Helland, C., Hole, E., Iversen, E., Olsson, M. C., Seynnes, O. R., Solberg, P. A., Paulsen, G. (2017). Training Strategies to Improve Muscle Power: Is Olympic-style Weightlifting Relevant?. *Medicine & Science in Sports & Exercise, 49*, 736-745.

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http://dx.doi.org/10.1249/MSS.0000000000001145

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http://dx.doi.org/10.1249/MSS.0000000000001145

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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29

30 **ABSTRACT**

31 **Introduction**

32 This efficacy study investigated the effects of (1) Olympic-style weightlifting (OWL), (2)

33 motorized strength and power training (MSPT), and (3) free weight strength and power

34 training (FSPT) on muscle power.

35

36 **Methods**

37 Thirty-nine young athletes (20±3 yr.; ice hockey, volleyball and badminton) were randomized

38 into the three training groups. All groups participated in 2-3 sessions/week for 8 weeks. The

39 MSPT and FSPT groups trained using squats (two legs and single leg) with high force and

40 high power, while the OWL group trained using clean and snatch exercises. MSPT was

41 conducted as slow-speed isokinetic strength training and isotonic power training with

42 augmented eccentric load, controlled by a computerized robotic engine system. FSPT used

43 free weights. The training volume (sum of repetitions x kg) was similar between all three

44 groups. Vertical jumping capabilities were assessed by countermovement jump (CMJ), squat

45 jump (SJ), drop jump (DJ), and loaded CMJs (10-80 kg). Sprinting capacity was assessed in a

46 30 m sprint. Secondary variables were squat 1-repetition-maximum, body composition and

47 quadriceps thickness and architecture.

48

49 **Results**

50 OWL resulted in trivial improvements, and inferior gains compared to FSPT and MSPT for

51 CMJ, SJ, and DJ. MSPT demonstrated small, but robust effects on SJ, DJ and loaded CMJs

52   (3-12%). MSPT was superior to FSPT in improving 30 m sprint performance. FSPT and

53   MSPT, but not OWL, demonstrated increased thickness in the vastus lateralis and rectus

54   femoris (4-7%).

55

56   **Conclusion**

57   MSPT was time-efficient and equally or more effective than FSPT training in improving

58   vertical jumping and sprinting performance. OWL was generally ineffective and inferior to

59   the two other interventions.

60

61

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

88   vertical jumping abilities after 8 weeks of training in recreationally trained students. OWL

89   was found superior to traditional strength training (leg extension, half-squats and leg press).

90   Finally, Chaouachi et al. (10) recruited boys aged 10 to 12 years and reported that two sessions

91   per week of OWL over 12 weeks was superior to traditional strength training (squats and

92   lunges) in improving isolated knee-extensor power (300 $°·s^{-1}$) and balance, but not for

93   improving jumping and sprinting capabilities.

94

95   In summary, few studies have investigated the training effects of OWL (and derivative

96   exercises) for improving jumping and sprinting properties, and the results of these studies are

97   ambiguous. Only one study involved athletes (18), and only two of the studies controlled for

98   training volume (4,10). Thus, in contrast to what has been advocated in reviews primarily

99   based on cross-sectional studies and power measurements during lifting (14,41), limited

100   longitudinal experimental evidence supports OWL as being superior to other strength and

101   power training exercises for improving lower body muscle power in athletes.

102

103   **Isokinetic squat exercises**

104   In essence, strength training is about challenging the ability to generate maximal force (or

105   joint torque). Unlike traditional isotonic resistance exercises (free weights), isokinetic

106   resistance exercises have the advantage that maximal force can be exerted throughout the

107   range of motion (ROM; (34)). Numerous investigators have examined isokinetic exercises

108   and training, but longitudinal experiments typically involved only single joint movements

109   (33). Isolated, single joint exercises may, however, have very limited performance value for

110   athletes. Isokinetic multi-joint exercises should have much greater potential to transfer to

111   sport performance, but only a few studies have investigated this hypothesis (45). Four decades

112   ago Pipes and Wilmore (34) investigated isokinetic leg press and bench press devices that

113 allowed maximal force-generation in full ROM. Compared to traditional, isotonic strength

114 training, the isokinetic training induced superior improvements in sprint, jumping and

115 throwing performance in adult men (non-athletes). Intriguingly, the isokinetic training was

116 purely concentric (no eccentric phase). More recently, isokinetic strength training (concentric

117 and eccentric) was investigated and reportedly improved performance in functional tests,

118 although no comparisons were made against traditional strength training (only a non-

119 exercising control group; (32,35,38)).

