



Does a dedicated optimal power phase enhance performance outcomes in trained athletes? A comparison of periodized maximum strength and strength–power training

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Abstract

Purpose This study investigated the effects of periodized maximum strength training and combined strength–power training regimens on maximal strength, vertical jump performance, and mechanical power output.

Methods Eighty athletes (62 males, 18 females) from various sports were matched by baseline vertical jump height to four groups: maximum strength training (SQ), strength and power training (JS), isokinetic training (ISO), and a control group (CON). Over a 14-week period, SQ performed block-periodized back squat training, while JS performed jump squats at the individual's optimal power load in the final block. ISO followed an equivalent program using an isokinetic leg press. Pre- and post-tests assessed squat one-repetition maximum (1RM), jump performance (squat jump, countermovement jump, drop jump), and mechanical power output in jump squats and isokinetic leg press tasks.

Results Significant improvements in absolute and relative 1RM were observed for SQ and JS ($p < 0.01$), whereas CON showed significant decreases ($p < 0.01$) and ISO demonstrated no change. Vertical jump height increased significantly only in SQ ($p < 0.01$). Reactive strength improved in JS at 20–30 cm drop heights ($p < 0.05$). Mechanical power increased significantly for JS at 40–80% 1RM loads, while ISO showed no meaningful adaptations.

Conclusion Both maximum strength and combined strength–power regimens elicited improvements in maximal strength and selected power measures, while isokinetic training was less effective. The findings suggest that, over a prolonged period, no statistically detectable superiority of either complete program can be established.

Keywords Resistance exercise · Muscular power · Explosive strength · Force-velocity relationship

Introduction

Strength training performed with high resistance and power-oriented training stimulate alterations to neural mechanisms that are considered key contributors to performance improvements (Cormie et al. 2010a, 2011; Cronin and Sleivert 2005; Harris et al. 2000; Heller et al. 2006). Studies comparing these training methods have, overall, failed to result in a consensus about how they differ in their ability to stimulate performance gains (Cormie et al. 2010a; Harris et al. 2000; McBride et al. 2002). However, when comparing different loading conditions, Schmidtbleicher (1980) reported greater improvements in strength development after training with explosive contractions that are performed against maximal resistance. Similarly, Harris et al. (2008) reported that training with the jump squat with loads that correspond to the optimal power output were less effective at improving

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performance than training with heavier loads. The term ‘optimal power load’ is usually defined as the highest point of the load-power relationship in a given movement, thus referring to the load that produces the highest mechanical power output (Cormie et al. 2011; Haff and Nimphius 2012). Additionally, Harris et al. (2008) noted a tendency toward high-load resistance training offering greater overall training benefits. In contrast, McBride et al. (2002) reported that speed-specific changes occurred when squat jumps were performed with a variety of training loads, with a tendency towards training with lower resistances resulting in higher power outputs and superior training outcomes. In this study, the intervention group that trained with squat jumps at 80% of their one-repetition maximum (1RM) showed significant improvements in 1RM and electromyographic (EMG) activity during jumps that were performed with high external loads, as well as maximal strength and power during jumps performed with moderate loads. However, these improvements were accompanied by a decreased 20-meter sprint performance. A second intervention group performed squat jumps with 30% of their 1RM, which resulted in significant improvements in 1RM, maximal power, and speed during squat jumps across all loads tested. However, there were insignificant improvements in sprinting speed. Collectively, these findings support the hypothesis that the choice of training load may impact different regions of the force-velocity curve. For example, Cormie et al. (2010a) reported significant improvements in sprint and jump performance following maximal strength training and training with squat jumps performed at the muscle power threshold in untrained subjects, with no significant differences between the groups for both sprint and jump performance. However, maximal strength development was reported to be superior in response to maximal strength training, leading to the conclusion that with weaker athletes targeting strength development is likely more beneficial.

To examine the impact of training with machines and free-weights, Wirth et al. (2016a, b) compared back squat training and training on a 45° leg press using identical training protocols and reported that back squat training resulted in greater improvements in vertical jump performance. These findings were corroborated by Rossi et al. (2018), who also observed larger increases in vertical jump performance following training with back squats compared to training on a leg press or a combination of back squat and leg press exercises. As isokinetic strength training has been shown to positively affect maximum strength and jump performance (Helland et al. 2017; Papadopoulos et al. 2019; Ratamess et al. 2016). Additionally, Helland et al. (2017) and Horwath et al. (2019) compared isokinetic training to free weight exercises and found comparable effects on maximal strength, mechanical performance in jump squats,

and body composition. However, both studies incorporated complex training programs that combined multiple exercises with different loading strategies. This, coupled with the fact that the isokinetic groups in both studies combined isokinetic and free-weight training, makes interpreting the results challenging.

A common feature of these studies is that they all examine training effects in response to relatively short training periods, typically lasting only a few weeks (i.e. 7–10 weeks). Furthermore, the mentioned investigations only compared single training blocks. For longer training periods in periodized approaches, both Baker (1996) and Harris et al. (2000) propose that power training following maximal strength training significantly impacts the transfer of increased strength potential to high-speed movement tasks, such as vertical jumps and sprinting. In support of the proposition that it is a necessity to develop and maintain high levels of maximum strength Cormie et al. (2011), assert:

“First, a fundamental relationship exists between strength and power, which dictates that an individual cannot possess a high level of power without first being relatively strong. Thus, enhancing and maintaining maximal strength is essential when considering the long-term development of power.”

Given the findings of Bobbert and Van Soest (1994) as well as those of Kyröläinen et al. (2004) and Schmidtbleicher (1980), the positive effects proposed by Baker (1996) and Harris et al. (2000) appear possible. Bobbert and Van Soest (1994) showed in a simulation study that increased maximal strength in the muscles involved in a vertical jump require the development of a new intermuscular coordination pattern to generate increases in jump height, while the results of Kyröläinen et al. (2004) and Schmidtbleicher (1980) suggest that performance improvements from speed-strength or “power” training are primarily due to improved intermuscular coordination.

Based on these observations, the present study was designed around a sequential periodization model in which an initial strength-oriented phase provides the neuromuscular foundation for a subsequent power-oriented phase. The rationale for this approach is that increases in maximal strength may enhance the force-generating capacity underlying power production, whereas a later optimal power phase may facilitate the transfer of this capacity to jump performance. Consequently, the present investigation did not compare strength and power training as parallel or isolated approaches. Rather, we examined whether the addition of a terminal optimal power training block, implemented after a common strength-oriented foundation produced additional improvements in mechanical power output, jump performance, and maximal strength compared with a fully strength-oriented program.

Therefore, the aim of this study was to investigate the effects of a periodized traditional strength training regimen compared to a periodized strength and power training regimen over several months and to assess the impact of choosing either barbell exercises or an isokinetic leg press on maximum strength, vertical jumping performance, and power production.

Methods

Experimental approach to the problem

A four-armed experimental design was used to investigate the effects of periodized maximum strength or strength and power programs for the lower extremity. The programs included using free weights or an isokinetic dynamometer. The subjects were matched into one of three training groups or the control group. One training group performed a block periodized training program targeting maximum strength development with the parallel back squat over a 14 week training period that was divided into 4 training blocks. The second training group performed the same training in the first 3 training blocks and jump squat training at the optimal power load during the 4th training block. The third training group performed the maximum strength and power training program in an isokinetic leg press. Absolute and relative back squat 1RM, vertical jump performance in the counter-movement jump (CMJ) and the squat jump (SJ), reactive jump ability in the drop jump (DJ) from different dropping heights, as well as absolute and relative mechanical power

in the jump squat with different loads and in the isokinetic leg press with different linear velocities were examined before and after the training.

