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Research article

Acute effects of eccentric overload training with different loading doses in male sprinters

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ABSTRACT

Objective: The primary objective of this study was to investigate the immediate effects of two doses (Dose1 and Dose2,D1 and D2) of inertial Flywheel Eccentric Overload (FEOL), Eccentric Hook (EH), and High-intensity Half Squat (HHS) on muscle explosiveness in male sprinters.
Methods: Twenty-one sub-elite male sprinters were randomly assigned to three groups: the FEOL group (n=7), the EH group (n=7), and the HSS group (n=7),Measurements of athletes' explosive jumps (CMJ, SJ, SLJ) heights, relative peak power indices, and 30-m sprint times were collected before and 6 min after the intervention.
Results: At D1 loading dose, CMJ, SJ jump height, and relative peak power increased significantly ($p < 0.05$) after HHS training intervention, while there was no significant change in FEOL and EH training ($p > 0.05$). At D2 loading dose, CMJ, SJ jump height, and relative peak power increased significantly ($p < 0.01$) after FEOL and EH training intervention, but at D2HHS intervention, these indexes tended to decrease ($p < 0.05$). None of the three training protocols significantly improved SLJ performance ($p > 0.05$). CMJ vertical jump height and relative peak power were significantly higher after D2FEOL and D2EH interventions than after D1HHS ($P < 0.05$).
Conclusion: D1HHS, D2FEOL and D2EH3 intervention methods can all improve the performance of sub-elite athletes in the 30-m test, CMJ test and SJ test. in the CMJ test, FEOL training demonstrated a higher acute augmentation effect compared to EH training.

1. Introduction

Entering the 21st century, competitive sports training models worldwide have pushed boundaries, with continuous innovation in models, theories, and methods serving as the three main drivers of the scientific development of sports training. These aspects represent the level of development of training grounded in the physiological structure of human movement. Resistance training, focusing on multiple neural and morphological adaptations of muscles, enhances various neuromuscular variables associated with strength and endurance [1]. This approach induces increases in muscular strength and explosiveness. Given that most daily and sports activities involve the"Stretch-Shortening Cycle" (SSC) of skeletal muscle, the ability to generate force during coupled contractions

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becomes crucial. The SSC is an intrinsic function of skeletal muscle in human locomotion, characterized by pre-activated muscles being actively lengthened before active shortening. This phase typically encompasses both concentric (CON) and eccentric (ECC) muscle contractions, with distinctive force generation mechanisms [2]. Skeletal muscles exhibit greater mechanical efficiency and force-generating capacity during the eccentric phase of exercise than the centripetal phase. Consequently, exercise loading based on the centripetal scheme may lead to underloading during the eccentric phase. Therefore, resistance exercise inducing an eccentric overload (EO) has been considered a superior scheme to increase the rate of muscular transitions and neuromuscular adaptations [3].

Flywheel Eccentric Overload (FEOL) and Adjustable Eccentric Hook (EH) training are two commonly employed forms of Eccentric Overload (EO) training. These methods provide increased resistance during the eccentric phase of muscle contraction, resulting in a higher overall electromyographic amplitude. This amplitude is a crucial stimulus for promoting muscle strength [4]. As biomechanical leverage and muscle length change, the ability to overcome weight loads depends on the occurrence of a “Sticking Point” during the movement. Both types of EO training can induce a pull reflex and enhance neuromuscular recruitment. Scholars both domestically and internationally recognize EO training as an effective method to enhance explosive muscle performance [5]. Consequently, EO training is considered a valuable approach to improving explosive muscle exercise performance. Given the introduction of new EO application methods, it is imperative for coaches and researchers to comprehend the application and characteristics of each method to ensure their correct implementation in training programs.

Pre-exercise neural activation and warm-up play a crucial role in enabling athletes to achieve optimal physical performance. Elite athletes commonly employ high-intensity warm-ups before training or competition to enhance their performance [6]. Numerous foundational studies have demonstrated the effectiveness of Post-Activation Performance Enhancement (PAPE) in both shorter, intense, and explosive single-movement structures, as well as multiple-movement structures [7]. The application and validation of PAPE effects extend across various sports [8,9]. After completing a high-intensity warm-up, temporary improvements in neuromuscular performance, body dynamics, and blood metrics changes can be observed. However, conflicting study results exist, and this inconsistency may be attributed to variations in intervention characteristics, including exercise modalities, intervention loads, forms of muscular activity, and rest periods between the pre-loaded exercise and the subsequent exercise-specific task. All these factors are considered key variables influencing the degree of response to this phenomenon [10]. Notably, differences in intervention dose, particularly, can directly impact the magnitude of the performance-enhancing effects of neural activation in athletes.

