Training Strategies to Improve Muscle Power: Is Olympic-style Weightlifting Relevant?

CHRISTIAN HELLAND[1], EIRIK HOLE[1], ERIK IVERSEN[1], MONICA CHARLOTTE OLSSON[2], OLIVIER SEYNNES[3], PAUL ANDRE SOLBERG[4], and GØRAN PAULSEN[1,3]

[1]The Norwegian Olympic and Paralympic Committee and Confederation of Sports, Oslo, NORWAY; [2]Biological and Environmental Systems Laboratory, Halmstad University, Halmstad, SWEDEN; [3]Norwegian School of Sport Sciences, Oslo, NORWAY; and [4]Defense Institute, Norwegian School of Sport Sciences, Oslo, NORWAY

ABSTRACT

HELLAND, C., E. HOLE, E. IVERSEN, M. C. OLSSON, O. SEYNNES, P. A. SOLBERG, and G. PAULSEN. Training Strategies to Improve Muscle Power: Is Olympic-style Weightlifting Relevant? *Med. Sci. Sports Exerc.*, Vol. 49, No. 4, pp. 736–745, 2017. **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 two to three sessions per week for 8 wk. The MSPT and FSPT groups trained using squats (two legs and single leg) with high force and high power, whereas 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 × kg) was similar between all three groups. Vertical jumping capabilities were assessed by countermovement jump (CMJ), squat jump (SJ), drop jump (DJ), and loaded CMJ (10–80 kg). Sprinting capacity was assessed in a 30-m sprint. Secondary variables were squat one-repetition maximum (1RM), body composition, quadriceps thickness, and architecture. **Results**: OWL resulted in trivial improvements and inferior gains compared with FSPT and MSPT for CMJ, SJ, DJ, and 1RM. MSPT demonstrated small but robust effects on SJ, DJ, loaded CMJ, and 1RM (3%–13%). 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%). **Conclusions**: 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. **Key Words:** ATHLETES, POWER TRAINING, STRENGTH TRAINING, JUMP PERFORMANCE, SPRINT RUNNING, MUSCLE ARCHITECTURE

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, for example, 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).

Address for correspondence: Gøran Paulsen, Ph.D., The Norwegian Olympic and Paralympic Committee and Confederation of Sport, Pb 4004 Ullevål stadion, 0806 Oslo, Norway; E-mail: goran.paulsen@olympiatoppen.no.
Submitted for publication March 2016.
Accepted for publication October 2016.

0195-9131/17/4904-0736/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0000000000001145

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 (four sessions per week; 15 wk). 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 wk (three 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 yr of age) training with either OWL or traditional strength training (i.e., squats and deadlifts; three sessions per week for 8 wk). However, based on the effect sizes (ES), 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 wk 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 age 10 to 12 yr and reported that two sessions per week of OWL over 12 wk was superior to traditional strength training (squats and lunges) in improving isolated knee-extensor power ($300°·s^{-1}$) 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 multijoint 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 with traditional isotonic strength training, the isokinetic training induced superior improvements in sprint, jumping, and throwing performance in adult men (nonathletes). Intriguingly, the isokinetic training was purely concentric (no eccentric phase). More recently, multijoint 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 nonexercising 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 mechanosensitive 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 musculus biceps brachii muscle after eccentric training compared with concentric training over a 12-wk study, but one 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, that is, 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 multijoint 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 (DJ) 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 with other forms of resistance exercise training. To the best of our knowledge, no previous study has investigated the effects of SJ 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 sprinting abilities. We designed and tested three intervention strategies in well-trained young athletes: 1) OWL, 2) motorized strength and power training (MSPT), that is, isokinetic resistance exercise combined with augmented eccentric load power training, and 3) 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 yr 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 yr (≥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 musculus 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 yr; 182 ± 10 cm; 78 ± 12 kg).

Experimental Procedure

The participants were familiar with maximal vertical jumping, strength, and sprint testing before commencing the study. All performance tests were conducted twice before and once after the intervention period. Two pretests were conducted to allow for familiarization to the tests. Before the tests, participants rested for a minimum of 24 h. All tests were performed after a standardized warm-up of 5 min submaximal cycling (100–150 W), followed by three to five 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 and 10 AM on test days.