Subjects

Eighty state- to national-level athletes from different sports (62 males (m), 18 females(f)) volunteered to participate in the current study. All subjects were part of the state- or national-team of the following sports: badminton (17 m, 3 f), rowing (8 m, 10 f), rugby (20 m, 1 f), track and field (12 m, 4 f), volleyball (2 m, 0 f) or table tennis (3 m, 0 f) and had at minimum one year experience in heavy-load resistance training. The subjects were matched into one of four experimental groups (squat training group (SQ), jump squat training group (JS), isokinetics training group (ISO), control group (CON)) based on their CMJ jump height. The anthropometric characteristics of each group can be found in Table 1. Subjects missing more than two training sessions throughout the training period were excluded from the study. Minimum completion therefore corresponded to 93% of training sessions.

Each subject was informed of the experimental risks involved with the research and signed informed written consent. The experimental protocols and procedures were approved by the Internal Review Board (Nr. 2015-236b) and conformed to the standards set by the Declaration of Helsinki.

Table 1 Anthropometric characteristics and group allocation of the experimental groups

Group	SQ	JS	ISO	CON
n				
total	20	20	20	20
m	15	17	14	16
f	5	3	6	4
badminton	8	6	3	3
rowing	7	4	2	5
rugby	1	6	8	6
track & field	4	4	5	3
volleyball	0	0	1	1
table tennis	0	0	1	2
Age [yrs]				
Mean±SD	24.2±2.7	24.2±2.7	23.0±3.1	24.6±2.5
Max	29	29	27	30
Min	19	18	18	18
Height [m]				
Mean±SD	1.77±0.08	1.76±0.07	1.76±0.08	1.75±0.07
Max	1.91	1.88	1.89	1.89
Min	1.62	1.6	1.57	1.59
Weight [kg]				
Mean±SD	75.5±10.9	74.6±12.7	76.3±13.6	77.9±12.0
Max	95	95	98	98
Min	57	52	52	59
Relative Squat 1RM at baseline [kg/kg]				
Mean±SD	1.46±0.27	1.52±0.30	1.41±0.31	1.50±0.26
Max	1.87	1.94	1.76	1.88
Min	0.83	0.85	0.79	1.11

Experimental protocol

One week before conducting the pre-test measurements, all the subjects were familiarized with the testing and training procedures. The pre-test measurements were performed one week before starting the strength training program, while the post-test was performed one week after the last training session. Between training blocks 3 and 4, one recovery week was incorporated in which the jump squat and isokinetic power were retested to calculate training loads for JS, and training velocities for ISO in training block 4. The measurements of the pre- and post-tests were each conducted on two days separated by 72 h. On day one, isokinetic power as well as vertical jump performance in SJ, CMJ, and DJ were assessed. On day two, the squat 1RM as well as jump squat performance were determined. Two days before each test, no fatiguing training was performed. The study timeline is illustrated in Fig. 1.

Squat 1RM

The 1RM was determined with the high-bar parallel back squat using a standard barbell and weight plates (Hammer

Strength, Rosemont, Illinois, USA). The test set up was based on the procedure described by Hartmann et al. (2012). Squatting depth was monitored visually by one examiner from a sagittal position and for a valid attempt the top of the thigh was required to be slightly below parallel with the floor. After an individualized warm-up, the 1RM was determined with a maximum of 5 attempts with 5 min of rest provided between attempts. Both the absolute as well as the relative 1RM ($\text{absolute 1RM} \times \text{body mass}^{-1}$) were determined.

SJ and CMJ

The SJ and CMJ height were quantified using a contact mat (Biovision, Wehrheim, Germany). Jump height was calculated from the flight time as previously described (Möck et al. 2023; Wirth et al. 2016a). For both tests, five attempts per jump were performed, with an inter-jump rest period of 30 s. The highest jump height from each jump type was used for further analysis. The jumps were performed in standard order, starting with the SJ, followed by the CMJ.

The SJ was executed from a starting position with a knee flexion of approximately 90 degrees, which was maintained

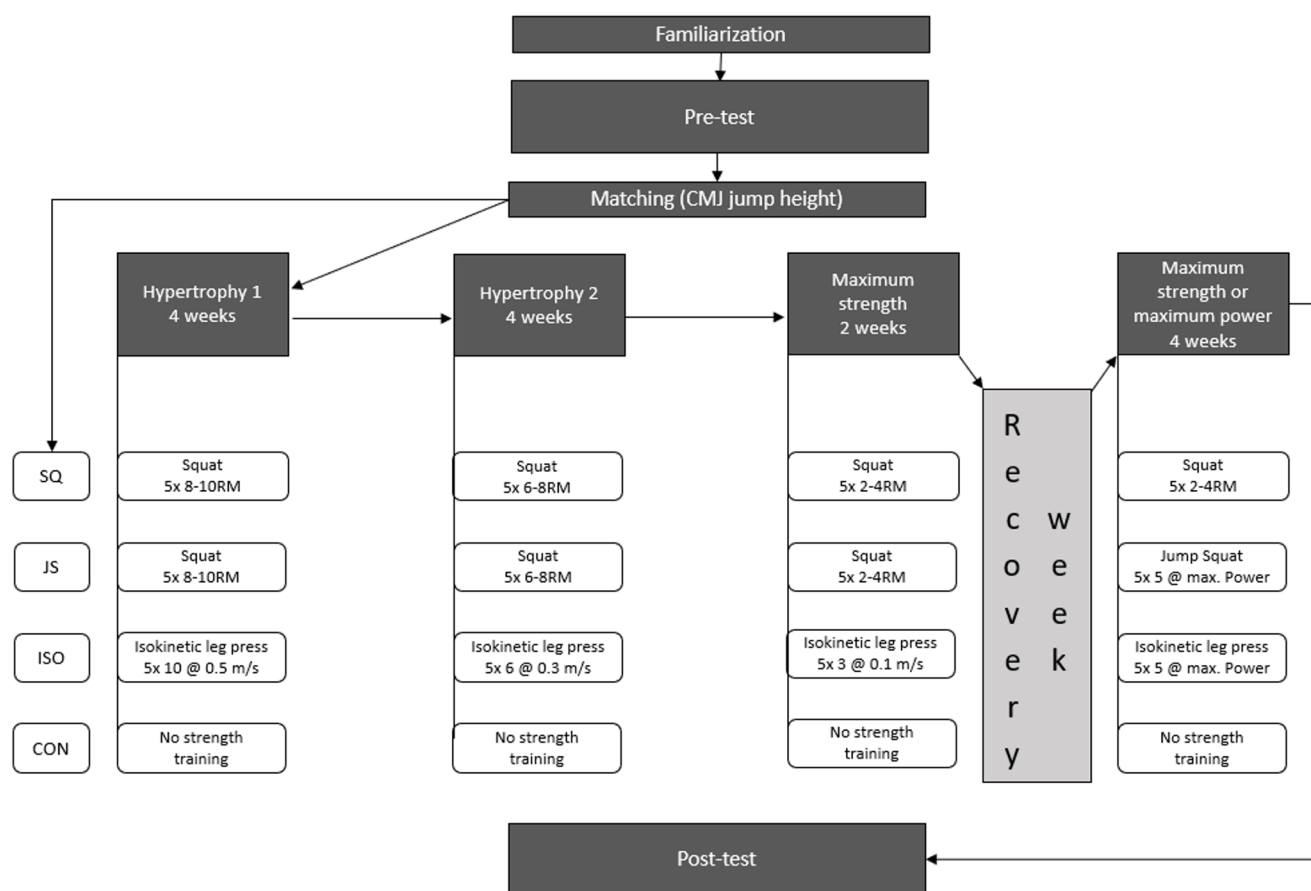


Fig. 1 Study Timeline

in a static state. This position was visually verified by an investigator. The hands were fixed at the hips, and the upper body position was constrained to remain upright. Any visible countermovement was strictly prohibited, and if a countermovement occurred, the SJ trial was deemed invalid.