120

121 The squat exercise – commonly considered more functional than the leg press – is the

122 cornerstone of the strength training regimes of many athletes. Isokinetic squat devices have

123 been developed and described (28,45), but to the best of our knowledge, no previous studies

124 have investigated the effects of isokinetic squat resistance training on strength and power in

125 athletes. Therefore, a goal of the present study was to investigate the effects of isokinetic

126 squat exercise training in comparison to OWL and free weight strength and power training

127 (FSPT).

128

129 **Eccentric exercise training**

130 Muscle force may be higher during eccentric than concentric contractions (3). High-force

131 eccentric contractions therefore have a larger potential for stimulating muscle cells via

132 mechano-sensitive pathways (23,26). In line with this, researchers have concluded that

133 eccentric exercise is superior to concentric exercise regimes in promoting muscle growth and

134 strength (11,21,37,43,44). Notably, eccentric training will primarily induce augmented

135 eccentric strength, and the transfer to concentric strength seems more variable (37).

136 Furthermore, few studies have investigated the effects of eccentric training in athletes. Vikne

137 et al. (43) recruited a mix of recreationally trained individuals and elite athletes engaged in

138 power-sports, such as track and field and powerlifting. They demonstrated more hypertrophy

139 in the exercised m. biceps brachii muscle after eccentric training compared to concentric

140 training over a 12-week study, but 1 repetition maximum (1RM) and maximal concentric

141 velocity at submaximal loads increased equally in both groups. In power-sports athletes (e.g.,

142 track and field), Friedmann-Bette et al. (12) compared eccentric overload training, i.e.,

143 maximal eccentric and concentric loads, with traditional isotonic training in a one-legged

144 knee-extension exercise. The results were equivocal, but type IIX fiber hypertrophy and

145 improved vertical jump performance were observed in the eccentric overload group only.

146 These results are intriguing, but isolated knee-extension is an open-chain exercise that may

147 have limited transfer to multi-joint jumping and sprinting abilities. In a recent study,

148 Papadopoulos et al. (32) used an isokinetic, eccentric bilateral leg press exercise and reported

149 robust effects on drop jump performance. However, this study was conducted on untrained

150 students with no active control groups, which raises questions about the effectiveness of this

151 intervention in athletes when compared to other forms of resistance exercise training. To the

152 best of our knowledge, no previous study has investigated the effects of squat-jump training

153 with computer-controlled augmented eccentric loading in athletes.

154

155 **Purpose**

156 The purpose of the present study was to examine training strategies for improving lower body

157 muscle power in the form of vertical jumping and horizontal sprinting abilities. We designed

158 and tested three intervention strategies in well-trained young athletes: (1) Olympic-style

159 weightlifting (OWL), (2) motorized strength and power training (MSPT), i.e., isokinetic

160 resistance exercise combined with augmented eccentric load power training, and (3) free

161 weight strength and power training (FSPT).

162

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 ($\geq$ 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.

188 Before the tests, participants rested for a minimum of 24 hours. All tests were performed after

189 a standardized warm-up of 5 minutes submaximal cycling (100-150 W), followed by 3-5 sub-

190 maximal CMJ. Two to three submaximal 40 m runs were conducted before the 30 m sprint

191 test. Body composition, muscle thickness and muscle architecture were assessed in the fasted

192 state between 7-10 a.m. on test days.

193

194 After the pre-tests, the participants were randomly allocated into three groups: Olympic-style

195 weightlifting (OWL; n=13, 4 women and 9 men), motorized strength and power training

196 (MSPT; n=13, 3 women and 10 men), and free weight strength and power training (FSPT;

197 n=13, 3 women and 10 men). The athletes continued their regular off-season training, but

198 were instructed not to conduct any strength and power training apart from the intervention

199 programs. Due to the complexity of the athletes' training programs, we did not quantify their

200 total training loads. In order to counteract possible group allocation bias, the group

201 randomization process was stratified by sex, sport and CMJ (jump height).

202

203 Prior to the first training session, all participants took part in two separate lifting-technique

204 courses (of 1-2 hours each). The intention was primarily to ensure that the participants had

205 proper and similar lifting-technique skills. Secondly, we aimed to identify individual flaws

206 and weaknesses in the participants' lifting techniques and provide feedback on how to

207 improve. The coaches who supervised the familiarization training continued to provide

208 technique supervision and correction during the intervention period.