In this study, high-intensity half squats (HHS) were chosen to induce PAPE in sprinters. Common interventions for post-activation potentiation enhancement include barbell half squats, barbell hip thrusts, and barbell deadlifts [11]. Through repeated weight-bearing high-intensity resistance exercise, lower limb muscles are activated to regulate myosin light chain phosphorylation and enhance the formation of cross-bridges [12], thereby improving muscle power. Eccentric Overload (EO) training seems to outperform High-Intensity Half Squat (HHS) training in enhancing neuromuscular adaptations. It can serve as an effective tool for improving neuromuscular function in various populations, including healthy individuals, athletes, and those with related diseases [13–15]. However, a consensus is lacking on the optimal loading dose for both EO and HHS training to induce acute enhancement effects [16]. The primary limitations of different protocols in terms of inducing acute enhancement effects in muscles are directly linked to intervention loading and fatigue accumulation. Beato et al. suggests that effective EO training necessitates the application of larger loads [17]. While more intense and prolonged conditioning activities may activate the PAPE mechanism to a greater extent, they also result in increased fatigue [18]. Consequently, regulating the effects of different training protocols in the relationship between fatigue and enhancement effects induced by PAPE conditioning activities becomes a key question explored in this study. Existing studies have found that trainers can improve performance by inducing PAPE with a flywheel trainer. The optimal activation time of flywheel-induced PAPE is similar to that of traditional resistance training, but whether it is better compared to traditional barbell training in terms of PAPE induction seems to be controversial. The dose effect of flywheel-induced PAPE has not yet been determined, and further research is needed to determine the optimal PAPE activation through inertial strength, induction frequency, interval time, and exercise mode. Based on this research background, the present study was conducted to compare the acute changes in lower limb explosive jumping performance, sprinting ability and related parameters before and after two types of EO training and HHS training interventions through experimental studies and empirical analyses in order to optimize the explosive training methods. This study

Table 1
Participant descriptive characteristics, Mean ± SD.

	FEOL (n = 7)	EH (n = 7)	HHS(n = 7)	Total (n = 21)	P Value
Height (cm)	181.51 ± 3.7	180.63 ± 3.15	181.24 ± 2.56	181.25 ± 2.28	0.654[a]
Body mass (kg)	76.4 ± 4.56	75.73 ± 2.38	77.02 ± 1.25	76.96 ± 2.55	0.833[a]
MSW (kg)	150 ± 15	145 ± 26	148 ± 13	148 ± 18	0.727[a]
Training period (years)	5.1 ± 0.88	5.3 ± 0.57	5.2 ± 0.36	5.2 ± 0.76	0.784[a]
CMJ Height (cm)	50.77 ± 1.11	50.10 ± 0.85	50.61 ± 1.27	50.45 ± 0.33	0.445[a]
CMJ PPO(W/kg)	60.05 ± 1.72	59.40 ± 1.43	59.76 ± 1.14	59.68 ± 1.45	0.443[a]
SJ Height (cm)	45.29 ± 1.55	44.10 ± 1.10	45.38 ± 1.65	44.78 ± 1.78	0.788[a]
SJ PPO(W/kg)	55.23 ± 1.30	54.19 ± 1.26	55.22 ± 1.31	54.69 ± 1.56	0.744[a]
SLJ(m)	2.72 ± 0.05	2.71 ± 0.05	2.71 ± 0.06	2.71 ± 0.07	0.967[a]
30 m(s)	4.04 ± 0.04	4.06 ± 0.08	4.03 ± 0.03	4.05 ± 0.05	0.933[a]

CMJ Height, Countermovement Jump Height, CMJ PPO Countermovement Jump peak power output Output, SJ Squat Jump Height, SJ PPO Relative peak power output of static squat jump, SLJ, standing long jump, MSW, Maximum squat weight.

[a] ShaPiro-Wilk Test.

provides valuable suggestions for athletes engaged in jumping and sprinting movement patterns, and provides data support for training practices.

2. Materials and methods

2.1. Participants

The study's sample size was pre-estimated using G*Power 3.1.9.7 software (Dusseldorf, Germany), selecting the "MANOVA: Repeated measures, within-between interaction" option. Effect Size (V), α err Prob, and Power (1-β err Prob) were set at 0.8, 0.05, and 0.95, respectively [19]. The estimation results indicated a minimum sample size requirement of 18 individuals. Considering a potential sample dropout rate of 20 %, a minimum of 20 subjects were recruited. The basic profile of the participants is as follows:The best 100-m official race performance of the participants in the last 6 months was 10.74 ± 0.27(s). Athletes participating in the study were all professional Chinese provincial team athletes with national level competition experience and national masters or level 1 athlete qualifications. The average training experience was 8.34 ± 0.20 years. Sample characteristics are shown in Table 1. Tus, sprint athletes were initially selected according to the following inclusion criteria:

(1) 100 m within the last six months of a competition time or official time of 10.8s,
(2) the athlete himself and the legal guardian sign the Free and Informed Consent Form
(3) ≥ 8 years of sprint training experience,
(4) no history of lower extremity neurologic disease or orthopedic injury in the last 6 months.
(5) completed all phases of this study.

