Submitted: 05 March, 2024 Accepted: 23 April, 2024 Published: 30 October, 2024 DOI:10.22514/jomh.2024.168

JOMH
Journal of Men's Health

ORIGINAL RESEARCH

Effects of complex training on muscle stiffness, half squat 1-RM, agility, and jump performance in healthy males

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Abstract

This study aimed to analyze effects of complex training (CPT) on muscle stiffness, half-squat one-repetition maximum (1-RM), agility, and jump performance and to compare its efficacy with that of compound training (CT) over a 6-week period. Twenty healthy men in their 20s, majoring in physical education, were randomly divided into the CT (n = 10) and CPT groups (n = 10). CT involved resistance and plyometric training performed in separate sessions, whereas CPT integrated both in the same session. Both groups performed resistance training at 75–90% of 1-RM and plyometrics at 0–30% of body mass intensity for 6 weeks (2 days/week). Participants' body composition, muscle stiffness, half-squat 1-RM, T-agility, and jump performance were assessed before and after the exercise program. After training, body-composition tests revealed a significant increase in fat-free mass in both the CT (p = 0.021) and CPT (p = 0.011) groups. Muscle stiffness increased in both the right (p = 0.004) and left hamstrings (p = 0.004) only in the CPT group. Half-squat 1-RM and T-agility test results demonstrated a significant increase in strength in both the CT ($p < 0.001$ and p = 0.002, respectively) and CPT ($p < 0.001$ and $p < 0.001$, respectively) groups. Significant increases in jump height were observed for squat and horizontal jumps in both groups. However, countermovement 5 jump power (p = 0.023) and reactive strength index (RSI) (p = 0.008); double-leg drop jump height (p = 0.005), power (p = 0.026), and RSI (p = 0.048); right single-leg drop jump height (p = 0.006), power (p = 0.035), and RSI (p = 0.048) significantly increased only in the CPT group. The results of this 6-week study suggest that CPT is a more effective strength- and power-training method than CT.

Keywords

Combined training; Plyometric; Power; Strength

1. Introduction

Strength, defined as the ability to exert the maximal force at a specified speed, and power, defined as work done per unit time or the rapid application of force, are fundamental fitness components in all sports [1], and maximal strength and power are crucial in sports requiring explosive performance [2, 3]. Additionally, athletes are required to perform high-intensity movements such as repetitive accelerations and direction changes, sprints and jumps [4]. Athletic performance relies on well-developed muscular strength, which requires high-intensity specific resistance training (RT) or plyometric training (PT) to induce significant neuromuscular adaptations [4]. RT, PT and combined RT and PT programs are necessary to improve neuromuscular performance during sprinting and jumping [5].

Conventionally, RT or PT have been used to improve power and strength [6]. However, strength and power improvements are better when both forms of training are combined compared with those with RT or PT performed separately [7–10]. This combination, referred to as compound training (CT) or complex training (CPT), can close the gap between strength and speed training, leading to improved performance in explosive tasks such as jumping, sprinting, and changing direction [7, 11] and variability and time efficiency in athletes' periodization protocol [12].

CT involves distinct sessions for strength and power training and enhances the stretch-shortening cycle (SSC) through improved movement speed and contraction time [13, 14]. Previous studies have reported greater vertical jump improvement with combined training than with single training [9]. In our previous study, performing high-load RT and sprints in the same training session simultaneously improved strength, running speed, and jump performance [10]. However, when power training is performed immediately after strength training, the time for muscle recovery may be inadequate, leading to overtraining and injury [7]. In contrast, combined lower- and upper-body training allows adequate muscle recovery time but may not be as intense [15]. Thus, CT increases power, strength, or both, but not simultaneously [16].

CPT, in which RT performed using a high load is followed by the execution of a biomechanically similar PT [8, 17, 18], is performed to overcome the main limitations of RT and PT. CPT enhances explosive muscle performance owing to a post activation potentiation (PAP) response following maximal/near-maximal contraction [8]. In addition, CPT increases the excitability and reflex potential of muscle motor units through high-load RT and can create optimal training conditions for subsequent PT [19–21]. PAP, which is a short-term increase in power after high-intensity training, can be explained based on two mechanisms [22, 23]. The first mechanism involves phosphorylation of the myosin regulatory light chain in the local muscle by myosin light chain kinase. Phosphorylation increases the sensitivity of actin-myosin interactions to Ca^{2+} ions released from the sarcoplasmic reticulum. This, in turn, enhances the ratio of cross-bridge interactions and accelerates cross-bridge binding, resulting in faster muscle contractions [18, 23, 24]. The second mechanism involves the increased excitability of the α-motor neurons in the spinal cord [22, 23, 25]. Regarding force potentiation after conditional contraction due to PAP, an increase in α-motor neuron excitability or a decrease in presynaptic inhibition of Ia afferent fibers occurs. This increases the H-reflex amplitude after conditional contraction, indicating that additional motor units are recruited *via* the reflex pathway [23]. Therefore, PAP increases the rate of force development in the muscles [14], and acute and chronic increases in muscle strength and power can be further enhanced by performing explosive power exercises with the muscles in a potentiated state [21]. In previous studies, performing squat jumps (SJs) after high-load back squats improved the jump height and ground-reaction force, and the combined use of RT and PT in CPT resulted in more significant improvements in vertical jump compared to those with single training [17, 21].

