The Optimal Load for Maximal Power Production During Lower-Body Resistance Exercises: A Meta-Analysis

Article *in* Sports Medicine · June 2015

DOI: 10.1007/s40279-015-0341-8 · Source: PubMed

Sports Med
DOI 10.1007/s40279-015-0341-8

SYSTEMATIC REVIEW

The Optimal Load for Maximal Power Production During Lower-Body Resistance Exercises: A Meta-Analysis

Marco A. Soriano[1] · Pedro Jiménez-Reyes[1] · Matthew R. Rhea[2] · Pedro J. Marín[3,4]

Abstract
Background The development of muscular power is often a key focus of sports performance enhancement programs.
Objective The purpose of this meta-analysis was to examine the effect of load on peak power during the squat, jump squat, power clean, and hang power clean, thus integrating the findings of various studies to provide the strength and conditioning professional with more reliable evidence upon which to base their program design.
Methods A search of electronic databases [MEDLINE (SPORTDiscus), PubMed, Google Scholar, and Web of Science] was conducted to identify all publications up to 30 June 2014. Hedges' g (95 % confidence interval) was estimated using a weighted random-effect model. A total of 27 studies with 468 subjects and 5766 effect sizes met the inclusion criterion and were included in the statistical analyses. Load in each study was labeled as one of three intensity zones: Zone 1 represented an average intensity ranging from 0 to 30 % of one repetition maximum (1RM); Zone 2 between 30 and 70 % of 1RM; and Zone 3 ≥70 % of 1RM.
Results These results showed different optimal loads for each exercise examined. Moderate loads (from >30 to <70 % of 1RM) appear to provide the optimal load for power production in the squat exercise. Lighter loads (≤30 % of 1RM) showed the highest peak power production in the jump squat. Heavier loads (≥70 % of 1RM) resulted in greater peak power production in the power clean and hang power clean.
Conclusion Our meta-analysis of results from the published literature provides evidence for exercise-specific optimal loads for power production.

Key Points

Heavier loads [≥70 % of one repetition maximum (1RM)] resulted in greater peak power production in the power clean and hang power clean.

Moderate loads (from >30 to <70 % of 1RM) appear to provide the optimal load for power production in the squat exercise.

Lighter loads (≤30 % of 1RM) showed the highest peak power production in the jump squat.

1 Introduction

The development of muscular power is often a key focus of sports performance enhancement programs. The ability to develop significant levels of power contributes to elite performance in many sports-related skills [1, 2]. Thus,

✉ Pedro J. Marín
pjmarin@uemc.es

1 Department of Physical Activity and Sport Sciences, Kinesiology and Biomechanics Laboratory, San Antonio Catholic University of Murcia, Murcia, Spain

2 Human Movement Program, A. T. Still University, Mesa, AZ, USA

3 Laboratory of Physiology, European University Miguel de Cervantes, C/ Padre Julio Chevalier 2, 47012 Valladolid, Spain

4 CyMO Research Institute, Valladolid, Spain

Published online: 11 June 2015

research can help to inform coaches about program design to select the most appropriate training method for developing muscular power.

Wilson et al. [3] demonstrated that athletes who trained at loads that maximized mechanical power achieved the greatest enhancement in dynamic athletic performance. Others have recommended that training with a load that maximizes power output is the best stimulus for further improvements in power [4–7]. Thus, the search for optimal loads for maximizing power is of particular interest for strength and conditioning coaches. Cormie et al. [8] compared different training loads in several different exercises, including the jump squat, squat, and power clean. Their study demonstrated exercise-specific loads for maximizing power for these separate exercises, suggesting that the biomechanical differences between exercises may alter the load–power relationship. Research examining optimal loads have been examined for the jump squat [7, 9, 10], squat [11, 12], and the power clean [13, 14] but only provide fairly large ranges for potential optimal loads for each exercise. Optimal loads for the jump squat are suggested to be somewhere in the range of 0–60 % of 1RM, approximately 60 % of 1RM for the squat, and between 70 and 80 % of 1RM for the power clean. While these ranges offer some direction in selection of optimal load for power output, further analysis of a larger number of studies would be helpful in narrowing the ranges or solidifying appropriate loads for power development. A narrative review by Nuzzo et al. [15] examined maximal power production in different loads.