Ultimately, 21 disease-free sub-elite 100-m or 200-m male sprinters volunteered. The 21 participants were numbered from 1 to 21 according to the expected sample size, and single-sequence random assignment was performed through the Research Randomizer (https://www.randomizer.org/) program using the random number table method. Due to the uniqueness of scientific research in athletic training and to avoid this bias, a single-blind blinding method was implemented in this study, blinding only the study participants. A randomized controlled parallel design was used to assess six protocols (D1FEOL, D2FEOL, D1EH, D2EH, D1HHS, D1FEOL, D1FEOL, D1FEOL, D1FEOL, D1FEOL, D1HHS, D2HHS, see Table 2) for Countermovement jumping (CMJ), Squatting jumping (SJ), Standing Long Jump (SLJ), and 30 m sprint performance. Prior to the intervention, participants familiarized themselves with the FEOL, EH, and HHS exercise and testing procedures. They were also required to abstain from medications or foods that could affect their test performance for 48 h [20].

All subjects were informed of the potential risks and benefits, and they signed an informed consent form. The study received approval from the Ethics Committee of Exercise Science Experimentation at Beijing Sport University (No.2023215H). All experimental procedures adhered to the Declaration of Helsinki.

2.2. Experimental design

On the first sessions (see Table 2), aimed at familiarizing participants with the experimental procedure and measuring the Barbell Squat's maximum one-repetition weight (1 Repetition Maximum, 1 RM), the Squat Repetition Maximum Test (1 RM squat test) was conducted upon arrival at the site. Subjects first signed an informed consent form and then had their height and weight measured using electronic scales and a body mass measuring device (Inbody370, Korea). Participants adjusted the position of the safety bar and the height of the barbell to commence the deep squatting 1 RM test. The test warm-up group performed 10 repetitions at 50 % of the estimated weight of the 1 RM, 5 repetitions at 70 % of the estimated weight, 5 repetitions at 80 % estimated weight, 3 repetitions at 80 % estimated weight, and 1 repetition at 100 % estimated weight, with a 3-min rest period between test sets. If an increase in load on the

Table 2
The intervention sessions.

Week	Intervention group	Repetition	Sets	Test contents	Testing time (post-interventional)
3	D1FEOL[a]	7	1	CMJ、SJ、SLJ、30 m	6min
4	D2FEOL[b]	7	2	CMJ、SJ、SLJ、30 m	6min
5	D1EH[c]	7	1	CMJ、SJ、SLJ、30 m	6min
6	D2EH[d]	7	2	CMJ、SJ、SLJ、30 m	6min
7	D1HHS[e]	7	1	CMJ、SJ、SLJ、30 m	6min
8	D2HHS[f]	7	2	CMJ、SJ、SLJ、30 m	6min

[a] Flywheel eccentric overload training with 1 set of intervention doses.
[b] Flywheel eccentric overload training with 2 set of intervention doses.
[c] Eccentric Hook training with 1 set of intervention doses.
[d] Eccentric Hook training with 2 set of intervention doses.
[e] High-Intensity Half Squat training 1 set of intervention doses.
[f] High-Intensity Half Squat training with 2 set of intervention doses (the same as below).

next repetition led to test failure, the ability to complete the 1 RM was reassessed, allowing for up to 5 attempts to determine the 1 RM.

On the 2 sessions, baseline data were collected for the 30-m sprint run, SLJ, and CMJ and SJ jump. During the initial phase of the study, six experts with knowledge and expertise in sprint training evaluated the test content validity. I-CVI (content validity index of items) and modified Kappa coefficient factors were used to examine item content validity. A 4-point ordinal scale was employed, with response options ranging from 1 (indicating 'not relevant') to 4 (indicating 'highly relevant'). Test Items with I-CVI values less than 0.78 were either modified or eliminated.

Sessions 3–8 constituted the formal experimental sessions (see Table 2),and all test procedures were repeated three times. Research has consistently shown that the optimal window for enhancing sprint running and jumping performance effects occurs between minutes 3–8 post-intervention, with the most favorable effect typically observed at minute 6 [21–23]. To avoid potential fatigue legacy effects during between-group tests, the 30 m sprint run, Standing Long Jump, countermovement jump and squat jump test were all conducted at minute 6 post-intervention. To minimize the likelihood of interactions between different interventions, subjects were explicitly instructed to refrain from engaging in high-intensity training activities during the washout period. This ensured that subjects were in optimal condition for each training session [24]. Ensure that there is a 72-h interval between each test. [25], with no other strenuous exercise allowed on the test day. In addition, all trials were conducted between 3pm and 5pm during the day to mitigate the effects of circadian rhythm and to maintain consistency in the warm-up regimen before and after the experiment [26].

2.2.1. EH intervention program

The loading capacity for the EH group was determined based on 7 maximal intensity squat repetitions at the subject's sub-limit intensity load for a 1 RM squat (ECC 80 %/CON 50 %) [27]. Additionally, a metronome was set to 4 s/beat to ensure the athletes maintained consistent squat rhythms during the deep squat maneuver. The EH group protocol involved repetitive half-squats using a squat rack (Shuhua, SH-G8902, China) and eccentric hooks (Fat Grigz, International, Boise, ID, USA). These hooks were positioned at the ends of the barbell, releasing from the barbell ends and dropping to the floor when the subject reached the appropriate depth during the squat.