209

210 **Intervention programs**

211 The participants underwent an 8-week, progressive training program, involving 21 sessions

212 (Table 1). During the first three weeks, participants completed two similar strength and power

213 training sessions per week. Thereafter the training frequency increased to three sessions per

214 week, including two combined strength and power training sessions, and one power training

215 session.

216

217 The training programs were designed to ensure equal training volumes between groups: sum

218 of repetitions x load on bar (kg). To achieve an equal training volume the OWL group was

219 assigned to perform the highest number of repetitions per session, while the MSPT group did

220 the least (due to the higher force per repetition in this technique). Inter-set and inter-exercise

221 rest periods were always 3 minutes. For the training sessions that combined strength and

222 power training (Table 1), the mean durations were approximately 25, 35 and 45 minutes for

223 the MSPT, FSPT and OWL sessions, respectively. The loads in the MSPT group were

224 calculated from the mean concentric force generated in each repetition, which were recorded

225 and digitally stored (1080 Quantum synchro, 1080 Motion AB, Stockholm, Sweden).

226

227 Generally, the training programs combined heavy lifts (strength) with lighter load power

228 training (Table 1). All training exercises were conducted with the intention to move as fast as

229 possible in the concentric phase, irrespective of load. The OWL group applied the heaviest

230 loads possible without compromising adequate lifting techniques (repetition maximum,

231 [RM]). The FSPT group applied RM loads during the heavy strength training. The MSPT

232 group conducted isokinetic squats with maximal effort in each repetition. For the MSPT and

233 FSPT groups, the power-training loads were reduced from 60% to 40% to 20% of squat 1RM

234 during the training period (20%, 15% and 10% for the single leg exercises; Table 1).

235

236 In the first 3 weeks, the heavy load strength training exercises were followed by power

237 training exercises in the MSPT and FSPT groups, while in weeks 4-8 the sessions started with

238 power training exercise (jump squats; Table 1). After the initial 3 weeks, a low volume power

239 session was added and conducted on every third training day (Table 1). For the OWL group

240 we chose power cleans, hang cleans and hang snatches, because these exercises are conducted

241 with relatively low loads and high velocity movements (Table 1). In contrast to the other

242 groups, the OWL group participants were motivated to increase the loads in these "power

243 sessions" during the training intervention (applying the heaviest loads possible in all

244 sessions). The rationale for this was based on the observations of McBride et al. (27) that

245 reported the highest power in the jump squat at low loads (only body weight), while the

246 opposite was the case for power cleans; the highest power was reached at the heaviest load

247 (90% of 1RM).

248

249 Olympic-style weightlifting

250 OWL included full cleans with front squat, hang cleans, power jerk behind the neck, full

251 snatches and hang snatches (Table 1). The exercises and combinations were based on best

252 practice at the Norwegian Olympic Training Center (Oslo, Norway). The idea was to combine

253 exercises with a focus on different ranges of motions (ROM). For example, the clean with

254 front squat ensures large knee and hip ROM and allows for quite heavy weights, while the

255 power jerk behind the neck, in contrast, involves a small ROM and a very rapid movement.

256 The snatch, hang snatch and hang clean were considered to be exercises that lay in between

257 the previously-mentioned exercises in terms of ROMs and loads.

258

259 Motorized strength and power training

260 A computerized robotic engine system (1080 Quantum synchro, 1080 Motion AB,

261 Stockholm, Sweden) controlled the load for the MSPT group. The robotic engine was

262 attached to a custom-made Smith machine.

263

264   The strength training was conducted as isokinetic squat training. The concentric velocity was

265   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

266   the intervention period (Table 1). The participants were instructed to switch from eccentric to

267   concentric phases with maximal effort and keep on pushing maximally until they reached the

268   upright position. The eccentric phase was always isotonic, with a velocity of less than 1.0 m/s.

269   The participants were instructed to lower the bar in a slow, controlled manner (~0.4-0.5 m/s).

270   The eccentric load was individually adjusted to match the concentric force generated; i.e., if

271   the mean concentric force for the full ROM was 1000 N, the constant eccentric load was set to

272   1000 N. The participants received feedback on their performance after each set via graphs

273   displaying the mean concentric force (N) for each repetition and the whole set.