After the pretests, the participants were randomly allocated into three groups: OWL (n = 13, four women and nine men), MSPT (n = 13, three women and 10 men), and FSPT (n = 13, three 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. Because of the complexity of the athletes' training programs, we did not quantify their total training loads. To counteract possible group allocation bias, the group randomization process was stratified by sex, sport, and CMJ (jump height).

Before the first training session, all participants took part in two separate lifting-technique courses (of 1–2 h each). The intention was primarily to ensure that the participants had proper and similar lifting-technique skills. Second, 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-wk, progressive training program, involving 21 sessions (Table 1). During the first 3 wk, 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 × load on bar (kg). To achieve an equal training volume, the OWL group was assigned to perform the highest number of repetitions per session, whereas the MSPT group did the least (due to the higher force per repetition in this technique). Interset and interexercise rest periods were always 3 min. For the training sessions that combined strength and power training (Table 1), the mean durations were approximately 25, 35, and 45 min 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 wk, the heavy load strength training exercises were followed by power training exercises in the MSPT and FSPT groups, whereas in weeks 4–8, the sessions started with power training exercise (loaded CMJ; Table 1). After the initial 3 wk, 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), whereas 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

TABLE 1. Overview of the three training interventions: OWL, MSPT, and FSPT.

OWL		MSPT		FSPT	
Sessions 1–6		**Sessions 1–6**		**Sessions 1–6**	
Warm-up. (40%, 60%, 80% of training load)	3 × 5	Warm-up. (increasing effort during the set)	1 × 10	Warm-up. (40%, 60%, 80% of training load)	3 × 5
Clean with front squat	4 × 5 RM	Squat 0.4 $m \cdot s^{-1}$	2 × 5	Squat	3 × 5 RM
Hang clean	3 × 5 RM	Single leg squat 0.4 $m \cdot s^{-1}$	2 × 2 × 5	Single leg squat	2 × 2 × 5 RM
Snatch	2 × 5 RM	CMJ 60% of 1RM + 120% ecc.	2 × 5	CMJ 60% of 1RM	2 × 5
Power jerk behind the neck	3 × 5 RM	Single leg CMJ 20% of 1RM + 120% ecc.	2 × 2 × 5	Single leg CMJ 20% of 1RM	2 × 2 × 5
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)	3 × 5	Warm-up. (increasing effort during the set)	1 × 10	Warm-up. (40%, 60%, 80% of training load)	3 × 5
Snatch	4 × 4 RM	CMJ 40% of 1RM + 130% ecc.	3 × 5	CMJ 40% of 1RM	3 × 5
Hang clean	4 × 4 RM	Single leg CMJ 15% of 1RM + 130% ecc.	2 × 2 × 5	Single leg CMJ 15% of 1RM	2 × 2 × 5
Clean with front squat	4 × 5 RM	Squat 0.3 $m \cdot s^{-1}$	3 × 5	Squat	5 × 4 RM
Power jerk behind the neck	4 × 4 RM	Single leg squat 0.3 $m \cdot s^{-1}$	2 × 2 × 5	Single leg squat	2 × 3 × 5 RM
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)	3 × 5	Warm-up. (increasing effort during the set)	1 × 10	Warm-up. (40%, 60%, 80% of training load)	3 × 5
Power clean	5 × 3 RM	CMJ 40% of 1RM + 130% ecc.	3 × 5	CMJ 40% of 1RM	3 × 5
Hang clean	3 × 3 RM	Single leg squat 15% of 1RM + 130% ecc.	2 × 3 × 5	Single leg CMJ 15% of 1RM	2 × 3 × 5
Hang snatch	3 × 3 RM				
Sessions 16, 18, and 19		**Sessions 16, 18, and 19**		**Sessions 16, 18, and 19**	
Warm-up. (40%, 60%, 80% of training load)	3 × 5	Warm-up. (increasing effort during the set)	1 × 10	Warm-up. (40%, 60%, 80% of training load)	3 × 5
Snatch	5 × 3 RM	CMJ 20% of 1RM + 140% ecc.	4 × 5	CMJ 20% of 1RM	4 × 5
Hang clean	5 × 3 RM	Single leg CMJ 10% of 1RM + 140% ecc.	2 × 2 × 5	Single leg CMJ 10% of 1RM	2 × 2 × 5
Clean with front squat	4 × 5 RM	Squat 0.2 $m \cdot s^{-1}$	4 × 5	Squat	6 × 3 RM
Power jerk behind the neck	4 × 3 RM	Single leg squat 0.2 $m \cdot s^{-1}$	2 × 2 × 5	Single leg squat	2 × 3 × 5 RM
Session 17 (power only)		**Session 17 (power only)**		**Session 17 (power only)**	
Warm-up. (40%, 60%, 80% of training load)	3 × 5	Warm-up. (increasing effort during the set)	1 × 10	Warm-up. (40%, 60%, 80% of training load)	3 × 5
Power clean	5 × 3 RM	CMJ 20% of 1RM + 140% ecc.	4 × 5	CMJ 20% of 1RM	4 × 5
Hang clean	3 × 3 RM	Single leg CMJ 10% of 1RM + 140% ecc.	2 × 3 × 5	Single leg CMJ 10% of 1RM	2 × 3 × 5
Hang snatch	3 × 3 RM				
Session 20 (power only)		**Session 20 (power only)**		**Session 20 (power only)**	
Warm-up. (40%, 60%, 80% of training load)	3 × 5	Warm-up. (increasing effort during the set)	1 × 10	Warm-up. (40%, 60%, 80% of training load)	3 × 5
Power clean	5 × 3 RM	CMJ 20% of 1RM + 140% ecc.	2 × 5	CMJ 20% of 1RM	3 × 5
Hang clean	3 × 3 RM	Single leg squat 10% of 1RM + 140% ecc.	2 × 1 × 5	Single leg CMJ at 10% of 1RM	2 × 2 × 5
Hang snatch	3 × 3 RM				
Session 21		**Session 21**		**Session 21**	
Warm-up. (40%, 60%, 80% of training load)	3 × 5	Warm-up. (increasing effort during the set)	1 × 10	Warm-up. (40%, 60%, 80% of training load)	3 × 5
Snatch	3 × 3 RM	CMJ 20% of 1RM + 140% ecc.	2 × 5	CMJ 20% of 1RM	2 × 5
Hang clean	3 × 3 RM	Single leg CMJ 10% of 1RM + 140% ecc.	2 × 1 × 5	Single leg CMJ 10% of 1RM	2 × 2 × 5
Clean with front squat	3 × 5 RM	Squat 0.2 $m \cdot s^{-1}$	2 × 5	Squat	3 × 3 RM
Power jerk behind the neck	3 × 3 RM	Single leg squat 0.2 $m \cdot s^{-1}$	2 × 1 × 5	Single leg squat	2 × 2 × 5 RM