For many years, researchers and trainers have been trying to gain an in-depth understanding of power production and optimal load in strength–power sports. However, there remains great controversy in the body of knowledge [16, 17]. Indeed, the literature reports a wide spectrum of optimal load for different exercises from 0 to 80 % of 1RM [8, 18, 19]. There is a need to identify the dose–response relationships between intensity and both peak power and optimal load, based on robust scientific evidence.

As the body of literature examining power development expands, it becomes possible for quantitative reviews of literature to integrate and evaluate the findings of each individual study towards the goal of identifying the appropriate training parameters for maximal power production. The meta-analysis represents one such method for combining the results of numerous studies [20]. The purpose of this meta-analysis was to examine different loads and the resultant increase in maximal power production in different exercises, thus integrating the findings of various studies to provide the strength and conditioning professional with more reliable evidence upon which to base their program design.

2 Methods

2.1 Literature Search

A search of electronic databases was conducted to identify all publications on *maximum mechanical power* and *power development* up to 30 June 2014. As a prerequisite, all studies were performed in healthy sports populations including both adolescents and adults (>15 years). The literature search was undertaken using 14 different keywords: “mechanical power”, “maximum power”, “power production”, “power training”, “weight training”, “power development”, “peak power”, “optimal load”, “power–load curve”, “lower body”, “squat”, “jump squat”, “power clean”, and “hang power clean”. Search terms were combined by Boolean logic (AND, OR), with no restrictions on date or language, in MEDLINE (SPORTDiscus), PubMed, Google Scholar, and Web of Science. We also extended the search spectrum to “related articles” and the bibliographies of all retrieved studies. The authors of published papers were also contacted directly if crucial data were not reported in the original papers.

2.2 Inclusion and Exclusion Criteria

The following inclusion criteria were used to select articles for the meta-analysis:

I. The study must have presented absolute data, not relative to body weight or allometric data. The data must have been written in text and tables or shown in figures.

II. The study must have used absolute loads or relative to one repetition maximum (1RM) (maximal strength) in the procedure.

III. The study must have reported “peak power”. Previous researchers have suggested using the peak power term for analyzing lower body performance [10, 21].

IV. The study must have analyzed the power–load spectrum and/or conducted a measure of different loads through the power–load curve.

V. The exercises must have been performed with free weights or a Smith machine. Some researchers suggest that these two modes may not affect the load at which maximum power is generated [10]. Furthermore, these two modes are frequently used in research and training.

VI. The data collection and measurement system must have used a force platform. It has been suggested that ground reaction force measured or calculated using a force platform provides the most accurate way of assessing strength or power qualities during lower-body exercise [22, 23]. Furthermore, body weight must have been included when calculating power to minimize error in the measure [10].

2.3 Methodological Quality of Included Studies

Study quality was evaluated by a standard procedure (see Table 1). Each study was read and ranked from 0 to 5, with the larger number indicating better quality. For each question, a 1 was awarded if the study met the standard. If insufficient description or data were provided to analyze a specific question, a 0 was awarded. The score was then tallied for each of the questions, with the highest score possible equaling 5 out of 5.