The CMJ was performed from an upright standing position. The subjects were instructed to perform a self-selected countermovement to a knee flexion of about 90 degrees, with the hands fixed at the hips. They were also instructed to keep their torso as upright as possible and jump as high as possible during the execution.

Drop Jump

The DJ was performed from different dropping heights to evaluate reactive strength (i.e., fast stretch-shortening-cycle (SSC)) with the use of the same contact mat (Biovision, Wehrheim, Germany). In the starting position, the subjects stood upright on a box with hands fixed on the hips. From this position, they stepped off the box and aimed to jump as high as possible after a short contact with the ground. Five attempts per drop height were performed with rest periods of 30 s. Ground contact times of 200ms or above, disengagement of the hands from the hips, ground contact of the heels during the takeoff, or excessive joint angle enlargement in the knee and hip joint led to an invalid jump. DJs were performed from the drop heights of 20, 30, 40, and 50 cm. RSI was calculated from the ground contact time and the jump height achieved using the formula:

$$RSI = \frac{\text{jump height [m]}}{\text{ground contact time [s]}}$$

Jump squat mechanical power

To generate a profile of the subjects' mechanical power output, jump squats with five different loads were performed. The movement execution was similar to the CMJ, but a slower countermovement was advised to reduce the occurrence of force peaks acting on the subjects' spine. Jump squats were performed with 0%, 20%, 40%, 55%, and 80% of the respective 1RM in the squat in ascending order to facilitate progressive adaptation to increasing loading demands prior to the heavier jump squat conditions and to ensure consistent movement execution. These loads were chosen to improve the comparability of the results to previous studies (Cormie et al. 2010a; De Vos et al. 2008; Harris et al. 2008; McBride et al. 2002). All participants were able to perform jump squats with all investigated loads (feet leaving the floor). Trials in which the feet did not leave the floor were discarded from analysis. To execute the jump squat with 0% 1RM, a wooden pole with a mass of 0.2 kg

was used. Peak power was obtained from the manufacturers' calculation in their software to the 3D-inertial measurement unit Vmaxpro (Blaumann & Meyer - Sporttechnologie UG, Magdeburg, Germany). To account for the participants' body being accelerated as well, load was defined as the sum of barbell mass and body mass. Therefore, body mass was added to the barbell mass in the manufacturers software. The peak power value provided by the software was used for the investigation. As stated by the manufacturer, peak power is calculated as the product of mass, gravity, vertical velocity, and vertical acceleration + 1. For each loading condition, 4 attempts were performed with rest periods of 30 s. Chavda et al. (2024) report an ICC of 0.993 (95% CI=0.978–0.998) with a SEM of 0.66 for peak power in the snatch quantified by the VmaxPro unit. For the post-test, jump squat loads were calculated from the post-test 1RM.

Isokinetic mechanical power

Isokinetic power was assessed using the ISOMED2000 isokinetic leg press (D&R Ferstl GmbH, Hemau, Germany). Maximum power was calculated for 0.1 m/s, 0.4 m/s, 0.9 m/s, and 1.2 m/s, respectively, as the product of maximum force and isokinetic velocity. For all conditions, maximum force was reached during the isokinetic phase of the movement. These velocities were chosen to achieve a high level of comparability to the relative intensities of the jump squat. As the results of Hemmling and Schmidtbleicher (1994) show a force output of 93% MVC at a 90° knee angle in an isokinetic leg press at 0.2 m/s, 82% MVC at 0.4 m/s, and 68% MVC at 0.7 m/s, a linear trend can be assumed which suggests relative intensities of approximately 96%, 82%, 57%, and 42% for the chosen isokinetic velocities. The subjects performed maximum concentric isokinetic leg press movements starting at a 90° knee angle. At each velocity, 3 submaximal warm-up repetitions were performed, followed by 4 maximal test repetitions. The different velocities were tested in an ascending manner according to Perrin (1993).

Training protocols

The subjects in the SQ, JS, and ISO groups performed two strength training sessions for the lower extremities per week, separated by three days. The training was matched by set count, repetition range, and approximate relative intensity. Subjects also engaged in training sessions of their respective sport on 3 to 5 days in each training week. Participants allocated to CON were asked to continue their sport-specific training (3–5 sessions per week) and to refrain from any additional lower-body resistance training for the duration of the intervention. Adherence to this instruction was monitored via coach reporting. Lower-body strength

training was structured using a sequential periodization model consisting of four training blocks. During all four blocks, SQ performed parallel back squats with 5 sets and an inter-set rest of 5 min. JS performed parallel back squats during the training blocks 1–3 and jump squats in training block 4 using the individual optimal power load, each with 5 sets and an inter-set rest of 5 min as well. The training loads for JS in the final block were determined individually from the jump squat profile determined during the preceding recovery week. The length of four weeks was chosen for the final training block as previous research suggests that maximal strength adaptations can generally be maintained over this time period (Tucci et al. 1992) and adaptations in intramuscular coordination are generally considered to plateau after approximately 4–8 weeks of training (Ivanov et al. 1979; Turner and Comfort 2018). For both groups, the barbell load during the squat training was managed as follows: If the upper limit of the assigned repetition range was reached during a set, the same load was used for the next set. If the upper limit of the repetition range could not be reached, the load was decreased by 5 kg for the next set. If the upper limit was reached during the first set of a training session, the load for the first set of the next training session was increased by 5 kg.

ISO performed strength training with an identical number of sets and identical rest periods for all training blocks but used the isokinetic leg press for the training. In isokinetic dynamometry, movement velocity instead of the applied resistance is controlled. The linear velocities used during the training intervention were again chosen according to the results of Hemmeling and Schmidtbleicher (1994), suggesting relative intensities of approximately 77%, 87%, and 96% for the first 3 training blocks. In the last training block, ISO trained at the velocity that produced the highest power output. The training velocities in this block were determined individually from the velocity-power profile determined during the preceding recovery week. Training intensity and volume of the lower-body strength training for the experimental groups can be found in Fig. 1.

Statistical analysis

The data was analyzed using Jamovi 2.6.26 with the GAMLj 3 module (The Jamovi Project). For each parameter, the best trial of each participant was analyzed. For the squat 1RM and the mechanical power values in the jump squat, performance relative to the body weight was calculated and analyzed as well. The Kolmogorov-Smirnov test was used to check for data normality and homogeneity of variance was verified via the Levene test. Since these tests confirmed normality and homogeneity of variance, a one-way ANOVA was performed to test for significant group differences in the

pre-test. To evaluate the effects of the applied training, linear mixed models (LMMs) were employed. For each LMM, group and time were set as fixed effects and their interaction modeled. Furthermore, the subject ID was included as random intercept to account for variability in baseline levels and baseline relative 1RM was included as a covariate. For significant results, the Scheffé post-hoc test was calculated. The global level of significance was set to $p < 0.05$ and was adjusted using the Bonferroni correction due to multiple testing.