The MSPT group trained isokinetic squats and the speed of the concentric phase is given in meter per second. 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 CMJ 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).
ecc, eccentric load.

Olympic Training Center (Oslo, Norway). The idea was to combine exercises with a focus on different ROM. For example, the clean with front squat ensures large knee and hip ROM and allows for quite heavy weights, whereas 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 ROM 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 $m \cdot s^{-1}$, starting with 0.4 $m \cdot s^{-1}$ and progressing to 0.3 $m \cdot s^{-1}$, and finally, 0.2 $m \cdot s^{-1}$ 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 $m \cdot s^{-1}$. The participants were instructed to lower the bar in a slow, controlled manner (~0.4–0.5 $m \cdot s^{-1}$). The eccentric load was individually adjusted to match the concentric force generated; that is, 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 off the eccentric overload when the eccentric velocity reached <0.2 $m \cdot s^{-1}$. 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

APPLIED SCIENCES

(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). 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 1 s 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. CMJ were performed from an upright position to a self-determined depth, followed by an immediate maximal vertical jump. DJ 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 of three to six attempts was used for further analysis.

Sprint performance. We assessed sprint performance on an indoor rubberized track (Mondo, Conshohocken, PA) 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 5 m 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 of 0.9%–1.6% with this system setup and procedure.