In a previous study, both CPT and CT induced similar improvements in vertical jump height and power after 4 weeks of training [13]. However, CT may be more effective in improving power in the short term, whereas CPT may more effectively increase muscle hypertrophy and strength [26]. In addition, Abade *et al.* [4] reported that in-season CPT had a significant positive effect on low-level athletes' jump and sprint performances and could improve their recovery ability after high-intensity exercise. However, the impact of CT on sprint and jump performance of high-level athletes was unclear, although CT can help maintain a high in-season physical level [4].

Therefore, although performing RT and PT in a single training session positively influences power improvement, combined training programs provide greater improvements. Numerous studies have compared single training (RT or PT) with combined training (RT and PT), and the outcomes were either similar or inconclusive. Previous combined-exercise studies only used machine or isotonic resistance training (RT), which may have contributed to the lack of efficient strength and power training. Therefore, comparisons of different types of combined-training programs are warranted. Furthermore, comparison of the differences between CT and CPT when performing overcome- and output-isometric exercises during combined training is required to determine the more efficient training method for muscle strength and power enhancement.

2. Materials and methods

2.1 Participants

This study included 20 healthy men in their 20s majoring in physical education. Participants were randomly divided into a CT group (n = 10; mean age, 24.5 ± 3.7 years) and a CPT group (n = 10; mean age, 25.5 ± 3.3 years). Participants who could perform a half squat with a 1-RM 1.5 times their body weight were selected. Individuals with $<$1 year of free-weight experience or a history of lumbar spine disorders or surgery were excluded. The physical characteristics of the participants in each group are shown in Table 1.

TABLE 1. Participants' characteristic.

Parameters	CT (n = 10)	CPT (n = 10)	*p*-value
Age (yr)	24.5 ± 3.7	25.5 ± 3.3	0.535
Height (cm)	174.2 ± 4.1	175.3 ± 5.5	0.620
Weight (kg)	68.5 ± 7.6	74.2 ± 10.9	0.186
BMI (kg/m^2)	22.5 ± 1.7	24.2 ± 3.6	0.200
LBM (kg)	48.5 ± 7.6	49.5 ± 10.5	0.820
BFM (kg)	15.1 ± 2.0	16.9 ± 4.2	0.233
Body fat (%)	22.1 ± 1.0	22.6 ± 3.0	0.612
Half squat 1-RM (kg)	127.7 ± 26.4	136.6 ± 27.3	0.469

Abbreviations: CT, complex training; CPT, compound training; BMI, body mass index; LBM, lean body mass; BFM, body fat mass; RM, repeated maximum; Values are expressed as mean ± standard deviation.

2.2 Body composition

Body composition was measured using an Inbody 770 apparatus (Inbody, Seoul, Korea) before and after the 6-week exercise program. Participants were instructed to fast for at least 4 h before measurement. The body weight, body mass index, lean body mass (LBM), body fat mass, and body fat percentage were measured.

2.3 Muscle stiffness

Muscle stiffness was determined using a Myoton PRO instrument (Myotonpro, Myoton AS, Tallinn, Estonia). The rectus femoris muscle and hamstring and Achilles tendons were evaluated in the supine and prone positions, respectively. The Myoton PRO was positioned perpendicular to the skin during measurement.

2.4 Half squat 1-RM

The National Strength and Conditioning Association protocol was used for direct measurement of 1-RM [27]. To check the half-squat angle, a measurement assistant was positioned beside the participant. After a general warm-up, participants performed two specific warm-up sets: the first set of 8 repetitions at 50% of their estimated 1-RM, and the second set of 3 repetitions at 70% of their estimated 1-RM, with a 3-min rest interval between sets. After a 3-min warm-up, participants were asked to perform up to 5 repetitions to reach their 1-RM load (*i.e.*, the maximum weight they could lift once with proper technique). Participants were allowed to rest for 3 min between sets.

2.5 T-agility

The T-agility test is used to evaluate the ability to change direction, including forward sprinting, right- and left-sided steps, and backpedaling [28]. A 3-min rest was allowed between each measurement, and measurements were performed thrice.

2.6 Jump performance

In the SJ test, participants placed their hands on their iliac crests and adjusted their knee angles to 90°. After a 1-s pause, they performed an SJ, and the jump height was measured. Each participant repeated this test thrice with a 30-s rest period between each attempt.