2.2.2. FEOL intervention program

The FEOL protocol involved performing repetitive half squats using an inertial flywheel training apparatus (Exxentric AB, Sweden). To determine the optimal inertial loading for the intervention protocol in the FEOL group, a linear sensor (GymAware RS, Australia) measured the average speed of subjects while they performed 7 repetitions of maximal intensity squats at 80 % of the maximum 1 RM squat weight [28]. This loading was then used for the subsequent interventions, with each set comprising 7 repetitions. To ensure consistency with the EH and HHS protocols, the inertial flywheel hooks were uniformly secured to adjustable straps, maintaining the same force generation position.

During the following 6 interventions, subjects were instructed to exert full force during the exercise, with video analysis used to assess the range of motion. The goal was to ensure that the knee was flexed at 90° to full extension. A 3-min rest period was provided between sets of exercises. Researchers qualitatively assessed each movement, offering kinematic feedback to athletes and standardized encouragement to maximize each movement repetition.

2.2.3. HHS intervention program

The HHS protocol involved performing half squats using a barbell squat rack (Shuhua, SH-G8902, China). The load applied was 80 % of each subject's 1 RM deep squat weight. Each training session included only one load set intervention, comprising 7 repetitions per set, with a 3-min rest interval between sets for passive recovery [29].

Utilized video analysis to assess range of motion, ensuring that your knees were bent to approximately 90°. During the half squat exercises in the high-stick position, participants should synchronize their movements with a metronome set to 1 beat per second. Specifically, athletes should squat for 4 beats during the eccentric phase and 1 beat during the concentric contraction, maintaining a consistent rhythm. This protocol mandates a slow descent in the eccentric stage and a rapid ascent in the concentric stage.

2.3. Measurement

2.3.1. Standardized warm-up

Participants performed a standardized warm-up, and then undergo a baseline test. Prior to testing and training, joint activity, dynamic stretching (including 10 the greatest stretches and 10 Inchworm stretches), intermediate area activation, and specific exercises (such as weighted half squats and sprints) should be conducted. After completing the warm-up, allow a 3-min rest period before commencing the test.

2.3.2. Countermovement jump test

CMJ scores were recorded, establishing the experimental baseline for each intervention protocol. After subjects had performed the FEOL, EH, and HHS intervention protocols at the same load intensity, CMJ jumping scores were measured again. A total of three tests were conducted for each protocol, and the best scores were selected. A three-dimensional dynamometer table (Kistler 9257B, Switzerland) measuring 900 × 600 mm at a frequency of 1000 Hz was utilized for assessing CMJ and SJ performance. Full-force CMJ jumps were performed with self-selected depths and arms placed on the hips to prevent the effects of arm swing [30]. Subjects were retested if they did not comply with the specific jumping protocol. Athletic tape marked the centers of the force platforms to guide subjects' foot placement.

2.3.3. Squat jump test

During the SJ test, subjects performed a maximum effort SJ with self-selected depth and hands on hips. To ensure the subject remained in the squat for a specific duration before jumping, the researcher checked that the force curve was a straight line, considering it a passable SJ. Researchers provided feedback on the technique, ensuring correct jumps and encouraging subjects to give their best effort during the test. Jump height directly reflects athletes' athletic ability on the sports field, while jump peak power output is a vital dynamic index indicating the explosive power of athletes' lower limbs. jump height and relative peak jump power output. As power equals force multiplied by speed, peak power signifies an athlete's capacity to generate maximum force in the shortest duration possible, aligning with the demands of sprint events. Jump height and peak power output calculations were performed by measuring the time to take off during the jump and the force output to the force platform. Data were analyzed using BioWare software (version 5.3.0.7) to select the best score for resolution, with a time intercept of 1/1000.

2.3.4. Standing long jump test

The endpoint aimed to investigate the effects of three intervention programs on human horizontal jumping ability. A 60-cm start line was established at the beginning of the SLJ. Subjects were given the freedom to choose the appropriate depth of the jumping squat and the amplitude of the arm swing. The jumping distance was measured from the starting line to the point where the heel touched the ground at the time of landing. This measurement approach was based on the protocols of Bianchi [31], Markovic [32], and others. Measurements were taken after subjects performed the FEOL, EH, and HHS intervention protocols with the same loading intensity, totaling three measurements. The best test result should be selected and recorded.

2.3.5. 30 m sprint test

Performance in 3 rounds of the 30 m sprint was recorded, with the best-performing round serving as the baseline value for the intervention protocol. Subsequently, subjects underwent the FEOL, EH, and HHS intervention protocols, and 30-m sprint performance was measured again at the end of the intervention. The timing system (SmartSpeed Dash, PB1281, Australia) was placed at the start and finish lines of the 30-m sprint track, positioned 1 m above the ground. A 1-m-long starting line was set less than 0.5 m from the starting line, providing a starting position for subjects with feet uniformly separated, the front foot behind the starting line, arms at the side, and hips and knees slightly bent. Subjects were tested after proper self-preparation, and researchers recorded sprint times to the nearest percentile [33].