274

275   Power training was conducted as CMJ with external loads (countermovement to half squat

276   depth). The loads were isotonic and set to 20-60% of the participant's squat 1RM (10-20% for

277   single leg CMJ; see Table 1). The eccentric load was 20-40% higher than the concentric load

278   (increasing from 20% to 30% and finally 40%; see Table 1). The robotic engine system

279   seamlessly switched on the eccentric overload when the eccentric velocity reached <0.2 m/s.

280   This allowed for continuous jumping in the five repetitions per set. The participants received

281   feedback on their performance after each set via graphs displaying the mean concentric power

282   (W) for each repetition and the whole set.

283

284   Free weight strength and power training

285   The FSPT was designed to be as simple as possible, and was identical to the MSPT group,

286   except for the use of free weights (isotonic) instead of a Smith machine (Table 1). We chose

287   free weights because most high-level athletes generally favor this over the Smith machine.

288

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

312 A linear encoder was used to assess vertical power during loaded CMJs (Musclelab Linear

313 Encoder, Ergotest Innovation, Porsgrunn, Norway). The encoder's string was mounted to the

314 bar, and the device measured the vertical displacement (d) and velocity (v) during the

315 concentric phase of the jump (200 Hz sampling rate; 0.019 mm resolution). The power output

316 (P) was estimated on the system mass (m), i.e., 90% of body mass and the external mass ($v =$

317 d/t; acceleration $[a] = v/t$, force $[F] = m \cdot g + m \cdot a$; $P = F \cdot v$). A concentric force-velocity

318 relationship was established and peak power could be estimated (best fit polynomial; software

319 from Ergotest Innovation). With the instruction to jump as high as possible, the participants

320 completed three CMJs at each load with ~5 seconds between each jump and 2 min between

321 sets. Participants performed the first set without external load (body weight and a plastic stick

322 [~300 g]), and then the female and male participants increased the load by 10 and 20 kg,

323 respectively. The women progressed to 60 kg and the men to 80 kg, or until the lifting

324 technique was judged inadequate by the test leader. The attempt with highest peak power

325 from each load was used for further analysis.

326

327 Squat

328 For measurements of 1RM in parallel squat, we used a Smith machine (Multipower,

329 Technogym, Cecena FC, Italy). The first 1RM attempt was conducted after two warm-up lifts

330 at ~85% and one repetition at ~92.5 % of expected 1RM. Warm-up sets and attempts were

331 separated by 3 minutes of rest. If the 1RM attempt was successful, the load was increased by

332 2.5-5% until the test leader predicted failure on the next attempt. To ensure the same squat

333 depth from pre to post testing, we measured the distance from the floor to the bar. The

334 distance was marked with a pen, providing visual feedback for the test leader.

335

336 Lean mass measurements and ultrasound measurements

337   Body composition was assessed using a narrow angle fan beam Lunar iDXA scan (DXA; GE-

338   Helthcare, Madison, WI, USA). The iDXA was calibrated daily according to the

339   manufacture's guidelines. The iDXA machine automatically chose scanning mode, with all

340   athletes scanned in the standard mode. The images were analyzed with enCORE software

341   (version 14.10.022, GE-Helthcare). The software automatically defined the different body

342   segments: arms, trunk and legs. However, all scans were manually controlled and adjusted to

343   ensure optimal pre- and post-training comparisons.

344

345   Muscle thickness and architecture of m. vastus lateralis and muscle thickness of m. rectus

346   femoris in the dominant leg were assessed using B-mode ultrasonography (probe size of 4.5

347   cm and 8-17 MHz scanning frequency; GE Logiq 9, GE Healthcare, Little Chalfont, UK). The

348   scans were obtained at 50% of the femur length (1). Two to three images were captured at

349   each position. The position of the probe was marked on the skin (hydrophobic pen) and

350   subsequently marked on a soft transparent plastic sheet superimposed on the thigh.

351   Landmarks such as moles and scars were also marked on the plastic sheets for relocation of

352   the scanned areas during post-training measurements. Both longitudinal and cross sectional

353   images were obtained from m. vastus lateralis, while only transverse images were obtained

354   from m. rectus femoris. Transverse images were used for assessing muscle thickness, whereas

355   longitudinal images were used for assessing pennation angle and fascicle length. ImageJ

356   software was used for image analyses (Wayne Rasband, National Institutes of Health,

357   Bethesda, MD, USA), where muscle thickness was measured at three different sites on the

358   transverse image and an average of these measurements was used for further calculations.