2.4 Statistical Methods and Data Extraction

Statistical analyses were performed using the Chi-square (χ^2) test with the Yates correction. For each study, standardized mean differences (Hedges' g) and 95 % confidence intervals (CIs) were computed separately. This was done based on the difference in performance between the training zone and the pooled standard deviation. Hedges' g (95 % CI) was estimated using a weighted random-effect model. When studies reported only standard errors, standard deviations were calculated by multiplying standard errors by the square root of the sample size. Overall outcome for the analyzed conditions was assessed by calculating weighted g averages. The significance limit was defined as $P < 0.05$. Egger's test was used to evaluate possible publication bias in the meta-analysis with the number of included studies >2 [24]. To evaluate the heterogeneity, I^2 was performed. $I^2 = 0$–40 % indicates the absence of heterogeneity, and $I^2 = 30$–60 %, $I^2 = 50$–90 %, and $I^2 = 75$–100 % indicate the presence of moderate, large, and extremely large heterogeneity, respectively [25] All statistical analyses were performed using MIX Pro software version 2.0 (BiostatXL, Sunnyvale, CA, USA) [26].

Since no available meta-analytic evidence favored any power–load model during lower-body resistance exercises (Table 2), we used comparisons (Zone 1 vs. Zone 2, Zone 1 vs. Zone 3, and Zone 2 vs. Zone 3). From 0 to 30 % of 1RM was labeled Zone 1; >30 to <70 % of 1RM Zone 2; and ≥70 % of 1RM Zone 3.

Table 1 Criteria list for the methodological quality assessment

No.	Item	Score
1	Sample description:	0 or 1
	Properties of the subjects (age, weight, height, sex)	
	Definition of the population (athlete, recreationally trained or active subjects, and untrained or sedentary subjects)	
	Training status and training years in strength or power training	
2	Procedure description:	0 or 1
	Detailed description of the test (performed any exercises on loading or unloading conditions)	
	Feedback for developed exercise maximize performance ("as fast as", "quickly")	
	Detailed description of the intervention protocol (randomized order to exercises, developed exercises in different days, developed exercises by the same order for all subjects)	
	Developed a familiarization period with the test (last weeks or last days)	
3	Intervention:	0 or 1
	Defined exercises technique (joint angle, bar position)	
	Defined loading conditions (Smith machine vs. free weights)	
	Defined number of trials to lifts	
	Defined adequate recovery between trials across all lifts	
4	Measurement system, data collection, and data analysis:	0 or 1
	Instrument description (brand of the product, model, origin country)	
	Defined sampling frequency of the product	
	Defined configuration and variable calculation of the product	
	Include body weight in the measure	
	Defined collected software to recording and analyzing data	
5	Results detailed:	0 or 1
	Measure of the central tendency	
	Amount of variation or dispersion from the average	

Table 2 Description of each of the exercises

Exercise	Description
Squat	Subjects set up in a standing position while holding a barbell across their shoulders. Subjects then initiate a downward movement to a knee angle of approximately 90°. That is followed by the initiation of a concentric phase with a triple extension of the knees, hips, and ankles without taking the feet off the floor [8]
Jump squat	Subjects set up in a standing position while holding a barbell across their shoulders. Subjects then initiate the jump squat via a downward eccentric phase to a knee angle of approximately 90° with the inclusion of a stretch-shortening cycle, enhancing a concentric phase of triple extension of the knees, hips, and ankles while lifting the feet from the floor [8]
Power clean	From the starting position (midway up the shin), subjects lift the bar in the vertical plane from the floor, followed by a triple extension of the knees, hips, and ankles, then scoop under and catch the bar on the shoulders with the elbows high in a full squat position [14]
Hang power clean	A power clean variation in which subjects set up in the standing position with the barbell starting approximately in line with the top of the patella, lower the barbell down to a position just above their knee and lift the bar in the vertical plane, rapidly rotate the elbows under the bar, and catch the bar across their shoulders in a semi-squat position. The hang power clean can be performed from a static position with the barbell at the mid-thigh position or just above the knee [52]

3 Results

3.1 Study Characteristics

A flow diagram of the literature search is shown in Fig. 1. According to the above-defined inclusion criteria, we identified 27 independent studies. An overview of these studies is given in Table 3. Quality scores ranged from 4 points (29.6 %) to 5 points (70.4 %).