The countermovement jump (CMJ) test required participants to place their hands on their iliac crests, maintain a standing posture, and perform a countermovement before executing a jump. The jump height was measured thrice with a 30-s rest interval between attempts.

During the countermovement 5 jump (CM5J) test, participants performed five consecutive jumps, and the jump height, power, and reactive strength index (RSI) were measured for each jump. RSI, an important indicator for evaluating muscle strength, considers contact time and jump height and is closely related to agility improvement [29].

In the drop jump (DJ) test, participants were instructed to perform a rapid and high jump from a 30-cm box, and the jump height, power, and RSI were measured. Both DJs and single-leg DJs (SDJs) were performed thrice, with a 30-s rest interval between attempts.

The horizontal jump (HJ) test measured the distance (in centimeters). They began in the standing position, swung their arms, bent their knees to a 90° angle, and then jumped. This test was repeated three times, with a 30-s rest period between each attempt.

The HJ test was conducted using K-108 equipment (K-108, KLsport, Anyang, Korea), whereas the remaining jump tests were conducted using Opto-Jump equipment (Opto-jump, Microgate, Bolzano, Italy). RSI was calculated as flight time/contact time [29].

2.7 Training

All participants completed a 6-week exercise program, comprising two sessions per week at intensities ranging from 75% to 90% of their 1-RM for RT and from 0 to 30% of their body mass for PT, and with the intensity gradually increasing every 2 weeks. Before starting the training program, all participants were educated about the movements and precautions. RT and PT sessions were performed on separate days for the CT group, whereas for the CPT group, RT and PT sessions were performed as a complex pair. The structure of the training program is shown in Table 2.

2.8 Sample size and blinding

The sample size for this study was determined based on the studies by Abade *et al.* [4] and Kontochristopoulos *et al.* [30]. Participants were divided into two groups of 10 individuals each using a double-blind random assignment procedure. One group served as the control group, whereas the other was designated as the experimental group (Table 1).

2.9 Statistical analyses

Data were analyzed using SPSS 25 statistical software (SPSS Institute, IBM Corp., Armonk, NY, USA). The mean and standard deviation were calculated for each item. Normality

TABLE 2. Exercise protocol in each group during week 1–6.

Group	Exercise	Sets × Reps	Load	Rest
CT				
	Day 1: FI squat (90°) EQI squat (90°) Calf raise	4 × 5 – 3 (3 s) 4 × 5 – 3 (3 s) 4 × 6 – 4	75–90% 1-RM	Rest between sets 3 min
	Day 2: Drop Jump Depth Jump Box Jump	4 × 8 – 6 4 × 8 – 6 4 × 8 – 6	0–30% Body Mass	Rest between sets 3 min
CPT				
	Day 1: FI squat (90°) + Depth Jump EQI squat (90°) + Drop Jump Calf raise + Box Jump	2 × 5 – 3 (3 s) + 2 × 8 – 6 2 × 5 – 3 (3 s) + 2 × 8 – 6 2 × 6 – 4 + 2 × 8 – 6	75–90% 1-RM + 0–30% Body Mass	Intraset rest-3 min Interset rest-3 min
	Day 2: FI squat (90°) + Depth Jump EQI squat (90°) + Drop Jump Calf raise + Box Jump	2 × 5 – 3 (3 s) + 2 × 8 – 6 2 × 5 – 3 (3 s) + 2 × 8 – 6 2 × 6 – 4 + 2 × 8 – 6	75–90% 1-RM + 0–30% Body Mass	Intraset rest-3 min Interset rest-3 min

Abbreviations: CT, compound training; CPT, complex training; FI squat, functional isometric squat; EQI squat, eccentric quasi-isometric squat; RM, repetition maximum.

and homogeneity of variance assumptions were checked using Shapiro-Wilk tests before performing parametric statistics. To investigate the effectiveness of the 6-week CPT and CT programs on muscle stiffness, half-squat 1-RM, agility, and jump performance, repeated two-way analysis of variance with a within-subjects factor was used; *post-hoc* paired Student's *t*-tests were performed when significant interaction effects or main effects between groups were observed. The significance level (α) for all statistical analyses was set at 0.05.

3. Results

3.1 Body composition

Changes in body composition in the CT and CPT groups after 6 weeks of exercise training are shown in Table 3. No body composition variables had significant interaction effects, whereas fat-free mass was a significant main effect ($p < 0.001$, $\eta_p{}^2 = 0.499$). *Post hoc* analysis revealed statistically significant increases in fat-free mass in the CT ($p = 0.021$) and CPT ($p = 0.011$) groups.