359   Pennation angle was measured three times at the same site on the longitudinal image and an

360   average was used for further calculations. Fascicle length was calculated from the following

361   equation: Fascicle length = thickness/sin(pennation angle). The thickness value was the

362 average of three measurements at three sites on the longitudinal image. For both transverse

363 and longitudinal images, the pre and post images were analyzed at the same time and great

364 care was taken to match the thickness and angle measurements sites on the pre and post

365 images. The assessor was blinded for the participants' group affiliations.

366

367 **Nutrition**

368 To ensure adequate energy and protein intake, a high-protein bar was ingested after each

369 training session (20 g protein, 31 g carbohydrates and 5 g fat; Yt, Tine, Oslo, Norway).

370

371

372 **Statistical analysis**

373 A priori power calculations with a standard deviation (SD) of 5% suggested 15 participants

374 were needed in each group in order to detect a difference of 5% with 80% power (GraphPad

375 StatMate version 2.00, GraphPad Software, Ca, USA). We ended up with 13 athletes in each

376 group, which gave us 80% power to detect a difference of 6% between groups with a standard

377 deviation of 5% (e.g., CMJ).

378

379 For all performance tests the means of the two pre-tests were used as baselines for further

380 calculations. Based on the two pre-tests, coefficient of variation (CV) and intraclass

381 correlation (ICC) were calculated for each test (19). The linear mixed model procedure in

382 SPSS Statistics (Version 21, IBM Corp. Armonk, NY, USA) was used to analyse the changes

383 and differences in the means, while adjusting for the effects of covariates in the three groups:

384 baseline level, bodyweight and training volume. A more detailed description of the

385 procedures used can be found elsewhere (40). Changes within groups are reported as % ± SD.

386 The magnitudes of within-group changes and between-group differences were assessed as

387 effect sizes (ES; mean change or difference divided by baseline SD of all subjects), and

388   evaluated with a modification of Cohen's scale that aligns with the effect sizes used for bi-

389   serial correlations: <0.2, trivial; 0.2-0.6, small; 0.6-1.2, moderate; >1.2, large (20). Inferences

390   were based on the assumption of the normality of sampling distribution of the differences. To

391   make inferences about true values of effects in the population studied, we used non-clinical

392   magnitude-based inference rather than null-hypothesis significance testing (20). Magnitudes

393   were evaluated mechanistically: if the confidence interval overlapped substantial positive and

394   negative values (0.2 and -0.2), the effect was deemed unclear. The effect is shown as the

395   difference or change with the greatest probability, and the probability is shown qualitatively

396   using the following scale: 25-75%, possibly (*); 75-95%, likely (**); 95-99.5%, very likely

397   (***); > 99.5%, most likely (20).

398

399   **RESULTS**
400   Adequate reliability was established for all performance tests. Loaded CMJs, DJ and SJ had

401   the highest CVs of 5-10%, and lowest ICCs of 0.92-0.96, while 1RM squat, CMJ, and 30 m

402   sprint had the lowest CVs: 1-5%, and highest ICCs: 0.96-0.98. Moreover, there were no

403   performance improvements from pre 1 to pre 2 for any tests (all participants pooled).

404

405   No group differences were detected before the intervention period (Table 2). The total

406   training volume (sum of repetitions x load [kg]) during the intervention period was similar

407   between the groups (Table 2).

408

409   Except for SJ with heavy loads (40 kg for women and 80 kg for men) 8 weeks of OWL did

410   not affect vertical jumping or sprinting performance (Table 3). Body composition was

411   unaltered, and no clear architectural changes were demonstrated in m. rectus femoris and m.

412   vastus lateralis.

413

414   MSPT demonstrated overall small but clear changes in both vertical jumping and sprinting

415   performance (Table 2). Total lean mass and bone mass increased significantly (p<0.05), but

416   the changes in whole body composition were trivial after 8 weeks of MSPT. However, the

417   thickness of m rectus femoris and m. vastus lateralis increased. A small increase in fascicle

418   angle in m. vastus lateralis was detected, although fascicle length was unaltered.

419

420   FSPT induced generally small but clear changes in 1RM squat and vertical jump performance.

421   Performance in the 30 m sprint, however, did not improve after 8 weeks' FSPT training

422   (Table 3). There were no clear changes in body composition, but muscle thickness of m.