3.2 Main Meta-Analysis Results

3.2.1 Loading Zones During Squat Exercise

3.2.1.1 Zone 1 Versus Zone 2 The association of Zone 1 versus Zone 2 during squat exercise was investigated in five studies [7, 8, 11, 12, 27] and 403 effect sizes. Peak power output during squat exercise was higher in Zone 2 than in Zone 1, with a pooled effect size (Hedges' g) of 0.47 (95 % CI 0.24–0.70, $P = 0.001$) and no evidence of publication bias ($P = 0.229$) or no heterogeneity among studies ($I^2 = 16.10$ %, $Q = 4.77$, $P = 0.311$) (Figs. 2a, 3).

3.2.1.2 Zone 1 Versus Zone 3 The association of Zone 1 versus Zone 3 during squat exercise was investigated in five studies [7, 8, 11, 12, 27] and 403 effect sizes. Peak power output during squat exercise was no different for Zone 1 and Zone 3, with a pooled effect size (Hedges' g) of 0.03 (95 % CI 0.44–0.51, $P = 0.89$) and no evidence of publication bias ($P = 0.224$) or heterogeneity among studies ($I^2 = 80.10$ %, $Q = 20.10$, $P = 0.001$) (Figs. 2b, 3).

3.2.1.3 Zone 2 Versus Zone 3 The association of Zone 2 versus Zone 3 during squat exercise was investigated in six studies [7, 8, 11, 12, 27, 28] and 366 effect sizes. Peak power output during squat exercise was higher in Zone 2 than in Zone 3, with a pooled effect size (Hedges' g) of −0.344 (95 % CI −0.56 to 0.13, $P = 0.002$) and no evidence of publication bias ($P = 0.209$) or no heterogeneity among studies ($I^2 = 6.93$ %, $Q = 5.37$, $P = 0.372$) (Figs. 2c, 3).

