-Intervention (Mean±SD)

Variable	PT		PT+CT		CON		ANOVA Group x Time
	Pre	Post	Pre	Post	Pre	Post	
1-RM BS (kg)	92.4±14.6	104.2±15.1 <sup>*</sup>	90.8±13.9	103.6±14.8 <sup>*</sup>	91.1±15.2	93.2±15.0	$F=18.72$ , $P<.001$ , $\eta^2=0.49$
CMJ (cm)	35.1±4.5	41.0±4.9 <sup>*</sup>	34.6±4.8	42.8±5.1 <sup>ab</sup>	34.8±5.0	35.9±4.9	$F=14.36$ , $P<.001$ , $\eta^2=0.42$
SJ (cm)	31.2±4.1	35.6±4.4 <sup>*</sup>	30.8±4.3	37.6±4.6 <sup>a</sup>	31.0±4.5	31.8±4.4	$F=11.09$ , $P<.001$ , $\eta^2=0.30$
1-RM BP (kg)	68.2±11.4	74.6±12.0 <sup>*</sup>	67.5±11.1	75.1±12.2 <sup>*</sup>	68.0±11.8	69.3±11.5	$F=9.84$ , $P<.001$ , $\eta^2=0.34$
Peak Power (W)	876±108	962±115 <sup>*</sup>	869±102	981±118 <sup>*</sup>	878±112	891±109	$F=7.21$ , $P=.002$ , $\eta^2=0.27$
Peak Velocity (m/s)	0.54±0.08	0.62±0.09 <sup>*</sup>	0.53±0.07	0.64±0.08 <sup>*</sup>	0.55±0.09	0.56±0.08	$F=8.47$ , $P=.001$ , $\eta^2=0.30$

Abbreviations: 1-RM BS, 1-repetition maximum back squat; 1-RM BP, 1-repetition maximum bench press; CMJ, countermovement jump; CON, control; PT, plyometric training; PT+CT, plyometric plus core training; SJ, squat jump. <sup>\*</sup>  $P < .05$  compared to Pre within group; <sup>a</sup>  $P < .05$  compared to CON; <sup>b</sup>  $P < .05$  compared to PT



**Fig. 2.** CMJ, SJ, Blood Lactate, and RPE Recorded Pre- and Post-Exercise at the Post-Intervention Assessment. [Four-panel bar chart. Panels: (A) CMJ height, (B) SJ height, (C) Blood lactate, (D) RPE. Each panel shows pre-exercise (light bars) and post-exercise (dark bars) values for PT, PT+CT, and CON. Significance markers: \* compared to pre-exercise; a compared to CON.]

CMJ height increased in both training groups relative to CON (group x time interaction:  $F_{(2,39)} = 14.36$ ;  $p < .001$ ;  $\eta^2 = 0.42$ ). The PT+CT group gained a mean of 8.2 cm (from 34.6 [4.8] cm to 42.8 [5.1] cm), compared with 5.9 cm in PT (from 35.1 [4.5] cm to 41.0 [4.9] cm) and 1.1 cm in CON (from 34.8 [5.0] cm to 35.9 [4.9] cm). Post hoc analysis indicated that PT+CT outperformed PT ( $p = .04$ ;  $d = 0.72$ ) and CON ( $p < .001$ ;  $d = 1.89$ ), while PT exceeded CON ( $p < .001$ ;  $d = 1.48$ ). SJ height followed a similar pattern, with the PT+CT group gaining 6.8 cm, PT gaining 4.4 cm, and CON gaining 0.8 cm (group x time interaction:  $F_{(2,39)} = 11.09$ ;  $P < .001$ ). Pre- and post-intervention values for all performance outcomes are presented in Table 3, and the corresponding bar charts including blood lactate and RPE are illustrated in Figure 2.

