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TITLE

Training strategies to improve muscle power: Is Olympic-style weightlifting relevant?

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SHORT TITLE

Olympic-style weightlifting and muscle power

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KEYWORDS

Athletes; power training; strength training; jump performance; sprint running; muscle architecture

ABSTRACT

Introduction

This efficacy study investigated the effects of (1) Olympic-style weightlifting (OWL), (2) motorized strength and power training (MSPT), and (3) free weight strength and power training (FSPT) on muscle power.

Methods

Thirty-nine young athletes (20±3 yr.; ice hockey, volleyball and badminton) were randomized into the three training groups. All groups participated in 2-3 sessions/week for 8 weeks. The MSPT and FSPT groups trained using squats (two legs and single leg) with high force and high power, while the OWL group trained using clean and snatch exercises. MSPT was conducted as slow-speed isokinetic strength training and isotonic power training with augmented eccentric load, controlled by a computerized robotic engine system. FSPT used free weights. The training volume (sum of repetitions x kg) was similar between all three groups. Vertical jumping capabilities were assessed by countermovement jump (CMJ), squat jump (SJ), drop jump (DJ), and loaded CMJs (10-80 kg). Sprinting capacity was assessed in a 30 m sprint. Secondary variables were squat 1-repetition-maximum, body composition and quadriceps thickness and architecture.

Results

OWL resulted in trivial improvements, and inferior gains compared to FSPT and MSPT for CMJ, SJ, and DJ. MSPT demonstrated small, but robust effects on SJ, DJ and loaded CMJs

(3-12%). MSPT was superior to FSPT in improving 30 m sprint performance. FSPT and MSPT, but not OWL, demonstrated increased thickness in the vastus lateralis and rectus femoris (4-7%).

Conclusion

MSPT was time-efficient and equally or more effective than FSPT training in improving vertical jumping and sprinting performance. OWL was generally ineffective and inferior to the two other interventions.

INTRODUCTION

Olympic-style weightlifting (OWL) includes the snatch and the clean and jerk. In both lifting techniques, high performance necessitates not only great strength, but also high power (work per unit time [W]). Indeed, high power outputs and rate of force development have been reported during these lifts (13,25,27). Moreover, high-level weightlifters exhibit impressive generic power abilities in the lower extremities, e.g., countermovement jump (CMJ) heights are higher than those for power lifters and equivalent to high-level track and field sprinters (8,29). Consequently, OWL and similar strength exercises ("weightlifting derivatives") are often advocated for a range of athletes to improve lower body muscle power (14,41). However, although cross-sectional studies have documented a positive association between OWL performance and lower body muscle power, there have been few experimental training studies conducted to establish cause and effect (15).

Hoffman et al. (18) compared OWL with heavy, slow velocity powerlifting in college American football players. No statistical significant improvements in vertical jump and sprint performance were found during the training period with either training protocol (4 sessions per week; 15 weeks). However, there was a group difference in the changes in vertical jump height, favoring the OWL group. Tricoli et al. (42) reported clear improvements in vertical jump performance in physically active college students who trained using OWL for 8 weeks (3 sessions per week). In Tricoli et al.'s study, OWL was more effective than plyometrics in improving squat jump (SJ) and CMJ heights, but not sprint performance. Channell and Barfield (9) found no statistical difference in vertical jump improvements between adolescent males (~16 years of age) training with either OWL or traditional strength training (i.e., squats and deadlifts; 3 sessions per week for 8 weeks). However, based on the effect sizes, Channell and Barfield (9) claimed that OWL might provide a modest advantage over traditional strength training. In a study by Arabatzi and Kellis (4), OWL resulted in robust increases in vertical jumping abilities after 8 weeks of training in recreationally trained students. OWL was found superior to traditional strength training (leg extension, half-squats and leg press). Finally, Chaouachi et al. (10) recruited boys aged 10 to12 years and reported that two sessions per week of OWL over 12 weeks was superior to traditional strength training (squats and lunges) in improving isolated knee-extensor power (300 $°\cdot s^{-1}$) and balance, but not for improving jumping and sprinting capabilities.

In summary, few studies have investigated the training effects of OWL (and derivative exercises) for improving jumping and sprinting properties, and the results of these studies are ambiguous. Only one study involved athletes (18), and only two of the studies controlled for training volume (4,10). Thus, in contrast to what has been advocated in reviews primarily based on cross-sectional studies and power measurements during lifting (14,41), limited longitudinal experimental evidence supports OWL as being superior to other strength and power training exercises for improving lower body muscle power in athletes.

Isokinetic squat exercises

In essence, strength training is about challenging the ability to generate maximal force (or joint torque). Unlike traditional isotonic resistance exercises (free weights), isokinetic resistance exercises have the advantage that maximal force can be exerted throughout the range of motion (ROM; (34)). Numerous investigators have examined isokinetic exercises and training, but longitudinal experiments typically involved only single joint movements (33). Isolated, single joint exercises may, however, have very limited performance value for athletes. Isokinetic multi-joint exercises should have much greater potential to transfer to sport performance, but only a few studies have investigated this hypothesis (45). Four decades ago Pipes and Wilmore (34) investigated isokinetic leg press and bench press devices that allowed maximal force-generation in full ROM. Compared to traditional, isotonic strength training, the isokinetic training induced superior improvements in sprint, jumping and throwing performance in adult men (non-athletes). Intriguingly, the isokinetic training was purely concentric (no eccentric phase). More recently, isokinetic strength training (concentric and eccentric) was investigated and reportedly improved performance in functional tests, although no comparisons were made against traditional strength training (only a non-exercising control group; (32,35,38)).