423   vastus lateralis and m. rectus femoris increased slightly. Changes in m. vastus lateralis

424   architecture, fascicle angle and length were trivial (Table 3).

425

426   The group comparisons showed that the FSPT group had small, but clear improvements in

427   1RM strength (ES = .32 ± .22), SJ height (ES = .22 ± .27), CMJ height (ES = .22 ± .25) and

428   loaded CMJ peak power (ES = .23 ± .35) compared to the OWL group. The OWL group

429   showed improved 30 m sprint performance (ES = .20 ± .25) compared with the FSPT group,

430   mainly due to a decrease in the FSPT group. The MSPT intervention was superior to OWL in

431   increasing 1RM strength (ES = .40 ± .22), SJ height (ES = .26 ± .27), loaded jump power

432   (40/80 kg; ES = .28 ± .31), DJ height (ES = .33 ± .31), 20-30 m flying sprint performance (ES

433   = .30 ± .25), fascicle angle (ES = .25 ± .40) and m. vastus lateralis thickness (ES = .24 ± .22).

434   MSPT was also more effective than FSPT in increasing DJ height (ES = .26 ± .33), 30 m

435   sprint performance (ES = .34 ± .24), and fascicle angle (ES = .26 ± .41).

436

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 $29\pm11\%$ ($p<0.001$; 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

462   training induced larger gains of lean mass in the arms than the lower body (3.3% vs -0.4%,

463   p<0.05; trivial effects). These results indicate that upper-body muscles were highly active

464   during the OWL training, thereby alleviating the load on the lower body muscles. Indeed, the

465   ability to transfer forces between joints via bi-articular muscles implies the possibility of

466   reducing the work of the lower limb muscles in OWL.

467

468   OWL is kinematically different from both vertical jumping (25) and sprinting (unilateral

469   movement). Thus, the transfer from OWL training to jump and sprint performance is not

470   obvious. Nevertheless, OWL might be more advantageous for improving hip extension

471   moments in joint positions more relevant for sprinting than vertical jumping. Interestingly, the

472   improvement in 30 m sprint was trivial for OWL, but still superior to free weight strength

473   training, due to a slight decrease in performance in the latter group.

474

475   Another possibility for limited improvements from OWL is low eccentric muscle force

476   production, since eccentric muscle actions are possibly more potent in increasing muscle mass

477   than concentric contractions (37). In OWL, the bar must be dropped to the hips or directly to

478   the floor, and the eccentric stimulus for the lower leg muscles is consequently negligible. In

479   addition to myofiber hypertrophy, eccentric-contraction-induced neural and tendon

480   adaptations could plausibly explain the group differences in jumping and sprinting

481   improvements.

482

483   In accordance with our results, Hoffman et al. (18) found no significant improvements in

484   either vertical jumping or sprinting after 15 weeks of OWL training. In contrast to other

485   previous studies (4,9,10,18,42), but similar to the present study, Hoffman et al. recruited well-

486   trained athletes. However, the authors concluded that OWL training was superior to

487   powerlifting training, mostly because the powerlifting group surprisingly showed reductions

488   in their vertical jump height. It seems fair to say that the efficacy of OWL training in athletes

489   warrants further research.

490

491   In the present study, we included OWL exercises only, similar to Chaouahi et al. (10). Other

492   previous investigations have included a mix of exercises, such as squats, lunges and leg press

493   exercises, in addition to the OWL exercises (4,9,18,42). The inclusion of other exercises

494   makes it impossible to conclude that OWL *per se* induced the observable training effects.

495

496   In accordance with the present study, some previous studies equalized or controlled for

497   training volume when comparing OWL with traditional strength and power training (4,10),

498   but not all did so (9,18). Without equal training volume, one cannot exclude the possibility of

499   a dose-response effect, and direct comparisons are not readily possible.

500

501   The motorized strength and power training, using a robotic engine training device, allowed for

502   maximal effort and force generation through the whole range of motion during the slow,

503   isokinetic squat exercises, and augmented eccentric loading during the power training

504   exercises. MSPT induced similar improvements in 1RM squat as did FSPT, but did lead to

505   larger progressions in drop jump performance (vertical rebound jump height) and sprint

506   running ability (and was clearly better than OWL). The muscle thickness of m. rectus femoris

507   and m. vastus lateralis consistently increased in both the MSPT and FSPT groups, but fascicle

508   angle increased only in the MSPT group. Previous studies have shown that various resistance

509   training modalities induce contrasting changes in fascicle angle (6,36). Training regimes

510   involving concentric contractions typically yield a higher angle of pennation with no

511   consistent change in fascicular length, while the opposite findings are observed with eccentric

512 contractions. With equal training volumes across groups, the higher concentric force

513 generation during isokinetic squats seems to have driven these adaptions.