2.4. Statistical analysis

Data was processed using GraphPad Prism (version 9.5.1, San Diego, California) statistical software. Descriptive statistics of the data were expressed as mean ± standard deviation (Mean ± SD). The normality of the data was initially tested using the Shapiro-Wilk Test. A three-way repeated measures ANOVA was then employed to assess significant differences between the three intervention regimens post-intervention at different doses. All the analyses for each group were checked for the main and interaction effects. If either of the two effects was significant, the multiple comparisons were conducted using the Newman-Keuls method. Statistical

Table 3
Variance results of repeated measurements of lower extremity explosive force during eccentric training.

	Effects	*F*	*P*	η_p^2
CMJ HIGHT (cm)	Method	32.41	<0.05	0.39
	time	36.52	<0.05	0.42
	Dosage	55.20	<0.05	0.36
	Interaction	7.81	<0.05	0.45
CMJ PPO(W/KG)	Method	14.45	<0.05	0.65
	time	16.08	<0.05	0.46
	Dosage	23.91	<0.05	0.36
	Interaction	3.28	<0.05	0.46
SJ HIGHT (cm)	Method	32.56	<0.05	0.39
	time	17.45	<0.05	0.46
	Dosage	56.06	<0.05	0.33
	Interaction	3.25	<0.05	0.65
SJ PPO(W/KG)	Method	14.32	<0.05	0.37
	time	17.34	<0.05	0.36
	Dosage	71.13	<0.05	0.54
	Interaction	5.79	<0.05	0.63
30 m sprint (s)	Method	34.34	<0.05	0.44
	time	46.47	<0.05	0.23
	Dosage	79.11	<0.05	0.26
	Interaction	7.14	<0.05	0.35
SLJ (m)	Method	0.20	>0.05	0.01
	time	0.45	>0.05	0.03
	Dosage	0.14	>0.05	0.01
	Interaction	0.35	>0.05	0.02

Table 4
Descriptive statistics of acute effects of different tests before and after 3 training interventions.

	D1						D2					
	FEOL (n = 7)		EH (n = 7)		HHS(n = 7)		FEOL (n = 7)		EH (n = 7)		HHS(n = 7)	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
CMJ HIGHT (cm)	50.77 ± 1.11	50.82 ± 1.96	50.10 ± 0.85	50.13 ± 1.18	50.61 ± 1.27	52.14 ± 1.46[c]	50.51 ± 1.19	53.63 ± 1.22[ad]	49.81 ± 1.14	51.53 ± 1.28[b]	50.68 ± 1.07	49.03 ± 1.13
CMJ PPO(W/KG)	60.05 ± 1.71	60.09 ± 2.11	59.40 ± 1.43	59.43 ± 1.68	59.76 ± 1.14	61.73 ± 1.43[c]	59.76 ± 1.22	62.52 ± 1.67[ad]	59.11 ± 1.15	60.59 ± 1.21[b]	59.81 ± 1.04	58.39 ± 0.99
SJ HIGHT (cm)	45.29 ± 1.55	45.25 ± 1.35	44.39 ± 0.94	44.24 ± 1.31	45.38 ± 1.65	47.09 ± 1.81[c]	45.24 ± 1.42	46.85 ± 1.77[a]	44.53 ± 1.42	46.66 ± 1.33[b]	45.39 ± 1.64	43.63 ± 1.27
SJ PPO(W/KG)	55.23 ± 1.30	55.22 ± 1.34	54.43 ± 1.05	54.32 ± 1.38	55.22 ± 1.30	56.69 ± 1.45[c]	53.78 ± 2.42	56.56 ± 1.28[a]	54.53 ± 1.18	56.39 ± 1.28[b]	55.23 ± 1.31	53.72 ± 1.07
30 m sprint (s)	4.04 ± 0.04	4.02 ± 0.07	4.06 ± 0.08	4.02 ± 0.04	4.03 ± 0.02	2.71 ± 0.04[c]	4.05 ± 0.08	3.97 ± 0.05[a]	4.07 ± 0.10	3.98 ± 0.04[b]	4.03 ± 0.05	3.93 ± 0.04
SLJ (m)	2.72 ± 0.05	2.72 ± 0.03	2.71 ± 0.05	2.73 ± 0.04	2.71 ± 0.05	2.71 ± 0.07	2.74 ± 0.04	2.71 ± 0.05	2.70 ± 0.06	2.72 ± 0.05	4.12 ± 0.05	2.65 ± 0.04

[a] Significantly different between pre-training and post-training in FEOL, $p < 0.05$.
[b] Significantly different between pre-training and post-training in EH, $p < 0.05$.
[c] Significantly different between pre-training and post-training in HHS, $p < 0.05$.
[d] D2FEOLcompared with D2EH, $p < 0.05$.

differences were considered at *P*-values less than 0.05. Cohen's d-value was utilized to assess the effect size (ES) of all dependent variables. Effect sizes were calculated and interpreted as follows: none≤0.2, 0.2≤smaller≤0.6, 0.6≤medium≤1.20, 1.20≤larger≤2.0, and large≥2.0 [34]. Significance was set at $P < 0.05$, with confidence intervals set at 95 %.