3.2 Muscle stiffness

Changes in muscle stiffness after 6 weeks of exercise training in both groups are shown in Table 4. Although no significant interactions or main effects were observed in the rectus femoris muscle and Achilles tendon stiffness, a significant interaction effect ($p = 0.037$, $\eta_p{}^2 = 0.219$) and a significant main effect ($p = 0.001$, $\eta_p{}^2 = 0.475$) were observed for the right and left hamstring muscles, respectively. *Post hoc* analysis revealed a significant increase in hamstring-muscle stiffness on both the left ($p = 0.004$) and right ($p = 0.004$) sides in the CPT group, indicating that CPT was more effective than CT in strengthening the hamstring muscles.

3.3 Half squat 1-RM and T-agility

Changes in half squat 1-RM and T-agility in the CT and CPT groups after 6 weeks of exercise training are shown in Table 5. Although no significant interaction effects were observed for either variable, significant main effects were observed for half squat 1-RM ($p < 0.001$, $\eta_p{}^2 = 0.887$) and T-agility ($p < 0.001$, $\eta_p{}^2 = 0.790$). *Post hoc* analysis revealed significantly increases in half-squat 1-RM and T-agility in both the CT ($p < 0.001$ and $p = 0.002$, respectively) and CPT ($p < 0.001$ and $p < 0.001$, respectively) groups.

3.4 Jump performance

The results of jump performance tests, including SJ, CMJ, CM5J, DJ, SDJ and HJ, for the two groups after 6 weeks of exercise training are shown in Table 6. Among all jump performance measures, a significant interaction effect was observed only for the right SDJ height ($p = 0.011$, $\eta_p{}^2 = 0.309$). Moreover, significant main effects were observed for SJ height ($p < 0.001$, $\eta_p{}^2 = 0.837$), CMJ height ($p < 0.001$, $\eta_p{}^2 = 0.657$), CM5J height ($p = 0.001$, $\eta_p{}^2 = 0.458$), power ($p = 0.016$, $\eta_p{}^2 = 0.284$), RSI ($p = 0.025$, $\eta_p{}^2 = 0.250$), DJ height ($p = 0.001$, $\eta_p{}^2 = 0.459$), power ($p = 0.006$, $\eta_p{}^2 = 0.347$), RSI ($p = 0.016$, $\eta_p{}^2 = 0.281$), SDJ power ($p = 0.038$, $\eta_p{}^2 = 0.219$), RSI ($p = 0.041$, $\eta_p{}^2 = 0.213$), and HJ height ($p < 0.001$, $\eta_p{}^2 = 0.605$). *Post hoc* analyses revealed that SJ height (CT, $p < 0.001$; CPT, $p < 0.001$), CMJ height (CT: $p = 0.011$, CPT: $p < 0.001$), CM5J height (CT: $p = 0.037$, CPT: $p = 0.014$), and HJ height (CT, $p = 0.038$; CPT, $p < 0.001$) significantly increased in the CT and CPT groups. However, CM5J power ($p = 0.023$), RSI ($p = 0.008$), DJ height ($p = 0.005$), power ($p = 0.026$), RSI ($p = 0.048$), right SDJ height ($p = 0.006$), power ($p = 0.035$), and RSI ($p = 0.048$) significantly increased only in the CPT group, indicating that CPT was more effective than CT in improving jump performance.

4. Discussion

In this study, significant improvements in LBM, half squat 1-RM, T-agility, and jump performance (SJ height, CMJ height, CM5J height, HJ height) were observed in both the CPT and CT groups. However, significant improvements in hamstring-muscle stiffness and factors related to CM5J (power, RSI), DJ (height, power, and RSI), and right SDJ (height, power and RSI), were observed only in the CPT group. Therefore, the hypothesis that CPT is more effective than CT in improving muscle stiffness and jump performance is accepted.

Body composition affects athletic performance and a higher proportion of LBM is associated with better performance in power- and strength-related tasks [31]. Aikawa *et al.* [32] analyzed the relationship between body composition and athletic performance in various track-and-field events among Japanese male collegiate athletes and demonstrated that morphological characteristics are significantly associated with performance and physical fitness, and vary according to the sport.

In this study, significant increases in LBM were observed in both groups after 6 weeks of training. Wei *et al.* [33] reported that progressive bodyweight squat training for 6 weeks in sedentary young women had a short-term effect on strength and musculoskeletal development, including knee strength and lower-extremity muscle circumference. Furthermore, an increase in LBM contributes to altered body fat percentage, even if it does not result in a change in body fat mass. Scott *et al.* [34] performed variable resistance CPT (VRCT) and traditional CPT (TCT) on rugby league players for 6 weeks and found that TCT induced greater musculoskeletal adaptations in the vastus lateralis. Additionally, Fathi *et al.* [35] reported a significant decrease in body fat percentage in adolescent volleyball players who performed either CPT or PT, and the CPT group exhibited a significant increase in LBM. They emphasized the importance of maintaining training to avoid an increase in body fat percentage and a decrease in LBM after training. RT increases neural stimulation of agonist muscles while decreasing the reciprocal activity of antagonist muscles, resulting in increased muscle cross-sectional area and changes in fiber type and pinnation angle. Simultaneously, PT alters muscle and connective-tissue elasticity, motor-unit recruitment, and neural-firing frequency [34]. In this study, CT and CPT induced increase in muscle cross-sectional area and changes in fiber type, similar to those with RT, resulting in an increase in LBM in both groups. Diet is an important factor that affects changes in body composition and training [12]. However, in this study, we did not evaluate participants'