The squat exercise – commonly considered more functional than the leg press – is the cornerstone of the strength training regimes of many athletes. Isokinetic squat devices have been developed and described (28,45), but to the best of our knowledge, no previous studies have investigated the effects of isokinetic squat resistance training on strength and power in athletes. Therefore, a goal of the present study was to investigate the effects of isokinetic squat exercise training in comparison to OWL and free weight strength and power training (FSPT).

Eccentric exercise training

Muscle force may be higher during eccentric than concentric contractions (3). High-force eccentric contractions therefore have a larger potential for stimulating muscle cells via mechano-sensitive pathways (23,26). In line with this, researchers have concluded that eccentric exercise is superior to concentric exercise regimes in promoting muscle growth and strength (11,21,37,43,44). Notably, eccentric training will primarily induce augmented eccentric strength, and the transfer to concentric strength seems more variable (37). Furthermore, few studies have investigated the effects of eccentric training in athletes. Vikne et al. (43) recruited a mix of recreationally trained individuals and elite athletes engaged in power-sports, such as track and field and powerlifting. They demonstrated more hypertrophy in the exercised m. biceps brachii muscle after eccentric training compared to concentric training over a 12-week study, but 1 repetition maximum (1RM) and maximal concentric velocity at submaximal loads increased equally in both groups. In power-sports athletes (e.g., track and field), Friedmann-Bette et al. (12) compared eccentric overload training, i.e., maximal eccentric and concentric loads, with traditional isotonic training in a one-legged knee-extension exercise. The results were equivocal, but type IIX fiber hypertrophy and improved vertical jump performance were observed in the eccentric overload group only. These results are intriguing, but isolated knee-extension is an open-chain exercise that may have limited transfer to multi-joint jumping and sprinting abilities. In a recent study, Papadopoulos et al. (32) used an isokinetic, eccentric bilateral leg press exercise and reported robust effects on drop jump performance. However, this study was conducted on untrained students with no active control groups, which raises questions about the effectiveness of this intervention in athletes when compared to other forms of resistance exercise training. To the best of our knowledge, no previous study has investigated the effects of squat-jump training with computer-controlled augmented eccentric loading in athletes.

Purpose

The purpose of the present study was to examine training strategies for improving lower body muscle power in the form of vertical jumping and horizontal sprinting abilities. We designed and tested three intervention strategies in well-trained young athletes: (1) Olympic-style weightlifting (OWL), (2) motorized strength and power training (MSPT), i.e., isokinetic resistance exercise combined with augmented eccentric load power training, and (3) free weight strength and power training (FSPT).

METHODS

Recruitment and inclusion

Badminton, volleyball and hockey players were recruited from a Norwegian High School for elite sports. In addition, we recruited volleyball players (< 30 years of age) from teams competing at the two highest levels in Norway. All participants confirmed that they had regularly performed strength and power training during the last 2 years (≥ 1 session per week), and all had some experience with OWL. Typically, the athletes based their strength and power training on exercises such as squats, jump squats, deadlifts, Bulgarian split squats, step-ups, lunges, power cleans and hang cleans. None of the athletes had experience with isokinetic exercise training or augmented eccentric load exercises.

Fifty-two athletes provided written informed consent to participate in this randomized controlled study. The National Regional Committee for Research Ethics approved the project. Before the intervention period started, six participants declined to participate due to scheduling problems. During the intervention period, seven participants dropped out: two due to injury during the intervention period (lower back pain and partial rupture of the m. rectus femoris muscle), two had difficulties attending at the scheduled times, two moved, and finally, one refused to participate because he was randomized into an unsatisfactory group. Thus, 39 participants (10 women and 29 men) completed the intervention (20±3 years; 182±10 cm; 78±12 kg).

Experimental procedure

The participants were familiar with maximal vertical jumping, strength and sprint testing prior to commencing the study. All performance tests were conducted twice before and once after the intervention period. Two pre-tests were conducted to allow for familiarization to the tests.

Before the tests, participants rested for a minimum of 24 hours. All tests were performed after a standardized warm-up of 5 minutes submaximal cycling (100-150 W), followed by 3-5 submaximal CMJ. Two to three submaximal 40 m runs were conducted before the 30 m sprint test. Body composition, muscle thickness and muscle architecture were assessed in the fasted state between 7-10 a.m. on test days.

After the pre-tests, the participants were randomly allocated into three groups: Olympic-style weightlifting (OWL; n=13, 4 women and 9 men), motorized strength and power training (MSPT; n=13, 3 women and 10 men), and free weight strength and power training (FSPT; n=13, 3 women and 10 men). The athletes continued their regular off-season training, but were instructed not to conduct any strength and power training apart from the intervention programs. Due to the complexity of the athletes' training programs, we did not quantify their total training loads. In order to counteract possible group allocation bias, the group randomization process was stratified by sex, sport and CMJ (jump height).

Prior to the first training session, all participants took part in two separate lifting-technique courses (of 1-2 hours each). The intention was primarily to ensure that the participants had proper and similar lifting-technique skills. Secondly, we aimed to identify individual flaws and weaknesses in the participants' lifting techniques and provide feedback on how to improve. The coaches who supervised the familiarization training continued to provide technique supervision and correction during the intervention period.

Intervention programs

The participants underwent an 8-week, progressive training program, involving 21 sessions (Table 1). During the first three weeks, participants completed two similar strength and power training sessions per week. Thereafter the training frequency increased to three sessions per week, including two combined strength and power training sessions, and one power training session.