3. Results

3.1. Effects of different training on CMJ performance

CMJ height ($F_{(3,72)} = 26.08$, $p < 0.05$, $n_p^2 = 0.73$) and relative peak power ($F_{(3,72)} = 37.32$, $p < 0.05$, $n_p^2 = 0.53$) were found to be significant main effect for intervention times. Additionally, the main effect of CMJ height ($F_{(3,72)} = 3.60$, $p < 0.05$, $n_p^2 = 0.39$) and relative peak power ($F_{(3,72)} = 4.17$, $p < 0.05$, $n_p^2 = 0.45$) showed significance for intervention dosages. The intervention groups also yielded significant main effects, as evidenced by CMJ height ($F_{(3,72)} = 3.565$, $p < 0.05$, $n_p^2 = 0.43$) and relative peak power ($F_{(3,72)} = 3.81$, $p < 0.05$, $n_p^2 = 0.45$) (see Table 3).

However, the jump height ($p < 0.01$,ES $= 1.35$) and relative peak power output ($p < 0.01$,ES $= 0.87$) of the D2FEOL group significantly differed from the baseline values. Additionally, the jump height of the D2EH group ($p < 0.05$,ES $= 0.74$) and relative peak power output ($p < 0.05$,ES $= 0.71$) were significantly different compared to baseline values. In the D1HHS group, both jump height ($p < 0.01$,ES $= 0.94$) and relative peak power output ($p < 0.01$,ES $= 0.92$) were significantly different compared to baseline values. Comparing interventions, jump height after D2FEOL intervention ($p < 0.05$,ES $= 0.78$) and relative peak power output ($p < 0.05$,ES $= 0.76$) were significantly higher than D1HHS(see Table 4).

3.2. Effects of different training on SJ performance

SJ height ($F_{(3,72)} = 31.92$,$p < 0.05$, $n_p^2 = 0.95$) and relative peak power ($F_{(3,72)} = 38.04$,$p < 0.05$, $n_p^2 = 0.89$) showed significant main effects for intervention time. Additionally, SJ height ($F_{(3,72)} = 7.83$,$p < 0.05$, $n_p^2 = 0.61$) and relative peak power ($F_{(3,72)} = 2.42$,$p < 0.05$, $n_p^2 = 0.64$) exhibited significant main effects for intervention groups. Furthermore, SJ height ($F = 6.58$,$p < 0.05$, $n_p^2 = 0.66$) and relative peak power ($F_{(3,72)} = 7.42$,$p < 0.05$, $n_p^2 = 0.54$) showed significant main effects for intervention dosages (see Table 3).

Post hoc analyses revealed no significant changes ($p > 0.05$) in D1FEOL and D1EH jump heights and relative peak power output after the intervention compared to baseline. However, there was a significant increase in D2FEOL jump height ($p < 0.05$,ES $= 0.61$) and relative peak power output ($p < 0.05$,ES $= 0.68$) compared to the baseline data. Additionally, D2EH jump height ($p < 0.05$,ES $= 0.58$), and relative peak power output ($p < 0.05$,ES $= 0.56$) were significantly increased from baseline data. The D1HHS group exhibited significant differences in jumping height ($p < 0.05$,ES $= 0.78$) and relative peak power output ($p < 0.05$,ES $= 0.75$) compared to baseline values. In addition, Comparing interventions, there was no significant difference between the D1HHS, D2FEOL, and D2EH groups (see Table 4).

3.3. Effects of different training on 30 m sprint performance

The main effect of 30 m was significant ($F_{(3,72)} = 72.97$, $p < 0.05$, $n_p^2 = 0.83$)for intervention times, indicating its influence on the outcome variable. Similarly, the main effect of the intervention groups was significant ($F_{(3,72)} = 6.98$,$p < 0.05$, $n_p^2 = 0.58$), suggesting its impact on the measured outcomes. Additionally, the main effect of intervention dosages was significant ($F_{(3,72)} = 6.75$,$p < 0.05$, $n_p^2 = 0.63$), highlighting its importance in influencing the observed results (see Table 3).

Cohort analyses revealed that 30 m performance after D1FEOL and D1EH interventions showed no significant change compared to baseline at post-intervention ($p > 0.05$). However, D1HHS ($p < 0.01$,ES $= 1.45$) exhibited a significant increase in 30 m performance at post-intervention. Furthermore, 30 m sprint time after D2FEOL compared to D1FEOL ($p < 0.05$,ES $= 1.65$) significantly improved, and 30 m sprint time after D2EH compared to D1EH ($p < 0.05$,ES $= 1.14$) also significantly improved. Additionally, D1HHS intervention compared to D2HHS ($p < 0.05$,ES $= 1.76$) showed significant improvement (see Table 4).