TABLE 3. Pre- and post-training data for body composition with main analysis of variance results.

Parameters	CT (n = 10)			CPT (n = 10)			p (η_p^2) value		
	Pre	Post	p-value	Pre	Post	p-value	Time	Group	Inter
Weight (kg)	68.5 ± 7.6	69.1 ± 7.2	0.336	74.2 ± 10.9	74.5 ± 9.9	0.720	0.371 (0.045)	0.180 (0.098)	0.741 (0.006)
BMI (kg/m^2)	22.5 ± 1.7	22.7 ± 1.6	0.320	24.2 ± 3.6	24.3 ± 3.2	0.750	0.370 (0.045)	0.186 (0.095)	0.686 (0.009)
LBM (kg)	48.5 ± 7.6	49.5 ± 7.4	0.021*	49.5 ± 10.5	50.5 ± 10.3	0.011*	0.001† (0.499)	0.815 (0.003)	0.968 (0.001)
BFM (kg)	15.1 ± 2.0	15.1 ± 1.9	0.335	16.9 ± 4.2	16.9 ± 4.3	0.601	0.807 (0.003)	0.222 (0.081)	0.297 (0.060)
Body fat (%)	22.1 ± 1.0	21.8 ± 1.2	0.197	22.6 ± 3.0	22.5 ± 3.3	0.814	0.267 (0.068)	0.545 (0.021)	0.435 (0.034)

*Abbreviations; CT, complex training; CPT, compound training; BMI, body mass index; LBM, lean body mass; BFM, body fat mass; η_p^2, partial Eta squared; †$p < 0.05$ significant interaction or main effect; *$p < 0.05$ vs. before intervention. Values are expressed as mean ± standard deviation.*

TABLE 4. Pre- and post-training data for muscle stiffness with main analysis of variance results.

Parameters	CT (n = 10)			CPT (n = 10)			p (η_p^2) value		
	Pre	Post	p-value	Pre	Post	p-value	Time	Group	Inter
RF_right (N/m)	272.3 ± 26.4	284.0 ± 27.3	0.247	274.0 ± 38.0	285.4 ± 36.8	0.213	0.086 (0.155)	0.907 (0.001)	0.981 (0.001)
RF_left (N/m)	273.7 ± 22.9	283.2 ± 30.5	0.323	273.5 ± 22.9	280.3 ± 27.3	0.543	0.262 (0.069)	0.911 (0.001)	0.850 (0.002)
HAM_right (N/m)	264.2 ± 43.7	277.2 ± 36.4	0.051	252.2 ± 41.1	291.5 ± 29.6	0.004*	0.001† (0.526)	0.943 (0.001)	0.037† (0.219)
HAM_left (N/m)	270.2 ± 49.9	289.2 ± 42.2	0.095	248.3 ± 53.3	288.9 ± 49.1	0.004*	0.001† (0.475)	0.595 (0.016)	0.161 (0.106)
AT_right (N/m)	807.5 ± 100.9	823.1 ± 84.4	0.493	852.4 ± 94.4	875.3 ± 116.4	0.395	0.268 (0.068)	0.255 (0.071)	0.831 (0.003)
AT_left (N/m)	845.7 ± 104.6	845.2 ± 96.5	0.986	885.1 ± 94.4	873.9 ± 133.1	0.551	0.686 (0.009)	0.651 (0.012)	0.667 (0.011)

*Abbreviations: CT, complex training; CPT, compound training; RF, rectus femoris; HAM, hamstrings; AT, Achilles tendon; η_p^2, partial Eta squared; †$p < 0.05$ significant interaction or main effect; *$p < 0.05$ vs. before intervention. Values are expressed as mean ± standard deviation.*

TABLE 5. Pre- and post-training data for half-squat 1-RM and T-agility with main analysis of variance results.