514

515 In contrast to hypertrophic strength training (1,22), power training has been accompanied by

516 no change or a decrease in fascicle angle and an increase in fascicle length (2,7,24). The

517 participants in the present study conducted both heavy strength and power training. Since the

518 fascicle angle increased and fascicle length trivially decreased in the MSPT group, we suggest

519 that the concentric, high-force contractions were the dominating stimulus for the architectural

520 changes. Arguably, hypertrophy was achieved in this group via sarcomerogenesis in parallel,

521 rather than in series. However, fascicle length was calculated using simple trigonometric

522 extrapolation techniques in the present study. Advanced techniques enabling direct

523 measurements may have been more sensitive to changes in this parameter.

524

525 The MSPT group performed power training with an augmented eccentric load (120-140% of

526 the concentric load). The idea was that this would give a stronger stimulus to the

527 neuromuscular system (30). This was, apparently, not the case for the SJ or the CMJ abilities.

528 On the other hand, the MSPT group did experience superior improvements in the DJ test.

529 Intriguingly, a DJ will cause a high eccentric load, quite similar to the augmented eccentric

530 load during the loaded CMJ training. Consequently, the augmented eccentric load training

531 appears to have transferred effectively to drop jump performance. In support of our findings,

532 strategies (e.g., use of rubber bands) to augment eccentric loading during plyometrics are used

533 in practice by athletes (30,39).

534

535 This study has several potential limitations. First, one could argue that it is atypical to train

536 using purely OWL exercises, and their effects could be optimized when combined with

537 traditional strength and power training; similar studies have successfully added squats and leg

538 press exercises to an OWL program (5,9,10,42). However, we chose the present design in

539 order to isolate the effects of OWL. Second, the motorized training included slow velocity,

540 isokinetic squat training and augmented eccentric load jump squat training. The relative

541 contribution of these training modes in terms of performance enhancements cannot be

542 inferred from the present results. Future experiments should investigate these training modes

543 separately. Third, the motorized squat training was an unaccustomed exercise modality for all

544 participants, and we therefore cannot exclude the possibility that some of the performance

545 gains were due to this being a novel stimulus and/or the enhanced feedback on performance.

546 Finally, we calculated the total training volume simply by summarizing the products of the

547 load on the bar and the number of repetitions for each set. This approach may not be optimal

548 when comparing training programs with different exercises, including ballistic exercises (such

549 as OWL).

550

551 **PRACTICAL APPLICATION**

552 In the present study, we demonstrated that using computer-controlled robotic engines for

553 strength and power training was a time-efficient approach to increase vertical jumping and

554 sprinting performance in athletes. Traditional FSPT seemed also effective in improving

555 vertical jumping height, while OWL appeared less effective as a sole training mode. If

556 anything, OWL appeared more favorable in improving sprinting than vertical jumping

557 performance. OWL may work well for certain athletes, but adequate lifting technique is

558 probably an important prerequisite. Moreover, for athletes with already high maximal

559 strength, OWL might be more relevant for improving lower body muscle power and speed

560 than for weaker athletes. It could also be important to combine OWL exercises with exercises

561 focusing on eccentric muscle actions (i.e., drop jumps). For young "power-athletes", such as

562 those recruited in the present study (ice hockey, volleyball and badminton players), we

563 recommend a base of simple heavy strength and power training exercises (e.g., squats) that

564 includes a controlled eccentric phase, to favor muscle growth and maximal force gains.

565

CONCLUSION

567 MSPT was more time-efficient while being equally as effective or superior to FSPT in

568 improving both vertical jumping and sprinting performance. Hence, isokinetic strength

569 training combined with eccentric augmented load power training emerges as an attractive

570 training approach for a wide range of athletes. In contrast, OWL appeared generally

571 ineffective and inferior to traditional FSPT in developing vertical jumping performance in

572 athletes.

573

CONFLICT OF INTEREST

581 The authors declare no conflicts of interest. The results of the present study do not constitute

582 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

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)