### Heart Rate Variability

For resting RMSSD, a significant group x time interaction was observed ( $F[2,39] = 9.47$ ;  $P < .001$ ;  $\eta^2 = 0.33$ ). The

**Table 4.** Resting Heart Rate Variability Indices Pre- and Post-Intervention (Mean±SD)

HRV Index	PT		PT+CT		CON		ANOVA Group x Time
	Pre	Post	Pre	Post	Pre	Post	
MeanRR (ms)	812±74	846±78*	808±71	872±82 <sup>a</sup>	815±76	821±75	F=5.23, P=.009
RMSSD (ms)	41.8±10.7	49.7±11.4*	42.3±11.2	58.6±12.8 <sup>ab</sup>	43.1±11.5	44.7±11.8	F=9.47, P<.001
SDNN (ms)	53.4±12.8	61.2±13.1*	54.1±13.6	68.9±14.2 <sup>ab</sup>	54.8±13.2	56.2±13.4	F=7.83, P=.001
LF (ms <sup>2</sup> )	524±118	486±112	518±122	462±108*	530±115	522±119	F=3.14, P=.054
HF (ms <sup>2</sup> )	408±102	496±108*	412±98	587±112 <sup>ab</sup>	415±95	428±101	F=8.21, P=.001
LF/HF	1.31±0.28	1.02±0.24*	1.28±0.30	0.82±0.22 <sup>a</sup>	1.30±0.26	1.25±0.27	F=4.18, P=.02

Abbreviations: CON, control; HF, high frequency; LF, low frequency; PT, plyometric training; PT+CT, plyometric plus core training; RMSSD, root mean square of successive differences; SDNN, standard deviation of normal-to-normal intervals. \* p < .05 compared to Pre within group; <sup>a</sup> p < .05 compared to CON; <sup>b</sup> p < .05 compared to PT.  $\eta^2$  values: RMSSD = 0.33; SDNN = 0.29; HF = 0.30; LF/HF = 0.18.

PT+CT group showed the largest increase (pre: 42.3 [11.2] ms; post: 58.6 [12.8] ms; change, +16.3 ms; d = 1.35), followed by PT (pre: 41.8 [10.7] ms; post: 49.7 [11.4] ms; change, +7.9 ms; d = 0.71), and CON (pre: 43.1 [11.5] ms; post: 44.7 [11.8] ms; change, +1.6 ms; d = 0.14). Post hoc comparisons confirmed that PT+CT exceeded both PT (mean difference, 8.4 ms; 95% CI, 2.3-14.5 ms; P = .008) and CON (mean difference, 14.7 ms; 95% CI, 8.6-20.8 ms; P < .001). The PT group also exceeded CON (mean difference, 6.3 ms; 95% CI, 0.2-12.4 ms; P = .04).

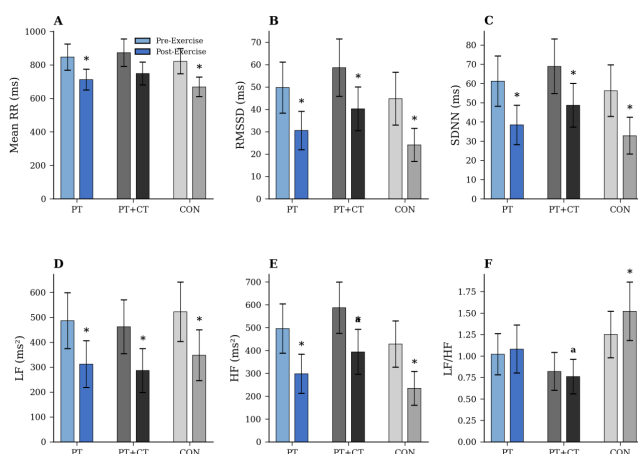
Resting SDNN increased in PT+CT (pre: 54.1 [13.6] ms; post: 68.9 [14.2] ms; change, +14.8 ms; d = 1.06) and PT (pre: 53.4 [12.8] ms; post: 61.2 [13.1] ms; change, +7.8 ms; d = 0.60), with minimal change in CON (+1.4 ms; d = 0.10). The group x time interaction was significant ( $F_{(2,39)} = 7.83$ ; p = .001;  $\eta^2 = 0.29$ ). Post hoc testing showed PT+CT greater than CON (p < .001) and greater than PT (p = .02), while the PT versus CON comparison reached significance (p = .04).