Parameters	CT (n = 10)			CPT (n = 10)			p (η_p^2) value		
	Pre	Post	p-value	Pre	Post	p-value	Time	Group	Inter
Half-squat 1-RM (kg)	127.7 ± 26.4	151.1 ± 22.3	0.001*	136.6 ± 27.3	161.7 ± 27.8	0.001*	0.001† (0.887)	0.406 (0.039)	0.682 (0.010)
T-agility (s)	11.30 ± 0.90	10.67 ± 0.70	0.002*	11.39 ± 0.84	10.56 ± 0.66	0.001*	0.001† (0.790)	0.970 (0.000)	0.269 (0.067)

*Abbreviations: CT, complex training; CPT, compound training; 1-RM, one repetition maximum; η_p^2, partial Eta squared; †$p <$ 0.05 significant interaction or main effect; *$p < 0.05$ vs. before intervention. Values are expressed as mean ± standard deviation.*

TABLE 6. Pre- and post-training data for jump performance with main analysis of variance results.

Parameters	CT (n = 10)			CPT (n = 10)			p (η_p^2) value		
	Pre	Post	p-value	Pre	Post	p-value	Time	Group	Inter
SJ height (cm)	38.0 ± 9.3	43.7 ± 9.1	0.001*	38.5 ± 6.8	43.8 ± 6.6	0.001*	0.001† (0.837)	0.929 (0.000)	0.771 (0.005)
CMJ height (cm)	42.3 ± 10.1	45.5 ± 9.1	0.011*	41.9 ± 7.8	46.0 ± 7.0	0.001*	0.001† (0.657)	0.993 (0.000)	0.449 (0.032)
CM5J times height (cm)	38.7 ± 8.4	40.2 ± 8.5	0.037*	38.4 ± 7.9	41.3 ± 5.7	0.014*	0.001† (0.458)	0.913 (0.001)	0.248 (0.073)
CM5J times power (W/kg)	27.9 ± 5.4	29.5 ± 6.4	0.210	27.3 ± 5.7	29.5 ± 3.9	0.023*	0.016† (0.284)	0.901 (0.001)	0.653 (0.011)
CM5J times RSI (m/s)	0.74 ± 0.20	0.81 ± 0.26	0.279	0.74 ± 0.22	0.83 ± 0.17	0.008*	0.025† (0.250)	0.927 (0.000)	0.724 (0.007)
DJ height (cm)	40.0 ± 9.6	42.5 ± 10.7	0.097	38.2 ± 5.9	43.3 ± 4.5	0.005*	0.001† (0.459)	0.893 (0.001)	0.203 (0.088)
DJ power (W/kg)	37.1 ± 11.7	40.5 ± 10.3	0.149	36.1 ± 7.8	44.7 ± 12.6	0.026*	0.006† (0.347)	0.729 (0.007)	0.195 (0.091)
DJ RSI (m/s)	1.20 ± 0.55	1.35 ± 0.50	0.208	1.16 ± 0.37	1.55 ± 0.63	0.048*	0.016† (0.281)	0.701 (0.008)	0.250 (0.073)
SDJ right height (cm)	21.4 ± 7.8	20.4 ± 5.8	0.464	17.2 ± 3.6	20.7 ± 3.4	0.006*	0.117 (0.131)	0.411 (0.038)	0.011† (0.309)
SDJ right power (W/kg)	21.5 ± 6.9	21.7 ± 6.0	0.820	18.3 ± 3.8	21.9 ± 4.4	0.035*	0.038† (0.219)	0.533 (0.022)	0.061 (0.182)
SDJ right RSI (m/s)	0.59 ± 0.27	0.61 ± 0.25	0.639	0.48 ± 0.16	0.63 ± 0.20	0.048*	0.041† (0.213)	0.618 (0.014)	0.105 (0.139)
SDJ left height (cm)	20.2 ± 8.4	19.5 ± 5.0	0.708	17.8 ± 4.2	21.1 ± 3.4	0.016	0.214 (0.084)	0.880 (0.001)	0.069 (0.172)
SDJ left power (W/kg)	20.6 ± 7.1	21.1 ± 6.2	0.655	20.6 ± 4.2	23.2 ± 4.8	0.273	0.228 (0.080)	0.642 (0.012)	0.423 (0.036)
SDJ left RSI (m/s)	0.56 ± 0.27	0.59 ± 0.26	0.550	0.56 ± 0.17	0.68 ± 0.21	0.254	0.188 (0.094)	0.653 (0.011)	0.435 (0.034)
HJ distance (cm)	251.4 ± 30.4	259.9 ± 23.8	0.038*	259.0 ± 20.7	271.7 ± 17.3	0.001*	0.001† (0.605)	0.360 (0.047)	0.312 (0.057)

*Abbreviations: CT, complex training; CPT, compound training; SJ, squat jump; CMJ, countermovement jump; CM5J, countermovement 5 jump; DJ, drop jump; SDJ, single leg drop jump; HJ, horizontal jump; η_p^2, partial Eta squared; †$p < 0.05$ significant interaction or main effect; *$p < 0.05$ vs. before intervention. Values are expressed as mean ± standard deviation.*

diet during the training period. Therefore, we were unable to investigate the effects of diet on LBM. Although the lack of dietary surveys limits the interpretation of changes in LBM, long-term training may induce favorable changes in body composition.