Results

Based upon the one-way ANOVA of the pre-test values, there were no significant differences between groups, indicating comparable performance levels at the start of the training interventions.

In the LMM analysis, both the absolute and relative 1RM in the squat showed significant main effects for the factor ‘time’, with significant increases for SQ and JS, and significant decreases for CON (all $p < 0.01$). No significant changes were observed for the ISO group (Table 2). For the relative 1RM, significant interaction effects between the factors ‘group’ and ‘time’ were observed, favoring SQ and JS compared to CON and ISO ($F = 77.0$; $p < 0.001$). (Fig. 2). For this model, a marginal $R^2 = 0.654$ and a conditional $R^2 = 0.750$ were obtained, indicating that 65.4% of the model’s variance were explained by the fixed effects and 75% of the variance were explained by the fixed and random effects combined.

Both the CMJ and SJ showed significant main effects for the factor ‘time’, with significant increases for SQ, while a significant decrease in jump height in the CMJ was observed for CON (all $p < 0.01$). No significant changes were found for JS or ISO (Table 2).

Although significant interactions were observed for absolute and relative 1RM, CMJ, and SJ, only relative 1RM between SQ and JS compared to CON and ISO showed a significant difference. However, the experimental groups exhibited considerable variations in the distribution of observed individual changes across the four measures (Fig. 3).

The RSI in the DJ revealed significant main effects for factor ‘time’ at 20 cm and 30 cm drop height for JS as well as for ISO at 30 cm drop height (all $p < 0.05$) (Table 2). Additionally, significant interactions between factors ‘group’ and ‘time’ at drop heights of 20 cm and 30 cm favoring JS compared to ISO could be observed (DJ 20: $F = 3.184$; $p = 0.029$; DJ 30: $F = 5.862$; $p = 0.001$) (Fig. 4).

For the DJ20 model, a marginal $R^2 = 0.348$ and a conditional $R^2 = 0.826$ were obtained, indicating that 34.8% of

Table 2 mean and standard deviation (SD) of pre- and post-test results for 1RM, relative 1RM (1RM rel.), SJ jump height, CMJ jump height and DJ RSI of the experimental groups

Test		SQ	JS	ISO	CON
1RM	Pre [kg]	110.88±27.29	114.50±32.29	109.75±36.82	117.13±28.53
	Post [kg]	132.25±31.02**	130.88±33.18**	112.50±35.11	107.13±23.10**
	Change [%]	19.7±6.4	15.7±8.1	4.0±7.1	-7.7±5.4
1RM rel.	Pre [kg/kg]	1.46±0.27	1.52±0.30	1.41±0.31	1.50±0.26
	Post [kg/kg]	1.71±0.32** # +	1.72±0.30** # +	1.43±0.27	1.36±0.21**
	Change [%]	16.9±6.5	14.4±7.5	2.7±7.6	-8.8±5.6
SJ	Pre [cm]	31.7±6.5	32.3±5.6	31.0±5.0	31.8±6.5
	Post [cm]	34.5±6.7**	33.7±5.1	30.9±5.6	30.3±6.3
	Change [%]	9.1±5.0	4.9±7.1	-0.4±9.6	-4.6±6.2
CMJ	Pre [cm]	37.0±7.4	37.1±6.9	36.9±7.1	37.0±7.3
	Post [cm]	39.3±8.3**	38.3±6.7	37.0±7.6	34.5±6.3**
	Change [%]	6.3±6.2	3.7±6.7	0.4±9.5	-6.6±3.8
DJ 20	Pre [m/s]	1.71±0.35	1.72±0.42	1.44±0.25	1.62±0.35
	Post [m/s]	1.66±0.28	1.86±0.36* +	1.39±0.31	1.62±0.38
	Change [%]	-1.3±10.8	10.4±15.6	-1.9±23.3	-0.1±11.2
DJ 30	Pre [m/s]	1.75±0.37	1.79±0.38	1.63±0.32	1.70±0.39
	Post [m/s]	1.72±0.40	1.96±0.44* +	1.47±0.33*	1.70±0.45
	Change [%]	-0.7±20.7	10.0±12.9	-8.7±16.8	-3.2±12.1
DJ 40	Pre [m/s]	1.88±0.45	1.91±0.55	1.58±0.32	1.67±0.50
	Post [m/s]	1.82±0.44	1.90±0.48	1.50±0.32	1.63±0.48
	Change [%]	-3.3±9.1	1.3±19.3	-4.4±7.7	-2.6±10.7
DJ 50	Pre [m/s]	1.94±0.42	1.79±0.65	1.57±0.32	1.59±0.63
	Post [m/s]	1.80±0.42	1.95±0.38	1.46±0.43	1.58±0.47
	Change [%]	-6.9±10.0	14.5±49.4	-6.4±19.4	12.7±65.4

*significant difference to pre-test ($p<0.05$)** significant difference to pre-test ($p<0.01$)# significant difference to CON ($p<0.01$)+ significant difference to ISO ($p<0.05$)

the model's variance were explained by the fixed effects and 82.6% of the variance were explained by the fixed and random effects combined. For the DJ30 model, a marginal $R^2=0.318$ and a conditional $R^2=0.815$ were obtained, indicating that 31.8% of the model's variance were explained by the fixed effects and 81.5% of the variance were explained by the fixed and random effects combined.

In the jump squat, the 20%, 40%, 55%, and 80% 1RM corresponded to absolute and relative loads in the pre-test of 22.61±6.20 kg or 0.29±0.06 times bodyweight, 45.23±12.40 kg or 0.59±0.11 times bodyweight, 62.18±17.05 kg or 0.81±0.16 times bodyweight, and 90.45±24.79 kg or 1.18±0.23 times bodyweight, respectively. In the post-test, these relative intensities corresponded to 24.14±6.46 kg or 0.31±0.06 times bodyweight, 48.28±12.93 kg or 0.62±0.13 times bodyweight, 66.38±17.78 kg or 0.86±0.18 times bodyweight, and 96.55±25.86 kg or 1.24±0.25 times bodyweight, respectively. The absolute and relative mechanical power values in the jump squat showed significant decreases for Con ($p<0.05$) at all loads except 0% 1RM. For JS, significant improvements of relative power could be observed at 40%

1RM, 55% 1RM, and 80% 1RM (Table 3). Significant interactions could be observed for JS compared to CON for relative power at 40% 1RM, 55% 1RM, and 80% 1RM (40% 1RM: $F=6.05$; $p<0.001$; 55% 1RM: $F=7.359$; $p<0.001$; 80% 1RM: $F=7.963$; $p<0.001$).

For the relative 40% 1RM model, a marginal $R^2=0.582$ and a conditional $R^2=0.691$ were obtained, while for the relative 55% 1RM model, a marginal $R^2=0.588$ with a conditional $R^2=0.639$ and for the relative 80% 1RM model, a marginal $R^2=0.490$ with a conditional $R^2=0.675$ were obtained.

For absolute and relative mechanical power in the isokinetic leg press, significant increases for SQ at 0.9 m/s and for JS at 0.1 m/s (both $p<0.05$) could be observed. CON displayed significant reductions at 0.9 m/s and 1.2 m/s for both absolute and relative power. For relative power, JS showed a significant increase at 0.9 m/s as well. For neither absolute nor relative mechanical power significant interactions could be detected (Table 4).