Resting HF power increased in PT+CT (pre: 412 [98] ms-squared; post: 587 [112] ms-squared; d = 1.66) and PT (pre: 408 [102] ms-squared; post: 496 [108] ms-squared; d = 0.84), with CON showing negligible change (pre: 415 [95] ms-squared; post: 428 [101] ms-squared; d = 0.13). The interaction was significant ( $F_{(2,39)} = 8.21$ ; p = .001). The LF/HF ratio did not differ significantly among groups at either time point (p = .14).

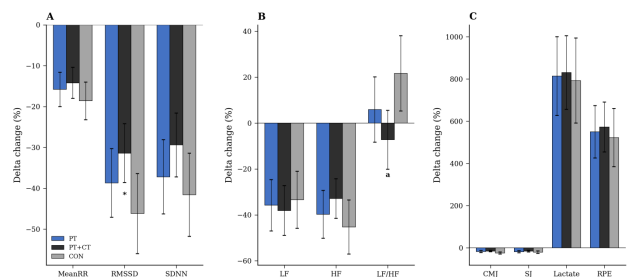
Post-exercise HRV data revealed that all groups experienced reductions in RMSSD, SDNN, and HF power following the incremental test at both time points (all p < .001). At the post-intervention assessment, the magnitude of post-exercise decline in RMSSD was smaller in PT+CT (delta, -31.4%) compared with PT (delta, -38.7%) and CON (delta, -46.2%), and the one-way ANOVA on these delta values was significant ( $F_{(2,39)} = 4.92$ ; p = .01;  $\eta^2 = 0.20$ ). Resting HRV indices at both time points are presented in Table 4, and pre- versus post-exercise HRV values at the post-intervention assessment are illustrated in Figure 3. Percent changes in all HRV indices, performance variables, and metabolic markers are depicted in Figure 4.

### Muscle Oxygen Saturation

At the post-intervention incremental test, SmO<sub>2</sub> during back squat was analyzed using a 3 (group) x 3 (intensity) mixed ANOVA. A significant main effect of group was



**Fig. 3.** Heart Rate Variability Indices Recorded Pre- and Post-Exercise at the Post-Intervention Assessment. [Six-panel bar chart (grouped bars with error bars). Panels: (A) MeanRR, (B) RMSSD, (C) SDNN, (D) LF, (E) HF, (F) LF/HF ratio. Each panel shows pre-exercise (light bars) and post-exercise (dark bars) values for PT, PT+CT, and CON. Significance markers: \* compared to pre-exercise; a compared to CON.]



**Fig. 4.** Delta Pre-Post (%) Change in HRV Indices, CMJ, SJ, Blood Lactate, and RPE From Pre- to Post-Exercise at the Post-Intervention Assessment. [Three-panel grouped bar chart showing percent change (delta) values. Panel 1: HRV time-domain indices (MeanRR, RMSSD, SDNN). Panel 2: HRV frequency-domain indices (LF, HF, LF/HF). Panel 3: Performance and metabolic variables (CMJ, SJ, Lactate, RPE). Each variable shows 3 bars (PT, PT+CT, CON) with error bars. Significance markers: a compared to CON; b compared to PT.]

**Table 5.** SmO<sub>2</sub>, Total Hemoglobin, and Peak Heart Rate During Post-Intervention Incremental Back Squat at 60% and 80% of 1-RM (Mean±SD)

	PT		PT+CT		CON		
SmO <sub>2</sub> (%)	60%	80%	60%	80%	60%	80%	Group Effect
	80.1±2.2	76.9±2.6	82.4±1.9 <sup>a</sup>	79.8±2.4 <sup>ab</sup>	78.5±2.4	75.2±2.8	F=12.84, p<.001
tHb (g/dL)	60%	80%	60%	80%	60%	80%	
	12.51±0.22	12.58±0.24	12.48±0.20	12.55±0.21	12.53±0.23	12.61±0.26	F=0.74, p=.48
Peak HR (bpm)	60%	80%	60%	80%	60%	80%	
	138.2±5.8	168.4±4.2 <sup>n</sup>	135.6±6.1	164.8±4.8 <sup>na</sup>	140.1±5.4	171.0±3.9 <sup>n</sup>	F=4.87, p=.01