We evaluated stiffness of the major muscles and tendons in the lower extremities, including the rectus femoris, hamstrings, and Achilles tendon, after 6 weeks of CT and CPT. The results showed a significant increase in muscle stiffness only in the hamstrings in the CPT group. The positive correlation between increased lower-extremity muscle stiffness and athletic performance has important implications for designing training programs in sports science [36]. Particularly, improvement in athletic performance, which reflects the SSC, suggests the potential for performance optimization through the modulation of muscle stiffness [37, 38]. This could help athletes develop greater power and speed, while minimizing the risk of injury [36].

Increased hamstring stiffness is associated with decreased loading of the anterior cruciate ligament [39]. Hamstring activation generates horizontal ground-reaction forces that influence sprint acceleration [40]. Additionally, changes in hamstring stiffness and increased activation of the antagonist muscle can have a negative impact on the power output of the quadriceps; however, they can also increase movement efficiency during the deceleration phase that occurs during the take-off phase of jumping owing to increased knee-joint stability [41]. Mroczek *et al.* [42] reported a tendency towards increased stiffness in muscle groups such as the quadriceps, hamstrings, and gastrocnemius in male volleyball players who underwent a 6-week PT program. However, these changes were not statistically significant. Notably, a significant increase in stiffness was observed only in the anterior tibialis muscle. This was attributed to the moderate exercise intensity in the study (140–150 beats per min). Kalkhoven and Watsford [43] reported an increase in quadriceps stiffness during jump performance. Additionally, they reported that hamstring stiffness was correlated with the rate of force development. Furthermore, the hamstring, which influences knee stability and reduces landing impact, may be affected by performing PT, that involves landing and leaping processes, after RT. The CPT conducted in this study aimed to improve explosive muscle performance through the PAP response after maximal contraction [17]. This sequential approach likely induced simultaneous activation (co-activation) of the quadriceps and hamstring, and created neuromuscular adaptations to balance joint loads, thereby leading to a more significant increase in hamstring stiffness [44, 45]. However, future research using biomechanical analysis is warranted to comprehensively evaluate the fundamental mechanisms through which CT and CPT influence muscle stiffness.

In this study, a significant increase in half-squat 1-RM was observed in both groups after 6 weeks of training. The T-agility test results revealed significant improvements in agility in both groups. Furthermore, regarding changes in power levels, significant increases in the SJ, CMJ, CM5J and HJ heights were observed in both groups. Additionally, in the CPT group, significant increases were noted in CM5J-related factors (power and RSI), DJ-related factors (height, power, and RSI), and right-sided SDJ-related factors (height, power and RSI). A systematic review and meta-analysis by Bauer *et al.* [46] indicated that CPT is beneficial for improving jump, strength and sprint performance in athletes. Significant improvements were observed in squat 1-RM and 20-m sprint performance compared to those with traditional training methods. Furthermore, Allégue *et al.* [47] reported that 8 weeks of combined isometric exercise and PT significantly improved sprint and ball-throwing velocity in male junior handball players compared with contrasting strength training. When examining the muscle-fiber ratio according to training, strength training consistently causes a shift in the fiber ratio from type IIX to type IIA [48]. In contrast, power training tends to maintain the ratio of type IIX fibers; similarly, CPT has been reported to maintain the ratio of type IIX fibers [48–50].

Stasinaki *et al.* [26] compared the effects of CT and CPT for 6 weeks on strength, power and morphological adaptations in healthy men and reported that both CPT and CT can preserve the ratio of type IIX fibers and minimize the shift toward type IIA fibers. They hypothesized that preserving type IIX fibers could be advantageous for muscle strength development because type IIX fibers have a faster contraction speed, power, and force development than type I and IIA fibers [48, 51]. Previous studies have reported that CPT induces changes in physiological factors, such as development of type IIA and IIX muscle fibers and increased muscle cross-sectional area, motor-unit mobilization, and firing patterns, which have implications for improving strength, agility, and power factors (SJ, CMJ and HJ height) [12, 49, 52, 53]. Arazi *et al.* [54] reported that CT combined with RT and PT increased agility and maximal strength in women due to the activation of neural factors, such as increased motor-unit excitability, efferent neural drive, and motor-unit firing frequency [54, 55]. Mihalik *et al.* [13] analyzed the effects of 4-week CT and CPT programs on CMJ height and power in university volleyball players. The results indicated a significant increase in CMJ performance (both height and power) in both groups, and both exercise programs were effective in enhancing power. This suggests that even in a short-term training regimen, CT and CPT can lead to significant performance improvements, possibly owing to changes in neural factors [13]. In the study by Scott *et al.* [56], VRCT induced greater improvements in RSI and leg stiffness, whereas TCT improved 10- and 20-m sprint times. Both CPT and CT activate the neuromuscular system and enhance muscle strength [11]. An increase in the maximal strength will likely improve power and acceleration, which are essential for enhancing short-distance sprinting performance [15, 57]. Thus, the 6-week CT and CPT training protocol used in our study might help preserve the type IIX fiber ratio, stimulate increases in motor units and strength, and contribute to improvements in agility and power factors (such as SJ, CMJ and HJ height).