Vertical jump power. A linear encoder was used to assess vertical power during loaded CMJ (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), that is, 90% of body mass and the external mass ($v = d/t$; acceleration [a] = v/t, force [F] = $mg + ma$; $P = Fv$). 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 CMJ at each load with ~5 s 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 min 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 pretesting to posttesting, 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 Healthcare, Madison, WI). The iDXA was calibrated daily according to the manufacturer'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-Healthcare). The software automatically defined the different body segments: arms, trunk, and legs. However, all scans were manually controlled and adjusted to ensure optimal pretraining and posttraining comparisons.

Muscle thickness and architecture of musculus vastus lateralis and muscle thickness of musculus 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 posttraining measurements. Both longitudinal and cross sectional images were obtained from musculus vastus lateralis, whereas only transverse images were obtained from musculus 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), 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 preimages and postimages were analyzed at the same time, and great care was taken to match the thickness and angle measurements sites on the preimages and postimages. 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 SD of 5% suggested 15 participants were needed in each group to detect a difference of 5% with 80% power (GraphPad StatMate version 2.00; GraphPad Software, CA). 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 pretests were used as baselines for further calculations. Based on the two pretests, 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) was used to analyze 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 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 ES used for biserial 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 nonclinical 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 CMJ, DJ, and SJ had the highest CV of 5%–10%, and lowest ICC of 0.92–0.96, whereas 1RM squat, CMJ, and 30-m sprint had the lowest CV, 1%–5%; and highest ICC, 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 × 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 wk of OWL did not affect vertical jumping or sprinting performance (Table 3). Body composition was unaltered, and no clear architectural changes were demonstrated in musculus rectus femoris and musculus vastus lateralis.

MSPT demonstrated overall small but clear changes in both vertical jumping and sprinting performance (Table 3). Total lean mass and bone mass increased significantly ($P < 0.05$), but the changes in whole body composition were trivial after 8 wk of MSPT. However, the thickness of musculus rectus femoris and musculus vastus lateralis increased. A small increase in fascicle angle in musculus 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-wk FSPT training (Table 3). There were no clear changes in body composition, but muscle thickness of musculus vastus lateralis and musculus rectus femoris increased slightly.

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

	All (N = 39)	OWL (n = 13)	FSPT (n = 13)	MSPT (n = 13)
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
1 RM squat (kg)	112 ± 25	109 ± 28	116 ± 27	111 ± 23
CMJ (cm)	37.4 ± 6.8	35.8 ± 8.8	39.3 ± 5.2	37.0 ± 6.1
SJ (cm)	35.0 ± 6.4	33.7 ± 8.2	36.6 ± 5.6	34.6 ± 5.1
DJ 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 40/80 kg (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
Musculus vastus lateralis fascicle angle (°)	21.3 ± 2.9	21.2 ± 3.1	21.5 ± 3.4	21.2 ± 2.4
Musculus vastus lateralis fascicle length (mm)	74.6 ± 10.0	73.9 ± 10.8	77.4 ± 9.5	72.8 ± 9.9
Musculus vastus lateralis thickness (mm)	26.8 ± 3.8	26.1 ± 4.5	28.0 ± 3.8	26.4 ± 3.0
Musculus rectus femoris thickness (mm)	16.6 ± 3.1	15.3 ± 3.8	17.3 ± 2.6	17.4 ± 2.6
Total training volume (kg)	58,084 ± 13,080	59,876 ± 18,595	55,674 ± 9067	58,700 ± 10,178