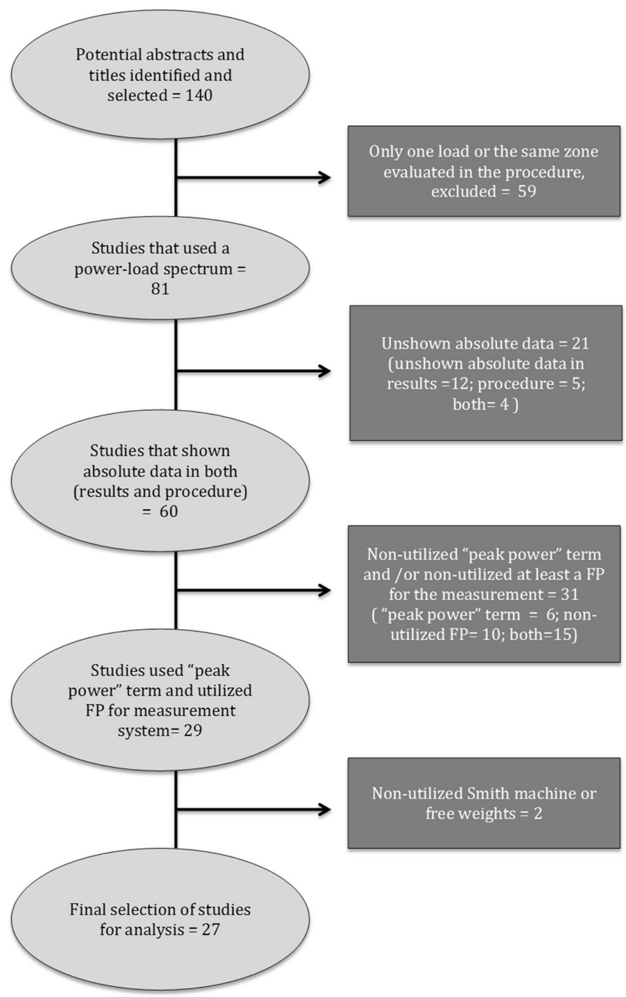

Fig. 1 Summary of the study selection process. *FP* force plate

Table 3 Descriptive characteristics of studies

Study, year	*n*	Sample characteristics (mean ± SD)	Training status (mean ± SD)	Exercise	Measurement system[a]	Power–load spectrum	Quality Score
McBride et al. [37]	28 M	G1 = 20 Age: 21.4 ± 1.0 years BW: 80.13 ± 5.27 kg Elite athletes (mixed) G2 = 8 Age: 22.3 ± 0.8 years BW: 75.6 ± 3.3 kg Recreationally trained	G1 3.9 ± 0.8 years S–P experience 1RM S: 224.6 ± 12.0 kg G2 No experience S–P training 1RM S: 161.3 ± 10.9 kg	JS free (FW) JS (SM)	FP (6) LPT [6]	JS free G1: 0, 9, 18 % 1RM JS free G2: 0, 12, 25 % 1RM JS G1: 30, 60, 90 % 1RM JS G2: 30, 60, 90 % 1RM G1 OL: 0–10 % 1RM G2 OL: 12 % 1RM	4
Jones et al. [36]	26 M	Age: 20.1 ± 1.4 years BW: 80.4 ± 11.2 kg Athletes (baseball)	2.9 ± 0.6 S–P experience 1RM S: 139.8 ± 14.4 kg	JS (FW)	FP (12) 960 Hz	30, 50 % 1RM OL: 30 % 1RM	5
McBride et al. [5]	26 M	Age: 22.7 ± 1.47 years BW: 81.33 ± 4.2 kg Athletes (mixed)	2–4 years S–P experience 1RM S: 148.3 ± 9.3 kg	JS (SM)	FP (6) LPT [1]	30, 55, 80 % 1RM OL: 30 % 1RM	4
Winchester et al. [13]	18 M	Age: 22.2 ± 2.1 years Athletes (American football)	≥1 year S–P experience	PC (FW)	FP (5) 600 Hz	50, 70, 90 % 1RM OL: 70 % 1RM	5
Kawamori et al. [43]	15 M	Age: 22.1 ± 2.0 years BW: 89.4 ± 14.7 kg Athletes (mixed)	≥6 months S–P experience 1RM HPC: 107 ± 18.8 kg	HPC (FW)	FP (9) 600 Hz	30, 40, 50, 60, 70, 80, 90 % 1RM OL: 70 % 1RM	5
Cormie et al. [27]	10 M	Age: 20.0 ± 1.5 years BW: 88.7 ± 15.1 kg Elite athletes (mixed)	≥4 years S–P experience 1RM PC: 112.7 ± 13.1 1RM full S: 171.0 ± 22.0 kg	S, PC, JS (FW)	FP (1) 2-LPTs [1] 1000 Hz	S, JS: 0, 12, 27, 42, 56, 71, 85 % 1RM PC: 30, 40, 50, 60, 70, 80, 90 % 1RM OL (S): 56 % 1RM OL (JS): 0 % 1RM OL (PC): 80 % 1RM	5
Cormie et al. [31]	12 M	Age: 19.8 ± 1.4 years BW: 90.1 ± 14.8 kg Elite athletes (mixed)	1RM S: 170.4 ± 21.7 kg 1RM PC: 112.5 ± 13.2 kg	S, JS, PC (FW)	FP (1) 2-LPTs [1] 1000 Hz	S, JS: 0, 12, 27, 42, 56, 71, 85 % 1RM PC: 30, 40, 50, 60, 70, 80, 90 % 1RM OL (S): 56 % 1RM OL (JS): 0 % 1RM OL (PC): 80 % 1RM	4
Cormie et al. [42]	8 M	Age: 22.8 ± 3.1 years BW: 86.8 ± 18.7 kg Recreationally trained	≥6 months S–P experience 1RM S: 139.7 ± 31.5 kg	JS (FW)	FP (1) 2-LPTs [1] 1000 Hz	30, 90 % 1RM OL: 30 % 1RM	5
Cormie et al. [8]	20 M	Age: 19.8 ± 1.4 years BW: 90.1 ± 14.8 kg Elite athletes (mixed)	1RM S: 170.38 ± 21.72 kg 1RM PC: 112.5 ± 13.15 kg	S, JS, PC (FW)	FP (1) 2-LPTs [1] 1000 Hz	S, JS: 0, 12, 27, 42, 56, 71, 85 % 1RM PC: 30, 40, 50, 60, 70, 80, 90 % 1RM OL (S): 56 % 1RM OL (JS): 0 % 1RM OL (PC): 80 % 1RM	4