The training programs were designed to ensure equal training volumes between groups: sum of repetitions x load on bar (kg). To achieve an equal training volume the OWL group was assigned to perform the highest number of repetitions per session, while the MSPT group did the least (due to the higher force per repetition in this technique). Inter-set and inter-exercise rest periods were always 3 minutes. For the training sessions that combined strength and power training (Table 1), the mean durations were approximately 25, 35 and 45 minutes for the MSPT, FSPT and OWL sessions, respectively. The loads in the MSPT group were calculated from the mean concentric force generated in each repetition, which were recorded and digitally stored (1080 Quantum synchro, 1080 Motion AB, Stockholm, Sweden).

Generally, the training programs combined heavy lifts (strength) with lighter load power training (Table 1). All training exercises were conducted with the intention to move as fast as possible in the concentric phase, irrespective of load. The OWL group applied the heaviest loads possible without compromising adequate lifting techniques (repetition maximum, [RM]). The FSPT group applied RM loads during the heavy strength training. The MSPT group conducted isokinetic squats with maximal effort in each repetition. For the MSPT and FSPT groups, the power-training loads were reduced from 60% to 40% to 20% of squat 1RM during the training period (20%, 15% and 10% for the single leg exercises; Table 1).

In the first 3 weeks, the heavy load strength training exercises were followed by power training exercises in the MSPT and FSPT groups, while in weeks 4-8 the sessions started with power training exercise (jump squats; Table 1). After the initial 3 weeks, a low volume power session was added and conducted on every third training day (Table 1). For the OWL group we chose power cleans, hang cleans and hang snatches, because these exercises are conducted with relatively low loads and high velocity movements (Table 1). In contrast to the other groups, the OWL group participants were motivated to increase the loads in these “power sessions” during the training intervention (applying the heaviest loads possible in all sessions). The rationale for this was based on the observations of McBride et al. (27) that reported the highest power in the jump squat at low loads (only body weight), while the opposite was the case for power cleans; the highest power was reached at the heaviest load (90% of 1RM).

Olympic-style weightlifting

OWL included full cleans with front squat, hang cleans, power jerk behind the neck, full snatches and hang snatches (Table 1). The exercises and combinations were based on best practice at the Norwegian Olympic Training Center (Oslo, Norway). The idea was to combine exercises with a focus on different ranges of motions (ROM). For example, the clean with front squat ensures large knee and hip ROM and allows for quite heavy weights, while the power jerk behind the neck, in contrast, involves a small ROM and a very rapid movement. The snatch, hang snatch and hang clean were considered to be exercises that lay in between the previously-mentioned exercises in terms of ROMs and loads.

Motorized strength and power training

A computerized robotic engine system (1080 Quantum synchro, 1080 Motion AB, Stockholm, Sweden) controlled the load for the MSPT group. The robotic engine was attached to a custom-made Smith machine.

The strength training was conducted as isokinetic squat training. The concentric velocity was set to 0.2-0.4 m/s, starting with 0.4 m/s and progressing to 0.3 m/s and, finally, 0.2 m/s during the intervention period (Table 1). The participants were instructed to switch from eccentric to concentric phases with maximal effort and keep on pushing maximally until they reached the upright position. The eccentric phase was always isotonic, with a velocity of less than 1.0 m/s. The participants were instructed to lower the bar in a slow, controlled manner (~0.4-0.5 m/s). The eccentric load was individually adjusted to match the concentric force generated; i.e., if the mean concentric force for the full ROM was 1000 N, the constant eccentric load was set to 1000 N. The participants received feedback on their performance after each set via graphs displaying the mean concentric force (N) for each repetition and the whole set.

Power training was conducted as CMJ with external loads (countermovement to half squat depth). The loads were isotonic and set to 20-60% of the participant’s squat 1RM (10-20% for single leg CMJ; see Table 1). The eccentric load was 20-40% higher than the concentric load (increasing from 20% to 30% and finally 40%; see Table 1). The robotic engine system seamlessly switched on the eccentric overload when the eccentric velocity reached <0.2 m/s. This allowed for continuous jumping in the five repetitions per set. The participants received feedback on their performance after each set via graphs displaying the mean concentric power (W) for each repetition and the whole set.

Free weight strength and power training

The FSPT was designed to be as simple as possible, and was identical to the MSPT group, except for the use of free weights (isotonic) instead of a Smith machine (Table 1). We chose free weights because most high-level athletes generally favor this over the Smith machine.

Tests

Jump performance

Participants performed SJ, CMJ, and DJ on a force platform with arms akimbo (sampling rate 2000 Hz, AMTI OR6-5-1, AMTI, Watertown, MA, USA). For SJ, participants were instructed to squat until their knee joint angle reached 80-90° (verified by a goniometer during warm-ups). The hips were flexed to 70-80° (180° in upright position). Approximately one second after reaching this position, the investigator gave the signal to perform a maximal vertical jump. SJ attempts flawed by an initial counter movement (more than 5% below body weight) were discarded. CMJs were performed from an upright position to a self-determined depth, followed by an immediate maximal vertical jump. DJs were performed from a 40 cm high box, with the same instructions as for CMJ. In each case, the mean of the two highest jumps out of 3 to 6 attempts was used for further analysis.

Sprint performance

We assessed sprint performance on an indoor rubberized track (Mondo, Conshohocken, PA, USA) with an electronic timing system (Biomekanikk, Oslo, Norway). As a timing trigger, a single-beamed timing gate was placed 0.6 m after the start line (0.5 m above ground level). Dual-beamed timing gates were placed every 5m along the 30-m sprint distance. A stand-still start was used, one foot in front of the other; and the participants accelerated as fast as possible. Haugen et al. (16,17) have previously reported coefficients of variation (CV) in the range 0.9-1.6% with this system setup and procedure.