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 (% change from baseline)						
1RM squat	3.4 ± 7.9	trivial ↑	11.4 ± 4.0	small↑***[a]	13.4 ± 4.3	sm/mod↑***[a]
CMJ	0.8 ± 6.2	trivial ↑	5.0 ± 4.5	small↑**[a]	3.3 ± .6.0	trivial ↑
SJ	1.2 ± 7.7	trivial ↑	5.4 ± 2.5	small↑**[a]	6.2 ± 5.3	small ↑**[a]
DJ 40	−0.4 ± 6.7	trivial ↓	1.0 ± 6.9	trivial↑	6.1 ± 7.7	small ↑**[a,b]
Peak power	2.6 ± 5.2	trivial ↑	8.1 ± 10.9	small ↑**[a]	6.1 ± 2.8	small ↑**
Power 40/80 kg	5.9 ± 8.1	small ↑**	10.1 ± 8.7	small ↑***	12.6 ± 9.4	sm/mod ↑***[a]
30 m sprint	−0.5 ± 1.8	trivial ↑[b]	0.7 ± 1.3	trivial ↓	−1.3 ± 1.7	small↑**[b]
20–30 m flying	0.5 ± 2.0	trivial ↓	−0.2 ± 2.5	trivial ↓	−1.5 ± 2.0	small ↑**[a]
Body composition (% change from baseline)						
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 ↑
Musculus vastus lateralis fascicle angle	2.2 ± 5.7	trivial ↑	2.0 ± 5.6	trivial ↑	5.4 ± 6.9	small ↑**[a,b]
Musculus vastus lateralis fascicle length	0.2 ± 7.1	trivial ↑	1.7 ± 6.7	trivial ↑	−0.4 ± 5.9	trivial ↓
Musculus vastus lateralis thickness	2.8 ± 4.0	trivial ↑	3.8 ± 4.8	small ↑**	6.1 ± 3.3	small ↑***[a]
Musculus 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 $P < 0.05$.
Differences between groups are marked with numbers:
[a]Different from OWL.
[b]Different from FSPT.
[c]Different from MSPT.

Changes in musculus 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 = 0.32 ± 0.22), SJ height (ES = 0.22 ± 0.27), CMJ height (ES = 0.22 ± 0.25) and loaded CMJ peak power (ES = 0.23 ± 0.35) compared with the OWL group. The OWL group showed improved 30-m sprint performance (ES = 0.20 ± 0.25) 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 = 0.40 ± 0.22), SJ height (ES = 0.26 ± 0.27), loaded jump power (40/80 kg; ES = 0.28 ± 0.31), DJ height (ES = 0.33 ± 0.31), 20–30 m flying sprint performance (ES = 0.30 ± 0.25), fascicle angle (ES = 0.25 ± 0.40), and musculus vastus lateralis thickness (ES = 0.24 ± 0.22). MSPT was also more effective than FSPT in increasing DJ height (ES = 0.26 ± 0.33), 30-m sprint performance (ES = 0.34 ± 0.24), and fascicle angle (ES = 0.26 ± 0.41).

DISCUSSION

In the present study, we observed that OWL was statistically inferior to FSPT in improving SJ and CMJ height, peak power during loaded CMJ, and 1RM squat. In contrast, MSPT, that is, 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 (two to three sessions per week). The intervention period was short (8 wk), 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 biarticular 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, because 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 wk 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 ROM 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 DJ performance (vertical rebound jump height) and sprint running ability (and was clearly better than OWL). The muscle thickness of musculus rectus femoris and musculus 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, whereas 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 adaptations.

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 DJ 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 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, whereas 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., DJ). 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.

CONCLUSIONS

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.

We would like to thank Magnus Midttun, Yngve Apneseth, Lene Puntervold, Charlotte Krohn, Vebjørn Vingsand, Line Rønningen, Marte Mo Anderssen, Jon Aase, Sindre Madsgaard and Annbjørg Engeseth for supervising the athletes during the training sessions, and all the athletes for their hard work.