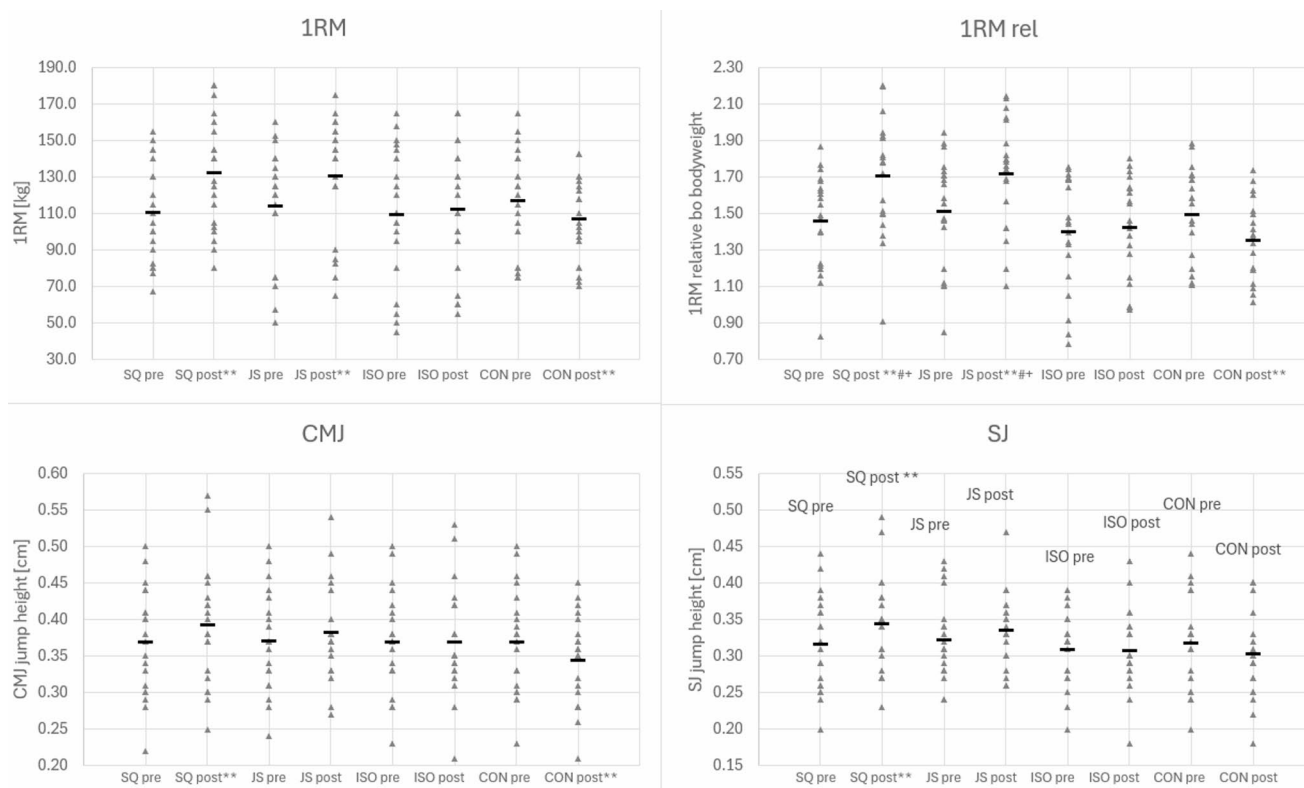


Fig. 2 Mean and individual pre- and post-test results for absolute and relative 1RM as well as CMJ and SJ. ** significant difference to pre-test; # significant difference to CON; + significant difference to ISO

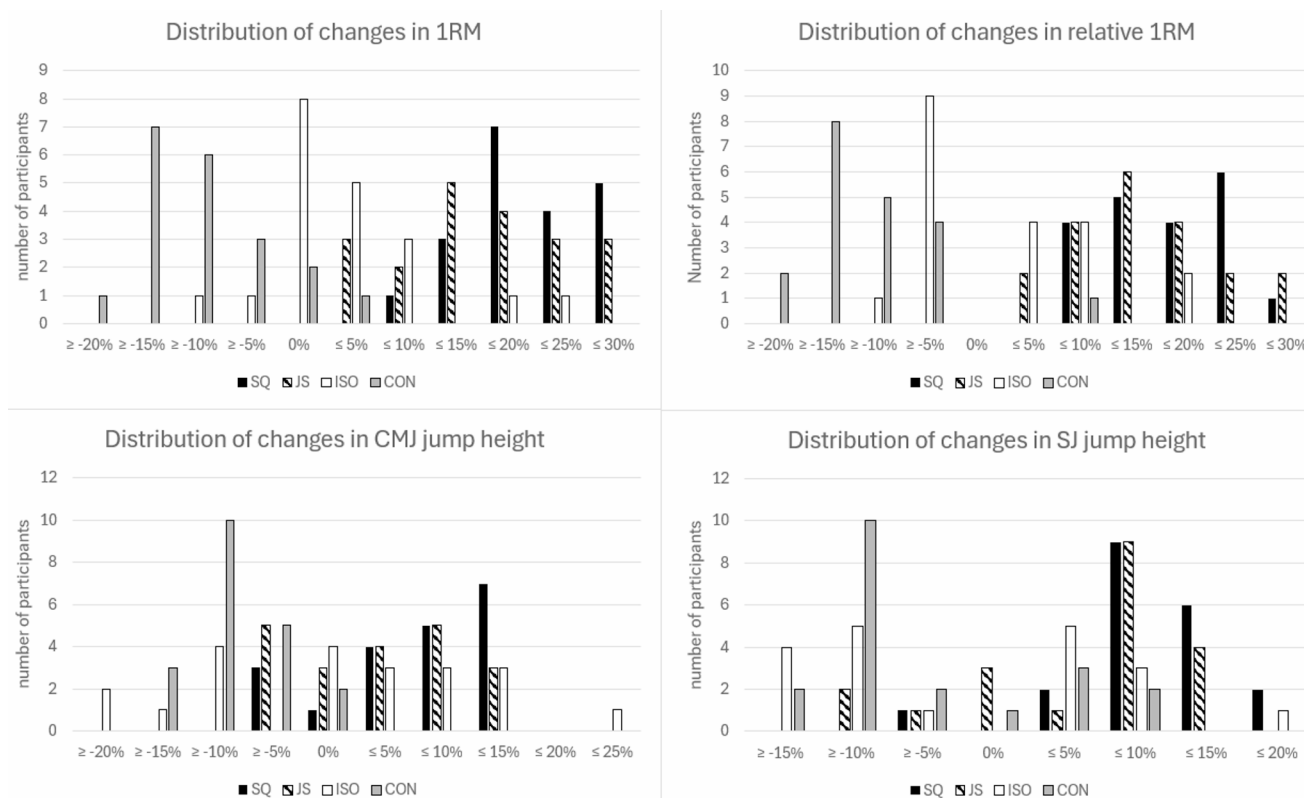


Fig. 3 Distribution of pre-post changes of 1RM, relative 1RM, CMJ jump height and SJ jump height across the experimental groups