As mentioned previously, combined training is practical for improving strength, agility, and jump performance. However, in this study, significant increases were observed only in the CM5J power and RSI; DJ height, power and RSI; and right SDJ height, power, and RSI in the CPT group. Abade *et al.* [4] analyzed the effects of 12-week CT and CPT programs on the strength and power in athletes with high and low training levels. They reported that athletes with low training levels who performed CPT exhibited significant increases in CMJ and sprint performance. Furthermore, CPT effectively increased the neuromuscular level due to repetitive PAP effects and increased the ability to recover from fatigue after high-intensity exercise. However, in highly trained athletes who underwent CT, no significant effects on sprint and jump performance were observed. However, CT can be beneficial in maintaining physical capability without losing significance. Struzik & Pietraszewski reported a significant correlation between the hamstring/quadriceps ratio and CMJ and DJ, indicating that a relatively higher knee-flexion torque compared to the knee-extension torque positively affects vertical jump height and enables a faster transition to the take-off phase during DJ. This could be attributed to the increased hamstring strength, which positively affects the knee-extension torque and CMJ height [58, 59]. When performing DJs, the immediate requirement of transitioning to high propulsion after braking must be considered [57]. Previous studies have shown that the hamstring/quadriceps ratio and left-right muscle strength imbalance can affect the performance of bilateral and unilateral vertical jumps [60]. Therefore, the increase in hamstring stiffness observed in the CPT group in this study reflects an increase in muscle strength that provides knee-joint stability upon landing and influences braking ability during SDJ, resulting in a significant increase in the right SDJ height, power and RSI. This increase in the right SDJ factors influenced the significant increase in the CM5J and DJ factors (height, power and RSI) due to the decreased differences between the left and right SDJ factors. Furthermore, inducing PAP to activate the neuromuscular system and enhance the capacity to store elastic energy during SSC has been suggested to reduce the ground-contact time and minimize energy loss, leading to improved jump performance [34, 61].

5. Limitations

This study had several limitations. First, the training period was relatively short. However, previous studies have confirmed that a program of at least 6 weeks with a frequency of two sessions per week and conditioning activities involving loads <85% of 1-RM can positively affect sprint and jump performance [53]. Nonetheless, studies with longer training periods are required to investigate the long-term effects of the two training programs on muscle stiffness, agility, strength and jump performance. Second, although we determined the sample size based on previous studies, the sample size was relatively small. Therefore, future studies with a larger and more diverse sample are required to confirm the reliability of our results. Third, we did not assess the amount of physical activity and dietary intake outside the training sessions during the study period, which could affect the interpretation of changes in LBM; however, long-term training may positively affect changes in body composition.

6. Conclusions

The main outcome of this study was that 6 weeks of CT and CPT positively affected half-squat strength, agility and jump performance in both groups, with CPT being particularly effective in improving hamstring stiffness and various aspects of jump performance compared to CT. These findings may have positive implications for sports that require explosive performance, underscoring the potential of CPT to enhance dynamic athletic skills critical for high-intensity sports activities. This holistic approach to training could enable athletes to achieve superior performance outcomes, while reducing the risk of injury associated with high-intensity sports. Future research should delve deeper into the mechanisms underlying these improvements, extending the findings to a wider range of athletic and clinical populations to develop comprehensive strategies for sports performance enhancement.

AVAILABILITY OF DATA AND MATERIALS

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

AUTHOR CONTRIBUTIONS

LHK and HYP—conceived and designed this study; collected data for analysis; conducted the data analysis; discussed the results and conclusions. LHK—wrote the original draft manuscript. All the authors have read and approved the final version of the manuscript.

ETHICS APPROVAL AND CONSENT TO PARTICIPATE

Ethical approval was obtained from the Institutional Review Board (IRB) of Konkuk University (7001355-202105-HR-441). All participants provided informed consent before participating in the study.

ACKNOWLEDGMENT

This study was supported by the KU Research Professor Program of Konkuk University.

FUNDING

This research received no external funding.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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How to cite this article: Lock-Hyun Kyung, Hun-Young Park. Effects of complex training on muscle stiffness, half squat 1-RM, agility, and jump performance in healthy males. Journal of Men's Health. 2024; 20(10): 79-88. doi: 10.22514/jomh.2024.168.