3.4. Effects of different training on SLJ performance

The SLJ results ($F_{(3,72)} = 2.161$,$p > 0.05$, $n_p^2 = 0.25$) revealed no significant main effect for intervention times, indicating that time did not significantly impact the outcome variable. Similarly, the main effect of intervention scheme was not significant ($F_{(3,72)} = 3.006$, $p > 0.05$, $n_p^2 = 0.11$), suggesting that the intervention groups did not have a significant effect on the measured outcomes. Additionally, the main effect of intervention dose was not significant ($F_{(3,72)} = 3.370$,$p > 0.05$, $n_p^2 = 0.13$), indicating that intervention dosages did not significantly influence the observed results (see Table 3).

4. Discussion

To the best of our knowledge, this comparative study is the first to investigate the acute effects of eccentric overload training with different loadings on lower limb muscles, and based on the timing of the different enhancement effects from various training protocols, this study provides important insights into acute capacity enhancement methods for lower limb muscles. Our study will provide coaches and athletes with more scientific and effective guidance for lower training methods.

4.1. Acute augmentation effects on explosive jumping ability

Height and peak power output during vertical jumps are among the most straightforward evaluation indices for assessing vertical jumping performance [35]. The study results indicated that D2FEOL, D2EH, and D1HHS demonstrated acute enhancements in jumping athletic performance post-intervention. In the CMJ test, the jump height achieved with the D2FEOL scheme was significantly greater than that observed with the D2EH scheme. However, here was no significant difference observed in the SJ jump height and relative peak power output after 2 dosages of FEOL training and EH training interventions. EO exercise led to increased activation of fast motor units and type II muscle fibers, potentially inducing a greater PAPE response [36]. This aligns with findings by Van den Tillaar R. et al., suggesting that faster eccentric durations can significantly enhance subsequent power and speed performance [37]. Slower cadence results in less centripetal force and relative power, reducing the stretch-shortening cycle by decreasing type IIx muscle fiber recruitment. Carzoli et al. also found that faster eccentric phases during movements like back squat and bench press resulted in subsequent enhancements in centripetal mean and peak velocity [38]. Faster eccentric muscle actions are argued to achieve greater effects on type IIa and IIx muscle fiber and motor unit recruitment [39]. Applying greater resistance loads during the eccentric contraction phase compared to isometric or centripetal contractions significantly increases the number of attached cross-bridges in muscle fibers. Moreover, the elastic potential energy stored in actin is more abundant during the stretch-shortening cycle before the muscle transitions from eccentric to centripetal contraction [40]. Power enhancement during the eccentric (ECC) phase contributes to an increase in the firing frequency of muscle motor units [41], and improved eccentric contraction coordination contributes to muscle SSC motor performance [42]. In the current study, there was no significant difference in the augmentation effect produced by the EO and HHS intervention protocols in the squat jump test. SLJ performance was improved after moderate intensity and high intensity centrifugal flywheel exercise (Bayes factor [BF10] = 32.7, strong; BF10 = 9.2, medium). CMJ height (BF10 = 135.6, extreme value; BF10 > 200, extreme value), CMJ peak power (BF10 > 200, extreme value; BF10 = 56.1, very strong). The eccentric elongation phase, serving as the primary energy storage phase of the muscle, may explain this outcome. The chosen squat jump test protocol in this study allowed the muscle to eliminate the activation effect of the tendon in the elongation reflex phase during the experimental process [43]. The selected subjects are sub-elite-level sprinters with high athleticism and a minimum of 8 years of sprint training, offering greater potential for selective recruitment of fast muscle fibers and activation of high-threshold motor units for subsequent explosive movements [44].

Explosive jumping ability in the sagittal plane was also tested through the SLJ test in this study. However, no significant enhancement of SLJ performance was observed between different training protocols. This lack of enhancement may be attributed to the fact that the chosen intervention protocol mainly focused on vertical force training, contrasting with the force pattern of the SLJ test. Other research, such as that by Michael J Williams et al., has suggested that using force in the horizontal plane through exercises may offer better lateral jump performance [45].

Conversely, the D2HHS protocol intervention led to significant reductions in both vertical and lateral explosive jumps. Studies have suggested that extreme intensity interventions may increase the number of recruited motor units but also lead to higher accumulation of metabolites, resulting in fatigue factors like decreased phosphocreatine, glycogen, and ATP stores, as well as increased phosphate and hydrogen ions [46]. Shorter intervals may not show an optimal PAPE effect if the intervention regimen causes more fatigue than the enhancement effect itself. Adequate recovery time is essential for the strength enhancement effect to outweigh skeletal muscle fatigue, leading to optimal muscle performance, as supported by studies like that of Kilduff et al., which found that explosive strength peaked between 8 and 12 min after exercise [47]. Ryan P Lowery et al.'s study also emphasized effective recovery time between 4 and 12 min, with the augmentation being lost after 12 min [48]. Consequently, this study suggests the need for a longer recovery time to achieve an enhancement effect after an acute intervention with higher intensity loads.

In summary, both EO training and HHS training have been shown to enhance athletes' vertical jumping performance and sprint ability. While EO training elicits a stronger "stretch-shorten cycle" mechanism in the muscles compared to HHS training, neither training significantly improves standing long jump performance. Further research is needed to explore optimal recovery times and intervention protocols for maximizing explosive jump performance.