Vertical jump power

A linear encoder was used to assess vertical power during loaded CMJs (Musclelab Linear Encoder, Ergotest Innovation, Porsgrunn, Norway). The encoder's string was mounted to the bar, and the device measured the vertical displacement (d) and velocity (v) during the concentric phase of the jump (200 Hz sampling rate; 0.019 mm resolution). The power output (P) was estimated on the system mass (m), i.e., 90% of body mass and the external mass ($v = d/t$; acceleration [a] = v/t, force [F] = $m \cdot g + m \cdot a$; $P = F \cdot v$). A concentric force-velocity relationship was established and peak power could be estimated (best fit polynomial; software from Ergotest Innovation). With the instruction to jump as high as possible, the participants completed three CMJs at each load with ~5 seconds between each jump and 2 min between sets. Participants performed the first set without external load (body weight and a plastic stick [~300 g]), and then the female and male participants increased the load by 10 and 20 kg, respectively. The women progressed to 60 kg and the men to 80 kg, or until the lifting technique was judged inadequate by the test leader. The attempt with highest peak power from each load was used for further analysis.

Squat

For measurements of 1RM in parallel squat, we used a Smith machine (Multipower, Technogym, Cecena FC, Italy). The first 1RM attempt was conducted after two warm-up lifts at ~85% and one repetition at ~92.5 % of expected 1RM. Warm-up sets and attempts were separated by 3 minutes of rest. If the 1RM attempt was successful, the load was increased by 2.5-5% until the test leader predicted failure on the next attempt. To ensure the same squat depth from pre to post testing, we measured the distance from the floor to the bar. The distance was marked with a pen, providing visual feedback for the test leader.

Lean mass measurements and ultrasound measurements

Body composition was assessed using a narrow angle fan beam Lunar iDXA scan (DXA; GE-Helthcare, Madison, WI, USA). The iDXA was calibrated daily according to the manufacture's guidelines. The iDXA machine automatically chose scanning mode, with all athletes scanned in the standard mode. The images were analyzed with enCORE software (version 14.10.022, GE-Helthcare). The software automatically defined the different body segments: arms, trunk and legs. However, all scans were manually controlled and adjusted to ensure optimal pre- and post-training comparisons.

Muscle thickness and architecture of m. vastus lateralis and muscle thickness of m. rectus femoris in the dominant leg were assessed using B-mode ultrasonography (probe size of 4.5 cm and 8-17 MHz scanning frequency; GE Logiq 9, GE Healthcare, Little Chalfont, UK). The scans were obtained at 50% of the femur length (1). Two to three images were captured at each position. The position of the probe was marked on the skin (hydrophobic pen) and subsequently marked on a soft transparent plastic sheet superimposed on the thigh. Landmarks such as moles and scars were also marked on the plastic sheets for relocation of the scanned areas during post-training measurements. Both longitudinal and cross sectional images were obtained from m. vastus lateralis, while only transverse images were obtained from m. rectus femoris. Transverse images were used for assessing muscle thickness, whereas longitudinal images were used for assessing pennation angle and fascicle length. ImageJ software was used for image analyses (Wayne Rasband, National Institutes of Health, Bethesda, MD, USA), where muscle thickness was measured at three different sites on the transverse image and an average of these measurements was used for further calculations. Pennation angle was measured three times at the same site on the longitudinal image and an average was used for further calculations. Fascicle length was calculated from the following equation: Fascicle length = thickness/sin(pennation angle). The thickness value was the average of three measurements at three sites on the longitudinal image. For both transverse and longitudinal images, the pre and post images were analyzed at the same time and great care was taken to match the thickness and angle measurements sites on the pre and post images. The assessor was blinded for the participants' group affiliations.

Nutrition

To ensure adequate energy and protein intake, a high-protein bar was ingested after each training session (20 g protein, 31 g carbohydrates and 5 g fat; Yt, Tine, Oslo, Norway).

Statistical analysis

A priori power calculations with a standard deviation (SD) of 5% suggested 15 participants were needed in each group in order to detect a difference of 5% with 80% power (GraphPad StatMate version 2.00, GraphPad Software, Ca, USA). We ended up with 13 athletes in each group, which gave us 80% power to detect a difference of 6% between groups with a standard deviation of 5% (e.g., CMJ).

For all performance tests the means of the two pre-tests were used as baselines for further calculations. Based on the two pre-tests, coefficient of variation (CV) and intraclass correlation (ICC) were calculated for each test (19). The linear mixed model procedure in SPSS Statistics (Version 21, IBM Corp. Armonk, NY, USA) was used to analyse the changes and differences in the means, while adjusting for the effects of covariates in the three groups: baseline level, bodyweight and training volume. A more detailed description of the procedures used can be found elsewhere (40). Changes within groups are reported as % ± SD. The magnitudes of within-group changes and between-group differences were assessed as effect sizes (ES; mean change or difference divided by baseline SD of all subjects), and evaluated with a modification of Cohen's scale that aligns with the effect sizes used for bi-serial correlations: <0.2, trivial; 0.2-0.6, small; 0.6-1.2, moderate; >1.2, large (20). Inferences were based on the assumption of the normality of sampling distribution of the differences. To make inferences about true values of effects in the population studied, we used non-clinical magnitude-based inference rather than null-hypothesis significance testing (20). Magnitudes were evaluated mechanistically: if the confidence interval overlapped substantial positive and negative values (0.2 and -0.2), the effect was deemed unclear. The effect is shown as the difference or change with the greatest probability, and the probability is shown qualitatively using the following scale: 25-75%, possibly (*); 75-95%, likely (**); 95-99.5%, very likely (***); > 99.5%, most likely (20).

RESULTS

Adequate reliability was established for all performance tests. Loaded CMJs, DJ and SJ had the highest CVs of 5-10%, and lowest ICCs of 0.92-0.96, while 1RM squat, CMJ, and 30 m sprint had the lowest CVs: 1-5%, and highest ICCs: 0.96-0.98. Moreover, there were no performance improvements from pre 1 to pre 2 for any tests (all participants pooled).