Table 3 continued

Study, year	*n*	Sample characteristics (mean ± SD)	Training status (mean ± SD)	Exercise	Measurement system[a]	Power–load spectrum	Quality Score
Kilduff et al. [18]	12 M	Age: 25.0 ± 4.0 years BW: 102.1 ± 11.4 kg Elite athletes (rugby players)	2.5 ± 1.4 years S–P experience 1RM HPC: 107 ± 13 kg	HPC (FW)	FP (10) 500 Hz	30, 40, 50, 60, 70, 80, 90 % 1RM OL: 80 % 1RM	5
Cormie et al. [30]	18 M	Age: 21.4 ± 2.6 years BW: 80.8 ± 16.9 kg Untrained subjects	No experience S–P training 1RM S: 112.8 ± 23.3 kg	JS (FW)	FP (1) 2-LPTs [1] 1000 Hz	0, 18, 37, 55, 74 % 1RM OL: 0 % 1RM	5
Hori et al. [22]	29 M	Age: 21.3 ± 2.7 years BW: 83.6 ± 8.2 kg Athletes (Australian Rules football players)	≥4 months S–P experience 1RM full S: 101 ± 10.4 kg	JS (FW)	FP (11) 200 Hz	0, 40 % 1RM OL: 0 %1RM	4
McBride et al. [38]	10 M	Age: 21.8 ± 1.9 years BW: 79.0 ± 7.1 kg Athletes (mixed)	≥2 years S–P experience 1RM S: 131.8 ± 29.5 kg	JS (FW)	FP (1) 2-LPTs [1] 1000 Hz	0, 20, 40 % 1RM OL: 0 % 1RM	5
McBride et al. [28]	8 M	Age: 24.8 ± 3.2 years BW: 107.6 ± 29.8 kg Elite athletes (powerlifters)	≥3 years S–P experience 1RM S: 200.1 ± 58.9 kg	S (FW)	FP (1) 2-LPTs [1] 1000 Hz	60, 70, 80 % 1RM OL: 60 % 1RM	5
Nuzzo et al. [53]	20 M	G1 = 14 Age: 21.5 ± 1.4 years BW: 85.7 ± 10.6 kg Athletes (mixed)	≥2 years S–P experience 1RM S: 243.3 ± 34.9 kg	JS (FW)	FP (4) 2-LPTs [1] 1000 Hz	0, 13, 27, 42 % 1RM OL: 0 % 1RM	5
Alcaraz et al. [12]	10 M	Age: 22.1 ± 3.6 years BW: 73.9 ± 6.5 kg Athletes (sprinters)	≥2 years S–P experience 1RM S: 199.7 ± 59.1 kg	S (SM)	FP (8) LPT [5] 500 Hz	30, 45, 60, 70, 80 % 1RM OL: 60 % 1RM	5
Dayne et al. [33]	11 M	Age: 15.6 ± 0.5 years BW: 80.5 ± 16.4 kg Athletes (football players)	1RM S: 141.1 ± 28.1 kg	JS (FW)	FP (1) 2-LPTs [1] 1000 Hz	0, 20, 40, 60, 80 % 1RM OL: 0 % 1RM	4
Crewther et al. [32]	30 M	Age: 25.7 ± 2.5 years BW: 107.1 ± 10.1 kg Elite athletes (rugby players)	≥2 years S–P experience 1RM S: 159.5 ± 26.3 kg	JS (FW)	FP (2) LPT [4]	0, 31 % 1RM OL: 0 % 1RM	4
Hansen et al. [34]	18 M	Age: 26.8 ± 4.5 years BW: 104.3 ± 8.5 kg Elite athletes (rugby players)	≥2 years S–P experience 1RM S: 197.15 ± 20.8 kg	JS (FW)	FP (7) 500 Hz	0, 10, 20, 31 % 1RM OL: 0 % 1RM	5
McBride et al. [11]	9 M	Age: 24.7 ± 2.1 years BW: 80.8 ± 7.2 kg	≥2 years S–P experience 1RM PC: 97.1 ± 6.4 kg 1RM S: 138.3 ± 20.9 kg	S, JS, PC (FW)	FP (1) 1000 Hz	S, JS: 0, 10, 20, 30, 40, 50, 60, 70, 80, 90 % 1RM PC: 30, 40, 50, 60, 70, 80, 90 % 1RM OL (S): 50 % 1RM OL (JS): 0 % 1RM OL (PC): 80 % 1RM	5
Comfort et al. [14]	19 M	Age: 21.5 ± 1.4 years BW: 78.8 ± 8.7 kg Athletes (mixed)	≥1 years S–P experience 1RM PC: 84.5 ± 7.3 kg	PC (FW)	FP (13) 1000 Hz	30, 40, 50, 60, 70, 80 % 1RM OL: 70 % 1RM	5