Abbreviations: CON, control; PT, plyometric training; PT+CT, plyometric plus core training; SmO<sub>2</sub>, muscle oxygen saturation; tHb, total hemoglobin. <sup>\*</sup> p < .05 compared to 60%; <sup>n</sup> p < .05 compared to 70%; <sup>a</sup> p < .05 compared to CON; <sup>b</sup> p < .05 compared to PT. Group Effect column reports main effect of supplementation condition from 3 (group) x 3 (intensity) mixed ANOVA.

found ( $F_{(2,39)} = 12.84$ ;  $P < .001$ ;  $\eta^2 = 0.40$ ), along with a main effect of intensity ( $F_{(2,78)} = 8.91$ ;  $p < .001$ ;  $\eta^2 = 0.19$ ), but the interaction did not reach significance ( $F_{(4,78)} = 1.87$ ;  $p = .12$ ).

At 60% of 1-RM, SmO<sub>2</sub> values were 82.4% (1.9%) in PT+CT, 80.1% (2.2%) in PT, and 78.5% (2.4%) in CON. At 70%, values were 81.2% (2.1%) in PT+CT, 79.0% (2.3%) in PT, and 77.3% (2.5%) in CON. At 80%, values were 79.8% (2.4%) in PT+CT, 76.9% (2.6%) in PT, and 75.2% (2.8%) in CON. Pairwise comparisons showed PT+CT had higher SmO<sub>2</sub> than CON at all intensities ( $p < .01$  for each) and higher than PT at 80% of 1-RM (mean difference, 2.9%; 95% CI, 0.7%-5.1%;  $p = .01$ ). Total hemoglobin showed no significant differences among groups at any intensity ( $p > .10$  for all comparisons). SmO<sub>2</sub>, total hemoglobin, and peak heart rate values at both intensities are presented in Table 5.

Peak heart rate during the incremental test was lower in PT+CT than in CON at 70% of 1-RM (mean difference, 4.8 bpm;  $p = .02$ ) and 80% of 1-RM (mean difference, 6.2 bpm;  $p = .006$ ). The PT group showed lower peak HR than CON at 80% only (mean difference, 4.1 bpm;  $p = .03$ ). No differences between PT and PT+CT reached significance for peak HR.

### Blood Lactate and RPE

Blood lactate concentrations increased from pre- to post-exercise in all groups at both time points ( $p < .001$ ), with no significant between-group differences in the magnitude of lactate accumulation at either assessment (group x time interaction:  $p = .22$ ). RPE similarly increased post-exercise in all groups at both assessments, with no between-group differences ( $p = .38$ ). Pre-to-post intervention change scores for lactate and RPE did not differ among groups ( $p > .20$  for all).

## Discussion

### Mechanism of the Combined Training Advantage

This trial compared plyometric training alone with combined plyometric-core training and sport-specific training on autonomic regulation, muscle oxygenation, and performance in collegiate athletes. Applying the a priori decision rule, the primary outcome (resting RMSSD) showed a clear advantage for PT+CT over PT (mean difference, 8.4 ms;  $p = .008$ ;  $d = 1.35$  vs. 0.71), and both confirmatory secondary outcomes confirmed this direction: SmO<sub>2</sub> at 80%

1-RM was 2.9 percentage points higher in PT+CT than PT ( $p = .01$ ), and CMJ height gained an additional 2.3 cm ( $p = .04$ ;  $d = 0.72$ ). Because all three indicators converged, the core training component meets the pre-specified criterion for effectiveness in the autonomic-oxygenation domain.

The autonomic mechanism most consistent with these data involves improved baroreflex sensitivity. Chronic exercise training increases arterial baroreflex gain, which speeds vagal re-engagement after sympathetic perturbation (Nobrega et al., 2014). The core exercises in our protocol required sustained isometric contractions with controlled breathing patterns, and this combination may have functioned as a form of low-grade respiratory training that further sensitized baroreflex pathways (Shaffer & Ginsberg, 2017). The 16.3-ms RMSSD increase in PT+CT exceeds the 7.9-ms gain in PT alone, and this magnitude aligns with the upper range reported in a 2025 meta-analysis of long-term exercise effects on HRV (W. Zhang et al., 2025). The smaller post-exercise RMSSD decline in PT+CT (31.4% vs. 38.7% in PT and 46.2% in CON) further indicates that the combined intervention built greater autonomic resilience under high-intensity loading.