No group differences were detected before the intervention period (Table 2). The total training volume (sum of repetitions x load [kg]) during the intervention period was similar between the groups (Table 2).

Except for SJ with heavy loads (40 kg for women and 80 kg for men) 8 weeks of OWL did not affect vertical jumping or sprinting performance (Table 3). Body composition was unaltered, and no clear architectural changes were demonstrated in m. rectus femoris and m. vastus lateralis.

MSPT demonstrated overall small but clear changes in both vertical jumping and sprinting performance (Table 2). Total lean mass and bone mass increased significantly ($p<0.05$), but the changes in whole body composition were trivial after 8 weeks of MSPT. However, the thickness of m rectus femoris and m. vastus lateralis increased. A small increase in fascicle angle in m. vastus lateralis was detected, although fascicle length was unaltered.

FSPT induced generally small but clear changes in 1RM squat and vertical jump performance. Performance in the 30 m sprint, however, did not improve after 8 weeks' FSPT training (Table 3). There were no clear changes in body composition, but muscle thickness of m. vastus lateralis and m. rectus femoris increased slightly. Changes in m. vastus lateralis architecture, fascicle angle and length were trivial (Table 3).

The group comparisons showed that the FSPT group had small, but clear improvements in 1RM strength (ES = .32 ± .22), SJ height (ES = .22 ± .27), CMJ height (ES = .22 ± .25) and loaded CMJ peak power (ES = .23 ± .35) compared to the OWL group. The OWL group showed improved 30 m sprint performance (ES = .20 ± .25) compared with the FSPT group, mainly due to a decrease in the FSPT group. The MSPT intervention was superior to OWL in increasing 1RM strength (ES = .40 ± .22), SJ height (ES = .26 ± .27), loaded jump power (40/80 kg; ES = .28 ± .31), DJ height (ES = .33 ± .31), 20-30 m flying sprint performance (ES = .30 ± .25), fascicle angle (ES = .25 ± .40) and m. vastus lateralis thickness (ES = .24 ± .22). MSPT was also more effective than FSPT in increasing DJ height (ES = .26 ± .33), 30 m sprint performance (ES = .34 ± .24), and fascicle angle (ES = .26 ± .41).

DISCUSSION

In the present study, we observed that OWL was statistically inferior to FSPT in improving CMJ height, peak power during loaded CMJ, and 1RM squat. In contrast, MSPT, i.e., isokinetic strength training combined with augmented eccentric load power training, induced generally small but robust effects on CMJ and SJ height, DJ rebound height, and sprint running, as well as loaded CMJ power and 1RM squat. MSPT was superior to FSPT in improving DJ rebound height and 30 m sprint times.

Our participants were encouraged to have a fast, “explosive” concentric phase in each lift, and all sessions included supervised training with technical feedback. Despite this, we observed that OWL training resulted in smaller improvements in jumping and sprinting performances than expected based on previous publications (9,10,14,18,41,42). We included several derivatives of OWL exercises, and the training volume and frequency seemed appropriate (2-3 sessions per week). The intervention period was short (8 weeks), but still relevant for athletes with limited preparatory periods, and of similar duration to the study of Channell and Barfield (9), in which OWL training did improve vertical jumping abilities. To illustrate the specific effects of the OWL training, our athletes improved their 1RM hang clean by 29±11% ($p<0.001$; estimated from training loads (31)); in line with the observations of others (42). This indicates that the problem may lie in the transfer from OWL techniques to jumping and sprinting movements.

Although studies have shown high lower body power outputs during OWL (13,25,27), there are often large differences between skilled weightlifters and athletes engaged in other sports that use OWL as part of their training. Inappropriate lifting techniques would probably reduce or abolish the transfer to other abilities, such as jumping and sprinting. Intriguingly, the OWL training induced larger gains of lean mass in the arms than the lower body (3.3% vs -0.4%, $p<0.05$; trivial effects). These results indicate that upper-body muscles were highly active during the OWL training, thereby alleviating the load on the lower body muscles. Indeed, the ability to transfer forces between joints via bi-articular muscles implies the possibility of reducing the work of the lower limb muscles in OWL.

OWL is kinematically different from both vertical jumping (25) and sprinting (unilateral movement). Thus, the transfer from OWL training to jump and sprint performance is not obvious. Nevertheless, OWL might be more advantageous for improving hip extension moments in joint positions more relevant for sprinting than vertical jumping. Interestingly, the improvement in 30 m sprint was trivial for OWL, but still superior to free weight strength training, due to a slight decrease in performance in the latter group.

Another possibility for limited improvements from OWL is low eccentric muscle force production, since eccentric muscle actions are possibly more potent in increasing muscle mass than concentric contractions (37). In OWL, the bar must be dropped to the hips or directly to the floor, and the eccentric stimulus for the lower leg muscles is consequently negligible. In addition to myofiber hypertrophy, eccentric-contraction-induced neural and tendon adaptations could plausibly explain the group differences in jumping and sprinting improvements.

In accordance with our results, Hoffman et al. (18) found no significant improvements in either vertical jumping or sprinting after 15 weeks of OWL training. In contrast to other previous studies (4,9,10,18,42), but similar to the present study, Hoffman et al. recruited well-trained athletes. However, the authors concluded that OWL training was superior to powerlifting training, mostly because the powerlifting group surprisingly showed reductions in their vertical jump height. It seems fair to say that the efficacy of OWL training in athletes warrants further research.

In the present study, we included OWL exercises only, similar to Chaouahi et al. (10). Other previous investigations have included a mix of exercises, such as squats, lunges and leg press exercises, in addition to the OWL exercises (4,9,18,42). The inclusion of other exercises makes it impossible to conclude that OWL *per se* induced the observable training effects.