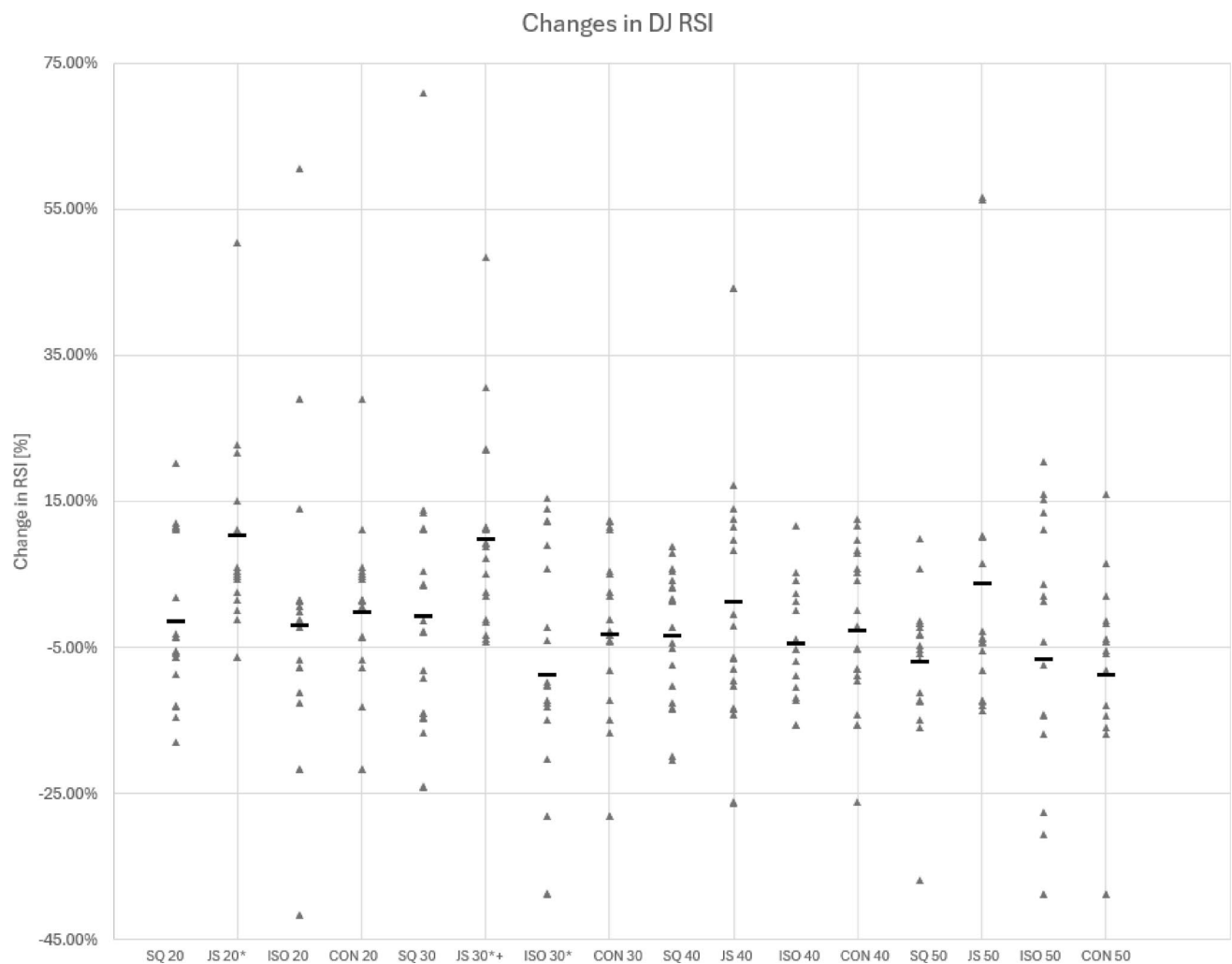


Fig. 4 Percentage changes of DJ RSI across the experimental groups. * significant pre-post change ($p < 0.05$); + significant interaction between JS and ISO ($p < 0.01$); Squares: SQ, Triangles: JS, Diamonds: ISO, Circles: CON

Discussion

The present study was designed to investigate the effects of periodized maximum strength and maximum strength plus maximum power training regimens on vertical jumping performance, mechanical power, and maximal back squat strength. Significant improvements in 1RM and jump height in SJ and CMJ were observed in response to SQ training, while JS training resulted in improvements in absolute and relative 1RM. Conversely, significant decreases in 1RM and CMJ jump height were observed in the CON treatment, while no significant changes were noted for any of the ISO measures. For the relative 1RM, significant Group*Time interactions were observed, favoring SQ and JS over CON and ISO. Additionally, different distributions of pre-post changes in vertical jumping and maximum strength were observed between the groups.

Considerable inter-individual variability was observed in baseline maximal strength and vertical jump performance. For example, relative 1RM ranged from 0.79 to 1.94 across participants, reflecting substantial variability in baseline strength within the sample. To account for such between-subject differences in baseline performance, subject ID was included as a random intercept in the statistical models. This approach accounts for clustering of repeated measures within individuals and allows estimation of group and time effects while adjusting for individual differences in overall performance level. Beyond these methodological considerations, previous literature has proposed that training status may influence adaptations to strength and power training, with untrained individuals often exhibiting larger general improvements in force-generating capacity and rate of force development, whereas more highly trained individuals may require greater training specificity to achieve further gains in explosive performance (Cormie et al. 2010a, b; Kraemer

Table 3 mean and standard deviation (SD) of pre- and post-test results of mechanical power in the jump squat of the experimental groups

		SQ	JS	ISO	CON
P 0% 1RM [W]	Pre	1191.1±583.3	1364.4±723.1	1397.8±629.4	1342.1±642.1
	Post	1248.1±668.4	1452.7±798.1	1415.9±551.6	1129.9±569.7
	Change [%]	9.1±23.6	13.2±31.7	12.4±41.5	-12.5±34.1
P 20% 1RM [W]	Pre	1545.6±849.2	1726.6±856.3	1691.4±719.0	1724.5±761.8
	Post	1537.8±786.6	1916.1±1115.0	1617.9±609.2	1262.3±539.2**
	Change [%]	3.8±20.5	11.5±27.0	4.5±35.3	-25.1±19.6
P 40% 1RM [W]	Pre	1658.8±1003.4	1849.3±826.6	1884.8±862.4	1826.8±867.5
	Post	1735.6±976.1	2134.7±1163.4	1774.4±701.3	1347.4±489.0**
	Change [%]	8.2±26.3	15.6±30.3	3.3±37.2	-22.6±20.7
P 55% 1RM [W]	Pre	1668.3±978.3	1765.9±804.3	1834.7±860.3	1812.5±922.4
	Post	1753.6±1025.6	2161.5±1146.6	1783.6±733.5	1330.3±514.1*
	Change [%]	7.4±24.0	23.1±33.1	7.1±40.1	-22.1±23.3
P 80% 1RM [W]	Pre	1467.9±853.8	1598.8±738.8	1644.9±800.7	1626.9±849.5
	Post	1594.4±947.2	1957.2±1031.4	1638.6±671.8	1178.8±520.0**
	Change [%]	10.1±22.2	23.8±31.4	10.2±40.9	-22.3±30.9
P 0% 1RM rel [W/kg]	Pre	15.5±6.9	17.7±8.0	18.2±7.5	16.9±7.3
	Post	16.1±8.2	19.0±9.3	18.3±6.4	14.2±6.9
	Change [%]	6.6±23.2	12.0±31.0	11.0±40.6	-13.8±34.1
P 20% 1RM rel [W/kg]	Pre	20.3±10.3	22.7±10.1	22.1±8.4	22.0±9.0
	Post	19.8±9.4	25.1±12.9	20.9±7.4	16.2±6.2**
	Change [%]	1.3±19.7	10.4±26.9	3.2±34.8	-25.4±18.6
P 40% 1RM rel [W/kg]	Pre	21.7±11.5	24.6±9.9	24.6±10.3	23.3±10.4
	Post	22.3±11.3	28.1±13.8 #	23.1±9.3	17.5±5.9**
	Change [%]	5.5±25.2	14.4±30.4	2.0±36.7	-22.6±19.1
P 55% 1RM rel [W/kg]	Pre	21.9±11.4	23.5±9.5	24.0±10.2	23.1±11.1
	Post	22.5±11.9	28.5±14.0* #	23.4±10.0	17.2±6.3*
	Change [%]	4.9±23.6	21.8±33.3	5.8±39.7	-22.2±22.2
P 80% 1RM rel [W/kg]	Pre	19.3±9.8	21.2±8.6	21.4±9.2	20.6±9.9
	Post	20.5±11.0	25.8±12.5* #	21.6±9.5	15.3±6.5**
	Change [%]	7.6±22.1	22.5±31.5	8.9±40.6	-22.3±29.4