4.2. Acute enhancement effect on sprinting ability

The 30 m sprint ability serves as a classic method for assessing horizontal speed or horizontal explosive power, which significantly contributes to the success of sprinters. Research by Ralph Mann and others has demonstrated that elite male 100-m sprinters achieve more than half of their maximum speed within the first two steps of the start, reaching speeds of 6 m/s during the first step after pushing off the starting block and further increasing to 7 m/s during the second step. Running, a fundamental exercise for human survival, reflects the body's ability to move quickly, encompassing qualities like strength [49]. Eccentric training has been shown to enhance the impact of eccentric speed and kinetic energy of muscles on performance. A study by Giovanni Fiorilli revealed that long-term eccentric training intervention effectively improves the eccentric speed of DJ, muscle elongation-shortening cycle, and the initial eccentric stage of turning running [50]. Additionally, it was found that eccentric training can also enhance muscle strength during the continuous concentric stage. In a study by Spiteri [51], prolonged eccentric training was found to be more effective than traditional resistance exercise regimens in assessing sprint ability among soccer players. Sprinting, crucial in various sports, relies on muscle activation sequence and improved recruitment of muscle fibers (IIa and IIx). D2FEOL, D2EH, and D1HHS significantly enhanced sprinting ability in sprinters, emphasizing differences in dosage regimens. FEOL and EH were similarly effective [52], while HHS required a distinct dose. Similar findings by Aaron D Piper and Yusuf Köklü highlighted improved sprint times post-intervention [53,54].

Results demonstrated EO training's acute effects on sprinting, with 2 doses outperforming 1 doses, aligning with findings on FEOL training. Sprinting ability links to reaction force, influenced by factors like elastic energy storage, central reflex regulation, and active muscle contraction force. According to the rationale for the PAPE effect, the post-resistance training improvements in 30 m sprinting result from shortened landing time and increased stroke value [55]. FEOL training augments ECC to CON transition, enhancing subsequent centripetal maneuvers. EO protocols, FEOL, and EH generate greater force and centripetal power, contributing to improved acceleration initiation [56]. In their study, Borja Sanudo et al. found that eccentric flywheel training significantly improved CMJ ($d > 0.9$, $p < 0.001$) and sprint performance ($d > 0.5$, $p < 0.05$) in healthy men. Moreover, sprint ability had a greater enhancement effect than that of the control group ($F_{(1,18)} = 5.11$, $p = 0.036$).

Future research should explore acute and long-term EO training. Different EO training forms enhance muscle explosive performance by increasing ECC resistance, activating motor units. This study affirms EO training's kinematic advantages in acute explosive power. Consistent acute enhancement effects support coaches and researchers, providing empirical data for lower limb explosive force training in male sprinters. Both EO training types effectively enhance lower limb muscle explosive force in acute sports performance.

4.3. Limitations

Despite presenting clinically significant findings, there are some limitations that need clarification. Firstly, we exclusively evaluated sub-elite athletes; employing a diverse study population could help reveal the effects of various training methods on the acute enhancement of lower extremity muscles on a broader scale. Secondly, our analysis focused solely on the immediate enhancement characteristics of eccentric overload training with different protocols. It is hoped that future studies will incorporate the findings of this research into long-term intervention studies to validate exercise effects. On the other hand, future research could explore the beneficial effects of PAPE on athletes by incorporating tests within different time windows. Finally, the absence of a control group is also one of the shortcomings of this study. It is suggested that the control group should be added to the experimental design in future studies to determine the gain effect of the experimental scheme.

5. Conclusions

In this study, we concluded that the three aforementioned training protocols (D2FEOL, D2EH, D1HHS) successfully induced significant enhancement in athletes' explosive athletic performance. D1HHS, D2FEOL and D2EH3 intervention methods can all improve the performance of sub-elite athletes in the 30-m test, CMJ test and SJ test. The EO training method and the HHS training method exhibited different loading dosage characteristics. Specifically, the two types of EO training, FEOL and EH, utilizing 2 sets of loads, effectively induced acute enhancement in athletes' longitudinal explosive jumping performance and sprinting ability. Particularly in the CMJ test, FEOL training demonstrated a higher acute augmentation effect compared to EH training.

Recent studies have corroborated that eccentric overload training effectively enhances muscle function and neural adaptability. Future research work should explore the role of long-term eccentric overload training in annual and multi-year periodic training, and explore the optimal combination ratio of eccentric overload training with other strength training methods. At the same time, we will also include sprinters of different levels and genders to clarify the individualized gain differences in the acute enhancement effects of eccentric overload training on athletes of different levels and genders.

Ethical statement

The study received approval from the Ethics Committee of Exercise Science Experimentation at Beijing Sport University (No.2023215H). All experimental procedures adhered to the Declaration of Helsinki.

Data availability statement

The data that support the finding of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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CRediT authorship contribution statement

Yuhang Liu: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Junjie Zhang:** Writing – review & editing, Validation, Supervision, Formal analysis. **Zhongzhong Hu:** Writing – review & editing, Software, Formal analysis, Data curation. **Zixuan Zhong:** Writing – review & editing, Data curation. **Xiaoyi Yuan:**

Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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