In accordance with the present study, some previous studies equalized or controlled for training volume when comparing OWL with traditional strength and power training (4,10), but not all did so (9,18). Without equal training volume, one cannot exclude the possibility of a dose-response effect, and direct comparisons are not readily possible.

The motorized strength and power training, using a robotic engine training device, allowed for maximal effort and force generation through the whole range of motion during the slow, isokinetic squat exercises, and augmented eccentric loading during the power training exercises. MSPT induced similar improvements in 1RM squat as did FSPT, but did lead to larger progressions in drop jump performance (vertical rebound jump height) and sprint running ability (and was clearly better than OWL). The muscle thickness of m. rectus femoris and m. vastus lateralis consistently increased in both the MSPT and FSPT groups, but fascicle angle increased only in the MSPT group. Previous studies have shown that various resistance training modalities induce contrasting changes in fascicle angle (6,36). Training regimes involving concentric contractions typically yield a higher angle of pennation with no consistent change in fascicular length, while the opposite findings are observed with eccentric contractions. With equal training volumes across groups, the higher concentric force generation during isokinetic squats seems to have driven these adaptions.

In contrast to hypertrophic strength training (1,22), power training has been accompanied by no change or a decrease in fascicle angle and an increase in fascicle length (2,7,24). The participants in the present study conducted both heavy strength and power training. Since the fascicle angle increased and fascicle length trivially decreased in the MSPT group, we suggest that the concentric, high-force contractions were the dominating stimulus for the architectural changes. Arguably, hypertrophy was achieved in this group via sarcomerogenesis in parallel, rather than in series. However, fascicle length was calculated using simple trigonometric extrapolation techniques in the present study. Advanced techniques enabling direct measurements may have been more sensitive to changes in this parameter.

The MSPT group performed power training with an augmented eccentric load (120-140% of the concentric load). The idea was that this would give a stronger stimulus to the neuromuscular system (30). This was, apparently, not the case for the SJ or the CMJ abilities. On the other hand, the MSPT group did experience superior improvements in the DJ test. Intriguingly, a DJ will cause a high eccentric load, quite similar to the augmented eccentric load during the loaded CMJ training. Consequently, the augmented eccentric load training appears to have transferred effectively to drop jump performance. In support of our findings, strategies (e.g., use of rubber bands) to augment eccentric loading during plyometrics are used in practice by athletes (30,39).

This study has several potential limitations. First, one could argue that it is atypical to train using purely OWL exercises, and their effects could be optimized when combined with traditional strength and power training; similar studies have successfully added squats and leg press exercises to an OWL program (5,9,10,42). However, we chose the present design in order to isolate the effects of OWL. Second, the motorized training included slow velocity, isokinetic squat training and augmented eccentric load jump squat training. The relative contribution of these training modes in terms of performance enhancements cannot be inferred from the present results. Future experiments should investigate these training modes separately. Third, the motorized squat training was an unaccustomed exercise modality for all participants, and we therefore cannot exclude the possibility that some of the performance gains were due to this being a novel stimulus and/or the enhanced feedback on performance. Finally, we calculated the total training volume simply by summarizing the products of the load on the bar and the number of repetitions for each set. This approach may not be optimal when comparing training programs with different exercises, including ballistic exercises (such as OWL).

PRACTICAL APPLICATION

In the present study, we demonstrated that using computer-controlled robotic engines for strength and power training was a time-efficient approach to increase vertical jumping and sprinting performance in athletes. Traditional FSPT seemed also effective in improving vertical jumping height, while OWL appeared less effective as a sole training mode. If anything, OWL appeared more favorable in improving sprinting than vertical jumping performance. OWL may work well for certain athletes, but adequate lifting technique is probably an important prerequisite. Moreover, for athletes with already high maximal strength, OWL might be more relevant for improving lower body muscle power and speed than for weaker athletes. It could also be important to combine OWL exercises with exercises focusing on eccentric muscle actions (i.e., drop jumps). For young “power-athletes”, such as those recruited in the present study (ice hockey, volleyball and badminton players), we recommend a base of simple heavy strength and power training exercises (e.g., squats) that includes a controlled eccentric phase, to favor muscle growth and maximal force gains.

CONCLUSION

MSPT was more time-efficient while being equally as effective or superior to FSPT in improving both vertical jumping and sprinting performance. Hence, isokinetic strength training combined with eccentric augmented load power training emerges as an attractive training approach for a wide range of athletes. In contrast, OWL appeared generally ineffective and inferior to traditional FSPT in developing vertical jumping performance in athletes.

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CONFLICT OF INTEREST

The authors declare no conflicts of interest. The results of the present study do not constitute endorsement by the American College of Sports Medicine.

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Table 1

Table 1. Overview of the three training interventions: Olympic weightlifting (OWL), motorized strength and power training (MSPT), and free weight strength and power training (FSPT). The MSPT group trained isokinetic squats and the speed of the concentric phase is given in meter per sec (m/s). For the MSPT and FSPT groups, CMJ loads (including single leg squats) are given as percentage of 1RM in the bilateral squat. For the MSPT group, the CMJs were conducted with augmented eccentric loads given as percentage of the concentric loads (i.e., 120 % ecc could mean a 50 kg concentric load and a 60 kg eccentric load).