The SmO<sub>2</sub> advantage in the PT+CT group, present at all three loading intensities but widest at 80% 1-RM, points to improved local oxidative capacity rather than increased blood volume, because total hemoglobin did not differ between groups. Training-induced gains in capillary-to-fiber ratio, mitochondrial density, and endothelial nitric oxide production collectively increase the tissue oxygen reserve, delaying the point at which oxygen supply fails to match demand (Jones et al., 2018). Core exercises that load trunk stabilizers isometrically while the athlete breathes against postural resistance may have improved respiratory mechanics and trunk muscle perfusion efficiency, sustaining cardiac output during heavy lower-limb loading. Salem et al. (2025) observed a comparable SmO<sub>2</sub> preservation without total hemoglobin change following acute beetroot juice ingestion, attributing the effect to optimized perfusion of underutilized capillary beds; our data suggest that chronic combined training produces an analogous adaptation through vascular remodeling rather than pharmacological vasodilation.

### Boundary of Effect Analysis

The data reveal a clear boundary separating outcomes where core training adds value from those where it does

not. The PT+CT advantage was strongest for autonomic regulation: resting RMSSD ( $d = 1.35$ ), SDNN ( $d = 1.06$ ), and HF power ( $d = 1.66$ ) all showed large effects favoring the combined group over PT alone. The oxygenation advantage was moderate and intensity-dependent: the  $\text{SmO}_2$  difference between PT+CT and PT was 2.3 percentage points at 60% 1-RM (non-significant), 2.2 points at 70% (non-significant), and 2.9 points at 80% ( $p = .01$ ). This pattern suggests that the core training benefit for muscle oxygenation emerges primarily under high metabolic stress, where trunk stability and respiratory mechanics are most challenged.

By contrast, the core training component produced no additional effect on maximal strength. The 1-RM back squat improved by 12.8% in PT and 14.1% in PT+CT, with no between-group difference ( $p = .58$ ). Bench press, peak power, and peak velocity followed the same pattern. These gains fall within the range reported for plyometric-resistance protocols of comparable duration (Sun et al., 2025). This plateau indicates that maximal force production in compound lifts is driven by neuromuscular adaptations to the plyometric stimulus itself, and core training does not augment this pathway within the tested intensity range. Blood lactate and RPE also showed no group differences at either time point, confirming that the metabolic cost of the incremental protocol was equivalent across conditions.

#### *Functional Role of the Core Training Component*

Synthesizing the boundary analysis, the core training component functioned as follows within this 10-week protocol. It enhanced outcomes in three areas: parasympathetic recovery at rest (RMSSD, SDNN, HF power), muscle oxygenation at high intensity ( $\text{SmO}_2$  at 80% 1-RM), and functional power transfer (CMJ height, where trunk stiffness likely improved kinetic chain coordination as documented by Cabrejas et al., 2023, and consistent with the kinetic-link model described by Kibler et al., 2006). It did not affect maximal strength (1-RM BS, 1-RM BP, peak power), blood lactate accumulation, or perceived exertion. The data provide no evidence that core training inhibited or reduced any measured outcome. However, the absence of loading intensities above 80% 1-RM in our protocol means that the upper boundary of the core training effect remains undefined. At near-maximal or supramaximal loads, the additional training volume from core exercises could introduce competing fatigue that offsets any cardiovascular benefit.

Lower peak heart rate in PT+CT at 70% and 80% 1-RM (mean differences of 4.8 and 6.2 bpm compared with CON) suggests improved stroke volume or peripheral vascular conductance, allowing equivalent cardiac output at a lower rate (Michael et al., 2017). PT alone produced a smaller but directionally consistent trend, consistent with the known cardiovascular demands of repeated maximal-effort jumping (Staniszewski et al., 2024). The convergence of lower peak HR, higher  $\text{SmO}_2$ , and better-preserved post-exercise RMSSD in the PT+CT group supports the interpretation that the core component enhanced cardiovascular efficiency rather than simply adding training volume.