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

REFERENCES

1. Aagaard P, Andersen JL, Dyhre-Poulsen P, et al. A mechanism for increased contractile strength of human pennate muscle in response to strength training: changes in muscle architecture. *J Physiol*. 2001;534(Pt. 2):613–23.
2. Alegre LM, Jiménez F, Gonzalo-Orden JM, Martin-Acero R, Aguado X. Effects of dynamic resistance training on fascicle length and isometric strength. *J Sports Sci*. 2006;24(5):501–8.
3. Amiridis IG, Martin A, Morlon B, et al. Co-activation and tension-regulating phenomena during isokinetic knee extension in sedentary and highly skilled humans. *Eur J Appl Physiol Occup Physiol*. 1996;73(1–2):149–56.
4. Arabatzi F, Kellis E. Olympic weightlifting training causes different knee muscle-coactivation adaptations compared with traditional weight training. *J Strength Cond Res*. 2012;26(8):2192–201.
5. Arabatzi F, Kellis E, Saèz-Saez De Villarreal E. Vertical jump biomechanics after plyometric, weight lifting, and combined (weight lifting + plyometric) training. *J Strength Cond Res*. 2010; 24(9):2440–8.
6. Blazevich AJ, Cannavan D, Coleman DR, Horne S. Influence of concentric and eccentric resistance training on architectural adaptation in human quadriceps muscles. *J Appl Physiol (1985)*. 2007; 103(5):1565–75.
7. Blazevich AJ, Gill ND, Bronks R, Newton RU. Training-specific muscle architecture adaptation after 5-wk training in athletes. *Med Sci Sports Exerc*. 2003;35(12):2013–22.
8. Carlock JM, Smith SL, Hartman MJ, et al. The relationship between vertical jump power estimates and weightlifting ability: a field-test approach. *J Strength Cond Res*. 2004;18(3):534–9.
9. Channell BT, Barfield JP. Effect of Olympic and traditional resistance training on vertical jump improvement in high school boys. *J Strength Cond Res*. 2008;22(5):1522–7.
10. Chaouachi A, Hammami R, Kaabi S, Chamari K, Drinkwater EJ, Behm DG. Olympic weightlifting and plyometric training with children provides similar or greater performance improvements than traditional resistance training. *J Strength Cond Res*. 2014; 28(6):1483–96.
11. English KL, Loehr JA, Lee SM, Smith SM. Early-phase musculoskeletal adaptations to different levels of eccentric resistance after 8 weeks of lower body training. *Eur J Appl Physiol*. 2014; 114(11):2263–80.
12. Friedmann-Bette B, Bauer T, Kinscherf R, et al. Effects of strength training with eccentric overload on muscle adaptation in male athletes. *Eur J Appl Physiol*. 2010;108(4):821–36.
13. Garhammer J. Power production by Olympic weightlifters. *Med Sci Sports Exerc*. 1980;12(1):54–60.
14. Garhammer J, Takano B. Training for weightlifting. In: Komi PV, editor. *Strength and Power in Sports*. 2nd ed. Blackwell Science Ltd; 2003. p. 502–15.
15. Hackett D, Davies T, Soomro N, Halaki M. Olympic weightlifting training improves vertical jump height in sportspeople: a systematic review with meta-analysis. *Br J Sports Med*. 2016;50(14):865–72.
16. Haugen T, Tonnessen E, Seiler S. Correction factors for photocell sprint timing with flying start. *Int J Sports Physiol Perform*. 2015;10(8):1055–7.
17. Haugen TA, Tonnessen E, Svendsen IS, Seiler S. Sprint time differences between single- and dual-beam timing systems. *J Strength Cond Res*. 2014;28(8):2376–9.
18. Hoffman JR, Cooper J, Wendell M, Kang J. Comparison of Olympic vs. traditional power lifting training programs in football players. *J Strength Cond Res*. 2004;18(1):129–35.
19. Hopkins WG. Spreadsheets for analysis of validity and reliability. *Sport Science*. 2015;19:36–42.
20. Hopkins WG, Marshall SW, Batterham AM, Hanin J. Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc*. 2009;41(1):3–13.
21. Isner-Horobeti ME, Dufour SP, Vautravers P, Geny B, Coudeyre E, Richard R. Eccentric exercise training: modalities, applications and perspectives. *Sports Med*. 2013;43(6):483–512.
22. Kawakami Y, Abe T, Fukunaga T. Muscle-fiber pennation angles are greater in hypertrophied than in normal muscles. *J Appl Physiol (1985)*. 1993;74(6):2740–4.
23. Lueders TN, Zou K, Huntsman HD, et al. The $\alpha7\beta1$-integrin accelerates fiber hypertrophy and myogenesis following a single bout of eccentric exercise. *Am J Physiol Cell Physiol*. 2011;301(4): C938–46.
24. Luteberget LS, Raastad T, Seynnes O, Spencer M. Effect of traditional and resisted sprint training in highly trained female team handball players. *Int J Sports Physiol Perform*. 2015;10(5):642–7.
25. MacKenzie SJ, Lavers RJ, Wallace BB. A biomechanical comparison of the vertical jump, power clean, and jump squat. *J Sports Sci*. 2014;32(16):1576–85.
26. Martineau LC, Gardiner PF. Insight into skeletal muscle mechanotransduction: MAPK activation is quantitatively related to tension. *J Appl Physiol (1985)*. 2001;91(2):693–702.
27. McBride JM, Haines TL, Kirby TJ. Effect of loading on peak power of the bar, body, and system during power cleans, squats, and jump squats. *J Sports Sci*. 2011;29(11):1215–21.