OWL		**MSPT**		**FSPT**	
Sessions 1-6		**Sessions 1-6**		**Sessions 1-6**	
Warm-up. (40, 60, 80% of training load)	3x5	Warm-up. (increasing effort during the set)	1x10	Warm-up. (40, 60, 80% of training load)	3x5
Clean with front squat	4x5RM	Squat 0.4 m/s	2x5	Squat	3x5RM
Hang clean	3x5RM	Single leg squat 0.4 m/s	2x2x5	Single leg squat	2x2x5RM
Snatch	2x5RM	CMJ 60% of 1RM + 120% ecc.	2x5	CMJ 60% of 1RM	2x5
Power jerk behind the neck	3x5RM	Single leg CMJ 20% of 1RM + 120% ecc.	2x2x5	Single leg CMJ 20% of 1RM	2x2x5
Sessions 7, 9, 10, 12 , 13 and 15		**Sessions 7, 9, 10, 12 , 13 and 15**		**Sessions 7, 9, 10, 12 , 13 and 15**	
Warm-up. (40, 60, 80% of training load)	3x5	Warm-up. (increasing effort during the set)	1x10	Warm-up. (40, 60, 80% of training load)	3x5
Snatch	4x4RM	CMJ 40% of 1RM + 130% ecc.	3x5	CMJ 40% of 1RM	3x5
Hang clean	4x4RM	Single leg CMJ 15% of 1RM + 130% ecc.	2x5	Single leg CMJ 15% of 1RM	2x2x5
Clean with front squat	4x5RM	Squat 0.3 m/s	3x5	Squat	5x4RM
Power jerk behind the neck	4x4RM	Single leg squat 0.3 m/s	2x5	Single leg squat	2x3x5RM
Sessions 8, 11 and 14 (power only)		**Sessions 8, 11 and 14 (power only)**		**Sessions 8, 11 and 14 (power only)**	
Warm-up. (40, 60, 80% of training load)	3x5	Warm-up. (increasing effort during the set)	1x10	Warm-up. (40, 60, 80% of training load)	3x5
Power clean	5x3RM	CMJ 40% of 1RM + 130% ecc.	3x5	CMJ 40% of 1RM	3x5
Hang clean	3x3RM	Single leg squat 15% of 1RM + 130% ecc.	2x3x5	Single leg CMJ 15% of 1RM	2x3x5
Hang snatch	3x3RM				
Sessions 16, 18 and 19		**Sessions 16, 18 and 19**		**Sessions 16, 18 and 19**	
Warm-up. (40, 60, 80% of training load)	3x5	Warm-up. (increasing effort during the set)	1x10	Warm-up. (40, 60, 80% of training load)	3x5
Snatch	5x3RM	CMJ 20% of 1RM + 140% ecc.	4x5	CMJ 20% of 1RM	4x5
Hang clean	5x3RM	Single leg CMJ 10% of 1RM + 140% ecc.	2x2x5	Single leg CMJ 10% of 1RM	2x2x5
Clean with front squat	4x5RM	Squat 0.2 m/s	4x5	Squat	6x3RM
Power jerk behind the neck	4x3RM	Single leg squat 0.2 m/s	2x2x5	Single leg squat	2x3x5RM
Session 17 (power only)		**Session 17 (power only)**		**Session 17 (power only)**	
Warm-up. (40, 60, 80% of training load)	3x5	Warm-up. (increasing effort during the set)	1x10	Warm-up. (40, 60, 80% of training load)	3x5
Power clean	5x3RM	CMJ 20% of 1RM + 140% ecc.	4x5	CMJ 20% of 1RM	4x5
Hang clean	3x3RM	Single leg CMJ 10% of 1RM + 140% ecc.	2x3x5	Single leg CMJ 10% of 1RM	2x3x5
Hang snatch	3x3RM				
Session 20 (power only)		**Session 20 (power only)**		**Session 20 (power only)**	
Warm-up. (40, 60, 80% of training load)	3x5	Warm-up. (increasing effort during the set)	1x10	Warm-up. (40, 60, 80% of training load)	3x5
Power clean	5x3RM	CMJ 20% of 1RM + 140% ecc.	2x5	CMJ 20% of 1RM	3x5
Hang clean	3x3RM	Single leg squat 10% of 1RM + 140% ecc.	2x1x5	Single leg CMJ at 10% of 1RM	2x2x5
Hang snatch	3x3RM				
Session 21		**Session 21**		**Session 21**	
Warm-up. (40, 60, 80% of training load)	3x5	Warm-up. (increasing effort during the set)	1x10	Warm-up. (40, 60, 80% of training load)	3x5
Snatch	3x3RM	CMJ 20% of 1RM + 140% ecc.	2x5	CMJ 20% of 1RM	2x5
Hang clean	3x3RM	Single leg CMJ 10% of 1RM + 140% ecc.	2x1x5	Single leg CMJ 10% of 1RM	2x2x5
Clean with front squat	3x5RM	Squat 0.2 m/s	2x5	Squat	3x3RM
Power jerk behind the neck	3x3RM	Single leg squat 0.2 m/s	2x1x5	Single leg squat	2x2x5RM

CMJ: Countermovement jump; RM: Repetition Maximum; Ecc: Eccentric load.

Table 2. Simple statistics for the main variables in each group at baseline.