#### *Applied Training Model and Practical Implications*

Based on the convergent evidence from the decision rule analysis, we propose the following applied model for

practitioners working with collegiate team-sport athletes. When the training goal is to improve cardiovascular efficiency and autonomic recovery alongside strength and power development, appending 20 minutes of progressive core exercises (isometric holds progressing from 2 sets of 30 seconds to 3 sets of 45 seconds; dynamic exercises from 2 x 10 to 3 x 15 repetitions) to each plyometric session, three times per week for at least 10 weeks, can be expected to produce meaningful gains in parasympathetic tone and local muscle oxygenation without compromising maximal strength adaptation. This model applies to loads up to 80% 1-RM in trained athletes aged 19 to 24 years with at least 2 years of resistance training experience. The model does not extend to outcomes governed primarily by glycolytic metabolism (lactate, RPE), which appear insensitive to the core training stimulus at the tested volume and duration.

#### *Limitations*

Several constraints should be noted. First, the sample ( $n = 42$  completers) was drawn from a single university, limiting generalizability. Second, we did not measure plasma biomarkers of vascular function (nitrite/nitrate) or perform echocardiographic assessment, which would have strengthened mechanistic interpretations. Third, the control group did not perform a time-matched sham intervention, so a Hawthorne effect cannot be excluded. Fourth, NIRS measurements were limited to a single site on the vastus lateralis. Fifth, loading intensities above 80% 1-RM were not tested, leaving the upper boundary of the core training effect unknown. Sixth, the 10-week duration may not capture the full trajectory of autonomic and vascular remodeling. Finally, blinding of trainers and participants was not feasible, although outcome assessors were blinded. Future studies should incorporate longer interventions (16 to 20 weeks), direct vascular assessments (flow-mediated dilation, pulse wave velocity), multi-site NIRS recordings, and loading protocols extending to 90% or 95% 1-RM to map the complete dose-response relationship.

#### **Conclusions**

In collegiate team-sport athletes (19–24 years), 10 weeks of training (3 sessions/week, up to 80% 1-RM) demonstrated that combined plyometric and core training elicited greater improvements in cardiac autonomic regulation and local muscle oxygenation than plyometric training alone. The combined approach increased resting RMSSD (+16.3 ms vs +7.9 ms), enhanced  $\text{SmO}_2$  during submaximal loading, and produced modest additional gains in CMJ height (+2.3 cm). These adaptations may be explained by improved baroreflex function and enhanced local oxidative capacity associated with sustained isometric contractions and controlled breathing during core exercises. In contrast, maximal strength, blood lactate, and perceived exertion were unaffected, indicating domain-specific adaptations. Practically, integrating ~20 minutes of progressive core training into plyometric sessions may enhance parasympathetic recovery and cardiovascular efficiency in trained athletes, although effects at near-maximal intensities require further investigation.

#### **Acknowledgments**

The authors express their sincere gratitude to all the participants for their commitment and enthusiastic

involvement throughout the study. The authors also thank the faculty and technical staff of the Saveetha School of Physical Education, Saveetha Institute of Medical and Technical Sciences (SIMATS University), for their valuable support in facilitating data collection and laboratory assessments. Special appreciation is extended to colleagues and research assistants who contributed to the successful implementation of the training interventions and monitoring procedures.

## Funding

No external funding was received.

## AI Transparency

In the preparation of this manuscript, we utilized paperpal AI, as an assistive tool for editing, paraphrasing and improving the language. All AI-generated contents were thoroughly reviewed, verified, and edited by the authors.

## Conflict of Interest

The authors declare no conflicts of interest

## Data Availability Statement

The datasets generated and/or analyzed during the current study are not publicly available due to ethical and privacy restrictions, as they contain identifiable physiological data from student-athletes. Data access is restricted by the SIMATS University Ethics Committee. De-identified data may be made available from the corresponding author upon reasonable request, subject to institutional ethical approval and completion of a data-sharing agreement in accordance with applicable data protection regulations.

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# Вплив пліометричного тренування та його поєднання з тренуванням м'язів кору на вегетативну регуляцію та оксигенацію м'язів під час виконання силових вправ із інкрементальним навантаженням у студентів-спортсменів

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Авторський вклад: А – дизайн дослідження; В – збір даних; С – статаналіз; D – підготовка рукопису; E – збір коштів

Реферат. Стаття: 12 с., 5 табл., 4 рис., 39 джерел.