Table 3 continued

Study, year	*n*	Sample characteristics (mean ± SD)	Training status (mean ± SD)	Exercise	Measurement system[a]	Power–load spectrum	Quality Score
Swinton et al. [40]	29 M	Age: 26.3 ± 4.6 years BW: 94.5 ± 13.1 kg Athletes (rugby players)	1RM S: 153.7 ± 20.3 kg	JS (FW)	FP (14) 1200 Hz	0, 20, 40, 60 % 1RM OL: 0 % 1RM	4
Turner et al. [19]	11 M	Age: 25.6 ± 3.3 years BW: 97.3 ± 11.6 kg Elite athletes (rugby players)	≥2 years S–P experience 1RM S: 183.6 ± 19.6 kg	JS (FW)	FP (2) LPT 500 Hz	20, 30, 40, 50, 60, 70, 80, 90, 100 % 1RM OL: 20 % 1RM	5
Caia et al. [29]	30 M	Age: 20.9 ± 2.0 years BW: 84.5 ± 7.0 kg Elite athletes (Australian Rules football players)	≥6 months S–P experience 1RM S: 126.2 ± 17.4 kg	JS (FW)	FP (2) LPT [2] 400 Hz	0, 20, 30, 40 % 1RM OL: 0 % 1RM	5
Nibali et al. [41]	10 M	Age: 29.7 ± 6.2 years BW: 80.7 ± 7.8 kg Recreationally trained	≥1 years S–P experience 1RM S: 137.8 ± 25.3 kg	JS (FW)	FP (2) LPT [3] 200 Hz	7, 15, 22, 29, 36, 44 % 1RM OL: 0 % 1RM	5
Suchomel et al. [45]	17 M	Age: 21.59 ± 1.28 years BW: 87.13 ± 15.6 kg Elite athletes (track and field)	≥2 years S–P experience 1RM HPC: 111.1 ± 20.4 kg	HPC (FW)	FP (3) 500 Hz	30, 45, 65, 80 %1RM OL: 80 %1RM	5
Suchomel et al. [44]	14 M	Age: 21.6 ± 1.3 years BW: 81.5 ± 8.7 kg Recreationally trained	≥2 years S–P experience 1RM HPC: 104.9 ± 15.1 kg	HPC (FW)	FP (3) 500 Hz	30, 45, 65, 80 % 1RM OL: 65 % 1RM	5