	All (N=39) Mean ± SD	OWL (n=13) Mean ± SD	FSPT (n=13) Mean ± SD	MSPT (n=13) Mean ± SD
1 RM squat (kg)	112 ± 25	109 ± 28	116 ± 27	111 ± 23
Counter movement jump (cm)	37.4 ± 6.8	35.8 ± 8.8	39.3 ± 5.2	37.0 ± 6.1
Squat jump (cm)	35.0 ± 6.4	33.7 ± 8.2	36.6 ± 5.6	34.6 ± 5.1
Drop jump 40 (cm)	36.8 ± 6.9	35.4 ± 8.5	38.7 ± 5.9	36.4 ± 6.3
Peak power (W)	1847 ± 388	1786 ± 490	1946 ± 362	1809 ± 301
Power 40/80kg (W)	1618 ± 365	1571 ± 449	1736 ± 321	1547 ± 309
30 m sprint (s)	4.29 ± 0.26	4.38 ± 0.37	4.19 ± 0.17	4.32 ± 0.19
20-30 m flying (s)	1.27 ± 0.09	1.30 ± 0.13	1.24 ± 0.06	1.28 ± 0.06
Bodyweight (kg)	78 ± 12	76 ± 15	80 ± 12	78 ± 11
Lean body mass (kg)	60.3 ± 11.0	58.8 ± 14.0	62.1 ± 10.4	59.9 ± 8.5
Fat mass (kg)	13.4 ± 3.9	13.2 ± 3.8	13.4 ± 2.7	13.6 ± 5.1
m. vastus lateralis fascicle angle	21.3 ± 2.9	21.2 ± 3.1	21.5 ± 3.4	21.2 ± 2.4
m. vastus lateralis fascicle length	74.6 ± 10.0	73.9 ± 10.8	77.4 ± 9.5	72.8 ± 9.9
m. vastus lateralis thickness	26.8 ± 3.8	26.1 ± 4.5	28.0 ± 3.8	26.4 ± 3.0
m. rectus femoris thickness	16.6 ± 3.1	15.3 ± 3.8	17.3 ± 2.6	17.4 ± 2.6
Total training volume (kg)	58084 ± 13080	59876 ± 18595	55674 ± 9067	58700 ± 10178

[a] Magnitude thresholds (for difference in means divided by baseline SD of the total sample): <0.20, trivial; 0.20-0.59, small; 0.60-1.19, moderate; >1.20, large.

Asterisks indicate effects clear at the 5% level and likelihood that the true effect is substantial, as follows: *possible, **likely, ***very likely, ****most likely.

OWL: Olympic-style weightlifting

FSPT: Free weight strength and power training

MSPT: Motorized strength and power training

Table 3

Table 3. Percent changes across groups and magnitude-based inferences for the changes when adjusted to baseline mean, bodyweight and total training volume.

	OWL (n=13)		FSPT (n=13)		MSPT (n=13)	
	Mean change ± SD	Inference	Mean change ± SD	Inference	Mean change ± SD	Inference
Performance tests						
1 RM squat	3.4 ± 7.9	trivial ↑	11.4 ± 4.0	small↑***[1]	13.4 ± 4.3	sm/mod↑***[1]
Counter movement jump	0.8 ± 6.2	trivial ↑	5.0 ± 4.5	small↑**[1]	3.3 ± .6.0	trivial ↑
Squat jump	1.2 ± 7.7	trivial ↑	5.4 ± 2.5	small↑**[1]	6.2 ± 5.3	small ↑**[1]
Drop jump 40	-0.4 ± 6.7	trivial ↓	1.0 ± 6.9	trivial↑	6.1 ± 7.7	small ↑**[1,2]
Peak power	2.6 ± 5.2	trivial↑	8.1 ± 10.9	small↑**[1]	6.1 ± 2.8	small↑**
Power 40/80kg	5.9 ± 8.1	small↑**	10.1 ±8.7	small ↑***	12.6 ±9.4	sm/mod↑***[1]
30 m sprint	-0.5 ± 1.8	trivial ↑[2]	0.7 ± 1.3	trivial↓	-1.3 ± 1.7	small**↑[2]
20-30 m flying	0.5 ± 2.0	trivial ↓	-0.2 ± 2.5	trivial↓	-1.5 ± 2.0	small↑**[1]
Body composition						
Bodyweight	0.3 ±2.2	trivial ↑	0.5 ± 2.8	trivial ↑	0.5 ± 2.2	trivial ↑
Lean mass (total)	0.7 ± 2.2	trivial ↑	1.2 ± 2.9	trivial ↑	2.0 ± 3.5	trivial ↑
Lean mass legs	-0.4 ± 2.7	trivial ↑	1.3 ± 2.6	trivial ↑	2.2 ± 3.2	trivial ↑
Lean mass arms	3.3 ± 3.8	trivial ↑	0.1 ± 4.3	trivial ↑	2.1 ± 4.5	trivial ↑
Fat mass	-1.3 ± 5.8	trivial ↓	-3.3 ± 10.9	trivial ↓	-0.6 ± 12.5	trivial ↓
Bone mass	0.3 ± 1.1	trivial ↑	0.8 ± 0.7	trivial ↑	0.8 ± 0.9	trivial ↑
m. vastus lateralis fascicle angle	2.2 ± 5.7	trivial ↑	2.0 ± 5.6	trivial ↑	5.4 ± 6.9	small ↑**[1,2]
m. vastus lateralis fascicle length	0.2 ± 7.1	trivial ↑	1.7 ± 6.7	trivial ↑	-0.4 ± 5.9	trivial ↓
m. vastus lateralis thickness	2.8 ± 4.0	trivial ↑	3.8 ± 4.8	small ↑**	6.1 ± 3.3	small ↑***[1]
m. rectus femoris thickness	2.8 ± 9.1	trivial ↑	5.4 ± 7.7	small ↑**	6.6 ± 6.5	small ↑**

Magnitude thresholds (for mean change divided by baseline SD of the total sample): <0.20, trivial; 0.20-0.59, small; 0.60-1.19, moderate; >1.20, large.

Asterisks indicate effects clear at the 5% level and likelihood that the true effect is substantial or trivial, as follows: *possible, **likely, ***very likely, ****most likely. **is significant at p<.05. Differences between groups are marked with numbers:

[1] Different to Olympic-style weightlifting (OWL)[1] Different to Olympic strength training

[2] Different to Free weight strength and power training (FSPT)

[3] Different to Motorized strength and power training (MSPT)