*significant difference to pre-test ($p<0.05$)** significant difference to pre-test ($p<0.01$)# significant difference to CON ($p<0.05$)

and Newton 2000; Suchomel et al. 2018; Zatsiorsky et al. 2021). Suchomel et al. (2018) also argue that training often shifts prematurely toward high-velocity, power-focused methods. Cormie et al. (2010b) supported this, suggesting that athletes with lower baseline strength benefit most from maximum strength training, while stronger athletes benefit more from power-based training. However, the present study was not designed to test whether baseline strength moderated training-induced adaptations, and therefore no inferences can be made regarding differential responsiveness across strength levels. Additionally, the results have to be interpreted as the outcome of the whole training program of every group. Post-test group differences cannot be attributed to program differences in a single training block between groups.

When interpreting these results, it is important to note that the experimental groups performed strength training only, without integrating unloaded vertical jumps into

the training program. Strength training alone has been reported to result in smaller or no changes in high-velocity movements like sprinting and jumping, compared to programs combining strength and plyometric training activities (Kibele 1998; Pagaduan et al. 2019; Wirth et al. 2012; Zatsiorsky et al. 2021). The heterogeneity of the subjects' main sports must also be considered when interpreting these results. Athletes in sports such as badminton and volleyball perform many vertical jumps, while rowers do not typically include jump training in their preparation. Therefore, the limited improvements observed in the present study may be partially attributed to the absence of plyometric training and the varying sport-specific demands of the participants.

Moreover, beyond differing levels of jump training, the diverse specific training requirements due to the mixed participant population might have masked some potential adaptations on another level. Aerobic endurance plays a different role in the various sports represented in this study (Brazier

Table 4 mean and standard deviation (SD) of pre- and post-test results of mechanical power in the isokinetic leg press of the experimental groups

		SQ	JS	ISO	CON
P 0.1 m/s [W]	Pre	401.9±86.0	367.1±76.2	412.2±103.0	406.3±138.3
	Post	438.1±124.0	415.7±99.7*	437.7±116.3	383.8±116.0
	Change [%]	7.7±13.6	13.2±12.4	6.5±13.2	-2.9±17.2
P 0.4 m/s [W]	Pre	1204.7±339.6	1197.7±372.3	1364.2±366.4	1281.6±466.9
	Post	1339.8±402.7	1221.7±262.3	1258.5±317.5	1169.1±386.9
	Change [%]	10.9±13.5	6.2±18.1	-6.6±13.4	-6.1±17.9
P 0.9 m/s [W]	Pre	1663.6±474.0	1664.5±486.7	1764.0±431.5	1789.1±644.7
	Post	1865.0±609.9*	1832.0±517.7	1860.9±515.2	1618.9±537.0*
	Change [%]	11.3±10.8	11.4±13.1	5.6±16.0	-7.9±12.3
P 1.2 m/s [W]	Pre	1584.0±510.3	1566.4±498.5	1620.7±400.8	1704.9±665.7
	Post	1745.5±590.3	1728.4±596.0	1728.3±452.1	1521.4±550.0*
	Change [%]	11.3±16.3	10.4±14.3	7.2±16.6	-9.2±13.8
P 0.1 m/s rel [W/kg]	Pre	5.4±1.1	5.0±0.8	5.4±1.0	5.2±1.6
	Post	5.7±1.6	5.6±1.3*	5.7±1.2	4.9±1.3
	Change [%]	5.3±13.8	11.9±12.0	5.2±13.2	-4.1±16.8
P 0.4 m/s rel [W/kg]	Pre	16.1±4.6	15.8±3.3	17.8±3.1	16.3±5.2
	Post	17.4±5.3	16.3±2.9	16.4±3.5	14.8±4.3
	Change [%]	8.4±13.7	5.0±17.7	-7.7±13.3	-7.3±17.5
P 0.9 m/s rel [W/kg]	Pre	22.0±5.7	22.0±4.1	23.1±3.9	22.7±7.0
	Post	24.2±7.7*	24.2±4.8*	24.4±6.1	20.4±5.8*
	Change [%]	8.7±10.7	10.2±13.1	4.4±15.9	-9.0±12.4
P 1.2 m/s rel [W/kg]	Pre	20.9±6.2	20.6±4.0	21.3±3.8	21.6±7.2
	Post	22.6±7.5	22.6±5.6	22.8±5.8	19.1±5.9*
	Change [%]	8.8±16.7	9.3±14.5	6.0±16.5	-10.2±14.2

*significant difference to pre-test ($p < 0.05$)

et al. 2020; Mäestu et al. 2005; Phomsoupha and Laffaye 2015). When implementing a concurrent training strategy, interaction effects between endurance and resistance training are inevitable. Compared to resistance-only training, concurrent training has been shown to slightly impair muscle hypertrophy, maximal strength development, and explosive strength (Lundberg et al. 2022; Monserdà-Vilaró et al. 2023; Schumann et al. 2022). These effects are moderated by training volume, intensity, and sequence. For instance, cycling, due to the lack of ground reaction forces, tends to produce lower interference effects compared to running (Lundberg et al. 2022). Sousa et al. (2020) found that low-intensity endurance training allowed for greater maximal strength gains compared to higher intensities. Additionally, low- and moderate-intensity endurance training tended to produce better outcomes for CMJ and sprint performance. The sequencing of endurance and resistance training is crucial, as it significantly affects maximal and explosive strength adaptations (Berryman et al. 2019; Gao and Yu 2023), while $\text{VO}_{2\text{max}}$ improvements seem unaffected (Gao and Yu 2023). Thus, differences in subjects' endurance training volumes may have contributed to the variability in performance outcomes and obscured group differences after the training period.

Regarding the comparison between JS and ISO, significant group differences were observed for relative 1RM, but not for SJ or CMJ. However, JS did show significant

improvements in 1RM and CMJ, while ISO did not. These findings align with Rossi et al. (2018); Wirth et al. (2016a, b), who also reported that squat-based training induced greater performance gains compared to leg press training. The biomechanical similarity between the squat and jump tasks likely facilitates the transfer of increased muscle activation to jumping. In contrast, the leg press excludes much of the hip extension range and removes the need for three-dimensional stabilization, which is crucial for both free-weight training and jumping (Wirth et al. 2016b). This difference may explain why squat-based training was more effective than machine-based training in improving jump performance.

Further support for the relevance of joint angles and movement constraints comes from Helland et al. (2017) and Horwath et al. (2019), who found similar strength and power gains with free weights and motorized machines for multi-joint exercises, though the multi-exercise design complicates interpretation. Nonetheless, a consistent pattern emerges suggesting that joint angles and movement mechanics play a significant role in training adaptations.