28. McBride JM, Skinner JW, Schafer PC, Haines TL, Kirby TJ. Comparison of kinetic variables and muscle activity during a squat vs. a box squat. *J Strength Cond Res*. 2010;24(12):3195–9.
29. McBride JM, Triplett-McBride T, Davie A, Newton RU. A comparison of strength and power characteristics between power lifters, olympic lifters, and sprinters. *J Strength Cond Res*. 1999; 13(1):58–66.
30. Moore CA, Schilling BK. Theory and application of agumented eccentric loading. *Strength and Conditioning Journal*. 2006;27(5): 20–7.
31. Morales J, Sobonya S. Use of submaximal repetition tests for predicting 1-RM strength in class athletes. *J Strength Cond Res*. 1996;10(3):186–9.
32. Papadopoulos C, Theodosiou K, Bogdanis GC, et al. Multiarticular isokinetic high-load eccentric training induces large increases in eccentric and concentric strength and jumping performance. *J Strength Cond Res*. 2014;28(9):2680–8.
33. Pereira MI, Gomes PS. Movement velocity in resistance training. *Sports Med*. 2003;33(6):427–38.
34. Pipes TV, Wilmore JH. Isokinetic vs isotonic strength training in adult men. *Med Sci Sports*. 1975;7(4):262–74.
35. Ratamess NA, Beller NA, Gonzalez AM, et al. The effects of multiple-joint isokinetic resistance training on maximal isokinetic and dynamic muscle strength and local muscular endurance. *J Sports Sci Med*. 2016;15(1):34–40.
36. Reeves ND, Maganaris CN, Longo S, Narici MV. Differential adaptations to eccentric versus conventional resistance training in older humans. *Exp Physiol*. 2009;94(7):825–33.
37. Roig M, O'Brien K, Kirk G, et al. The effects of eccentric versus concentric resistance training on muscle strength and mass in healthy adults: a systematic review with meta-analysis. *Br J Sports Med*. 2008;43:556–68.
38. Sharp RL, Troup JP, Costill DL. Relationship between power and sprint freestyle swimming. *Med Sci Sports Exerc*. 1982;14(1):53–6.
39. Sheppard J, Hobson S, Barker M, et al. The effect of training with accentuated eccentric load counter-movement jumps on strength and power characteristics of high-performance volleyball players. *Int J Sports Sci Coach*. 2008;3(3):355–63.
40. Solberg PA, Hopkins WG, Ommundsen Y, Halvari H. Effects of three training types on vitality among older adults: a self-determination theory perspective. *Psychol Sport Exerc*. 2012;13:407–17.
41. Suchomel TJ, Comfort P, Stone MH. Weightlifting pulling derivatives: rationale for implementation and application. *Sports Med*. 2015;45(6):823–39.
42. Tricoli V, Lamas L, Carnevale R, Ugrinowitsch C. Short-term effects on lower-body functional power development: weightlifting vs. vertical jump training programs. *J Strength Cond Res*. 2005; 19(2):433–7.
43. Vikne H, Refsnes PE, Ekmark M, Medbo JI, Gundersen V, Gundersen K. Muscular performance after concentric and eccentric exercise in trained men. *Med Sci Sports Exerc*. 2006; 38(10):1770–81.
44. Vogt M, Hoppeler HH. Eccentric exercise: mechanisms and effects when used as training regime or training adjunct. *J Appl Physiol (1985)*. 2014;116(11):1446–54.
45. Wilson GJ, Walshe AD, Fisher MR. The development of an isokinetic squat device: reliability and relationship to functional performance. *Eur J Appl Physiol Occup Physiol*. 1997;75(5): 455–61.

APPLIED SCIENCES