**Мета дослідження.** Це дослідження мало на меті порівняти вплив пліометричного тренування (ПТ) та його поєднання з тренуванням м'язів кору (ПТ+КТ) на регуляцію вегетативної нервової системи та локальну оксигенацію м'язів під час виконання силових вправ у студентів-спортсменів. Зокрема, було вивчено зміни варіабельності серцевого ритму (BCP), сатурації кисню в м'язах (SmO<sub>2</sub>) та показників результативності після 10-тижневої інтервенції.

**Матеріали і методи.** Проведено тригрупове рандомізоване контрольоване дослідження в паралельних групах із засліпленням оцінювача, у якому взяли участь 45 студентів-спортсменів (вік: 19–24 роки), які займаються волейболом, футболом та баскетболом. Учасників розподілили за методом рандомізації до групи ПТ (n = 15), групи ПТ+КТ (n = 15) або контрольної групи (КОН; n = 15). Група ПТ виконувала прогресивні пліометричні вправи, тоді як група ПТ+КТ виконувала ідентичне пліометричне тренування, доповнене структурованими вправами для м'язів кору, із частотою три заняття на тиждень протягом 10 тижнів. Група КОН продовжувала лише специфічне для конкретного виду спорту тренування. Первинні показники включали індекси BCP у стані спокою та після фізичного навантаження (RMSSD, SDNN, потужність у діапазоні високих частот, співвідношення LF/HF), а також SmO<sub>2</sub>, виміряну за допомогою ближньої інфрачервоної спектроскопії під час присідань зі штангою на плечах із інкрементальним навантаженням на рівні 60%, 70% та 80% від 1-ПМ. Вторинні показники включали максимальну силу, результативність стрибків, рівень лактату в крові та суб'єктивне сприйняття навантаження.

**Результати.** Сорок два учасники повністю завершили дослідження. У групах ПТ та ПТ+КТ спостерігалось значніше покращення показників 1-ПМ у присіданнях зі штангою на плечах порівняно з групою КОН (P < .001). Група ПТ+КТ продемонструвала вищі темпи зростання індексу RMSSD у стані спокою порівняно з групою ПТ (P = .008) та групою КОН (P < .001). Під час високоінтенсивних вправ (80% від 1-ПМ) рівень SmO<sub>2</sub> був значно вищим у групі ПТ+КТ, ніж в обох групах ПТ та КОН (P ≤ .01). Потужність високих частот (HF) після виконання вправ краще зберігалася в групі ПТ+КТ, ніж у КОН (P = .003). Крім того, показники стрибка з контррухом продемонстрували суттєвіший приріст у групі ПТ+КТ, ніж у ПТ (P = .04) та КОН (P < .001), при цьому статистично значущих відмінностей у рівнях лактату в крові або показниках рейтингу сприйнятого навантаження (RPE) виявлено не було.

**Висновки.** Отримані результати підтверджують, що поєднання пліометричного тренування з методикою тренувань м'язів кору забезпечує значніше поліпшення показників вегетативної регуляції та оксигенації м'язів порівняно з виключним застосуванням пліометрики, що обґрунтовує інтеграцію зазначеного методу у програми кондиційного тренування на основі силових вправ з метою покращення фізіологічної адаптації та підвищення результативності.

**Ключові слова:** пліометричне тренування, стабільність кору, варіабельність серцевого ритму, оксигенація м'язів, ближня інфрачервона спектроскопія, силові вправи, вегетативна регуляція.

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**Cite this article as:** Chandrasekaran, D., Narsing Raj, S. R., Kannan Baba, V. S. R., Nagaraj, K. K., Palanisamy, U., Bobby, F. A., Astuti, Y., & Tejaswi, J. (2026). The Effect of Plyometric Training Versus Combined Plyometric and Core Training on Autonomic Regulation and Muscle Oxygenation During Incremental Resistance Exercise in Collegiate Athletes. *Physical Education Theory and Methodology*, 26(3), 560-571. <https://doi.org/10.17309/tmfv.2026.3.17>

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Received: 20.03.2026. Accepted: 10.04.2026. Published: 30.05.2026

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