The present findings can be further interpreted within a force-velocity (F-V) framework, where the SQ condition predominantly targeted the high-force end of the curve through heavy-load back squat training and associated maximal strength development (Hartmann et al. 2012; Wirth et al. 2016a). In contrast, the JS condition included a terminal

training block that emphasized the high-power region of the F-V continuum by accentuating ballistic intent and intermediate loading intensities, which are typically associated with peak power expression (Cormie et al. 2011; Haff and Nimphius 2012). The ISO condition, by contrast, sampled discrete points along the F-V curve at fixed contraction velocities, thereby providing strength stimuli that are velocity-specific but mechanically constrained. From this perspective, maximal strength outcomes would broadly be expected to be most sensitive to SQ, whereas jump performance, rate of force development, and moderate-load power expression may be expected to show greater sensitivity to JS, with ISO adaptations being primarily velocity-specific and showing limited transfer to unconstrained explosive tasks such as CMJ and DJ. This concept, however, cannot be directly applied as maximum strength levels are believed to moderate transferability to high-velocity tasks (Barker et al. 1993; Stone et al. 2002; Suchomel et al. 2018; Wisløff et al. 2004).

Isokinetic training characteristics also need to be considered. Möck et al. (2022) found stronger correlations between peak force in the isokinetic leg press and 1RM squat at higher isokinetic speeds. However, slow isokinetic speeds may have less transfer to explosive strength development, which could explain the lack of improvements in the ISO group (Hauraix et al. 2013).

For the DJ, significant improvements were only observed in the JS group at 20 cm and 30 cm drop heights, with significant group*time interactions between JS and ISO at these heights. This lack of substantial improvement in fast SSC performance is not unexpected, as the DJ involves reflex pathways and the elastic properties of the muscle-tendon unit, which differ from the strength qualities targeted by maximal strength training (Komi 2003). While plantar flexor strength contributes to DJ performance (Möck et al. 2023; Wirth et al. 2011), the present study found that only JS specifically trained the plantar flexors during the final phase of training. As the ankle joint plays a crucial role in DJ performance, this may explain why only JS showed minor improvements. Additionally, some participants, particularly from sports like rowing and rugby, demonstrated difficulty executing the DJ correctly, which may have contributed to the mixed results.

The results for mechanical power in the jump squat and isokinetic leg press showed few significant group differences. In the CON group, significant reductions in power output were observed across most loading conditions in the jump squat, whereas JS achieved significant increases in power at 40%–80% 1RM. In contrast, the isokinetic leg press revealed significant improvements for SQ at 0.9 m/s and for JS at 0.1 m/s, while ISO showed no significant changes. These differing outcomes are not surprising given

the distinct motor demands of each task. The lack of alignment between mechanical power outcomes and vertical jump performance is partially expected, as both tasks measure different performance profiles (Fessler et al. 2022).

From a neuromuscular perspective, the training responses likely reflect distinct adaptations in maximal neural drive, rapid force production, and stretch-shortening cycle function. Heavy-load resistance training is associated with increased maximal voluntary activation and enhanced recruitment and firing rates of high-threshold motor units (Baker 1996; Suchomel et al. 2018), providing a plausible basis for the observed improvements in maximal strength. In contrast, the greater emphasis on ballistic intent at the individual optimal power load in the JS condition may have promoted adaptations in rapid force expression, particularly early-phase force development and neuromuscular coordination at high contraction velocities (Cormie et al. 2010a; Schmidtbleicher 1980), which may explain the increases in reactive strength at lower drop heights and power output at moderate loads. It has to be noted, though, that the present design does not allow determining whether these adaptations were specifically induced by the final power-oriented phase or represent accumulated adaptations across the entire intervention. Nonetheless, drop jump performance is also influenced by musculotendinous properties, including tendon stiffness (Wirth et al. 2011; Zatsiorsky et al. 2021), which typically require prolonged and repeated exposure to high-intensity loading to induce adaptations. Finally, the limited transfer observed in the ISO condition can be attributed to the absence of a stretch-shortening cycle and the constrained, velocity-fixed nature of the movement (Hemmling and Schmidtbleicher 1994; Möck et al. 2022), which likely reduced elastic energy utilization and posed unique demands on task-specific coordination. Collectively, these mechanisms suggest a continuum of adaptations, with SQ primarily associated with improvements in maximal force capacity, JS favoring rapid force expression, and ISO adaptations remaining highly specific but poorly transferable. However, these interpretations should be considered with caution, as the present design does not allow isolation of the specific contribution of the final phase but only of the entire periodized training applied.

Several limitations should be considered when interpreting the present findings. First, the participant population was heterogeneous and included athletes from sports with substantially different strength, power, endurance, and jumping demands. These aspects were discussed previously in relation to differences in jump training exposure, concurrent endurance training, and sport-specific demands. Second, substantial variability in baseline maximal strength and training experience was present within the sample, as reflected by the wide range in relative 1RM values. As

discussed earlier, this variability may have contributed to differing neuromuscular adaptations and mixed individual responses to training. However, the present study was not powered to examine whether baseline strength influenced individual responses to the different training interventions. Third, the experimental groups performed strength training only and did not integrate unloaded vertical jumps or plyometric training into the intervention, which may have limited improvements in high-velocity movements such as sprinting and jumping. Fourth, some participants, particularly from sports such as rowing and rugby, demonstrated difficulty executing the DJ correctly, which may have contributed to the mixed DJ results. Furthermore, the sequential design only allows for interpretation with respect to the overall periodized training. Differences between groups cannot be attributed exclusively to a single training block. Finally, the differing movement mechanics, joint constraints, and velocity characteristics of the isokinetic leg press complicate direct comparisons with free-weight squat training and may have influenced the transferability of adaptations.

In conclusion, no significant differences in training outcomes between maximum strength or maximum strength and maximum power training can be observed in the present study. The hypothesis of a possible augmented transfer of increased strength into high-speed movements by incorporation of maximum power training cannot be supported. Overall, three recommendations can be derived from the present findings:

- For mixed strength/power sport athletes already engaged in structured training, a 14-week sequentially periodized program that ends with either a strength-focused or a power-focused final phase seems to produce broadly comparable maximal-strength and selected power outcomes, however, the results do not demonstrate statistical equivalence. The choice between the periodization model might therefore be driven by sport-specific demands rather than by an expectation of strict superiority.
- Isokinetic leg-press training is unlikely to be a sufficient stand-alone substitute for free-weight resistance training in athletes for whom maximal strength and vertical-jump performance are competitive priorities.
- Discontinuing structured lower-body resistance training, even for athletes who continue full sport-specific training, is associated with measurable declines in maximal strength and vertical-jump performance over 14 weeks. Coaches should therefore maintain a minimum strength-maintenance dose during competitive phases.

These recommendations should, however, be regarded in the context of the mixed population and the limitations of this study.

Author contributions SPM and KW conceived and designed research, SPM performed experiments, SPM analyzed data, SPM, GGH, and KW interpreted results of the experiment, SPM prepared figures, SPM drafted manuscript, SPM, GGH, MB, and KW edited and revised manuscript, SPM, GGH, MB, and KW approved the final version of the manuscript. The corresponding author attests that all listed authors meet authorship criteria and that no others meeting the criteria have been omitted.

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Declarations

Conflict of interest The authors state no conflict of interest.

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