1RM one repetition maximum (maximum strength), *BW* body weight, *FP* force platform, *FW* free weights, *G* group, *HPC* hang power clean, *JS* jump squat, *LPT* lineal position transducer, *M* males, *OL* optimal load, *PC* power clean, *S* squat, *SD* standard deviation, *SM* Smith machine, *S–P* strength–power training

[a] (*1*) AMTI BP6001200, Watertown, MA, USA; (*2*) 400 series FP, Fitness Technology, Adelaide, SA, Australia; (*3*) Kistler Quattro Jump 9290AD, Kistler, Wintenthur, Switzerland; (*4*) BNC-2010 National Instruments, NI PCI-6014, Austin, TX, USA; (*5*) AMTI OR5-5 Biomechanics Platform, Watertown, MA, USA; (*6*) Kistler 9287, Amherst, NY, USA; (*7*) AMTI Accupower, Watertown, MA, USA; (*8*) Extensiometric FP (Dinascam-IBV600M), Valencia, Spain; (*9*) AMTI FP, AMT, Newton, MA, USA; (*10*) Kistler 9286AA, Furnborough, UK; (*11*) Performance Plate, Fitness Technology, Adelaide, SA, Australia; (*12*) OR-2000, AMT, Inc., Newton, MA, USA; (*13*) Kistler, version 3.22; CA, USA (*14*) Kistler 9281, B, Winterthur, Switzerland; [*1*] PT5A-150, CTP, Chatsworth, CA, USA; [2] PTA5, CTP, Chatsworth, CA, USA; [3] BMS, Fitness Technology, Adelaide, SA, Australia; [*4*] PT9510, CTP, Chatsworth, CA, USA; [*5*] Globus, Cadoyne, Italy; [*6*] IDM Instruments, Melbourne, VIC, Australia

3.2.2 Loading Zones During Jump Squat Exercise

3.2.2.1 Zone 1 Versus Zone 2 The association of Zone 1 versus Zone 2 during jump squat exercise was investigated in 19 studies [5, 7, 8, 11, 19, 22, 27, 29–41] and 1368 effect sizes. Peak power output during jump squat exercise was higher in Zone 1 than in Zone 2, with a pooled effect size (Hedges' g) of −1.246 (95 % CI −1.70 to 0.79, $P = 0.001$) and evidence of publication bias ($P = 0.012$) and heterogeneity among studies ($I^2 = 92.50$ %, $Q = 226.60$, $P = 0.001$) (Figs. 3, 4a).

3.2.2.2 Zone 1 Versus Zone 3 The association of Zone 1 versus Zone 3 during jump squat exercise was investigated in ten studies [5, 7, 11, 19, 27, 30, 33, 37, 42] and 750 effect sizes. Peak power output during jump squat exercise was higher in Zone 1 than in Zone 3, with a pooled effect size (Hedges' g) of −2.99 (95 % CI −4.02 to 1.959, $P = 0.89$) and evidence of publication bias ($P = 0.018$) or heterogeneity among studies ($I^2 = 96.08$ %, $Q = 22.89$, $P = 0.001$) (Figs. 3, 4b).

3.2.2.3 Zone 2 Versus Zone 3 The association of Zone 2 versus Zone 3 during jump squat exercise was investigated in nine studies [5, 7, 11, 19, 27, 31, 33, 37] and 574 effect sizes. Peak power output during jump squat exercise was higher in Zone 2 than in Zone 3, with a pooled effect size (Hedges' g) of −1.52 (95 % CI −2.16 to −0.89, $P = 0.001$) and evidence of publication bias ($P = 0.046$) or no heterogeneity among studies ($I^2 = 90.66$ %, $Q = 16.90$, $P = 0.001$) (Figs. 3, 4c).

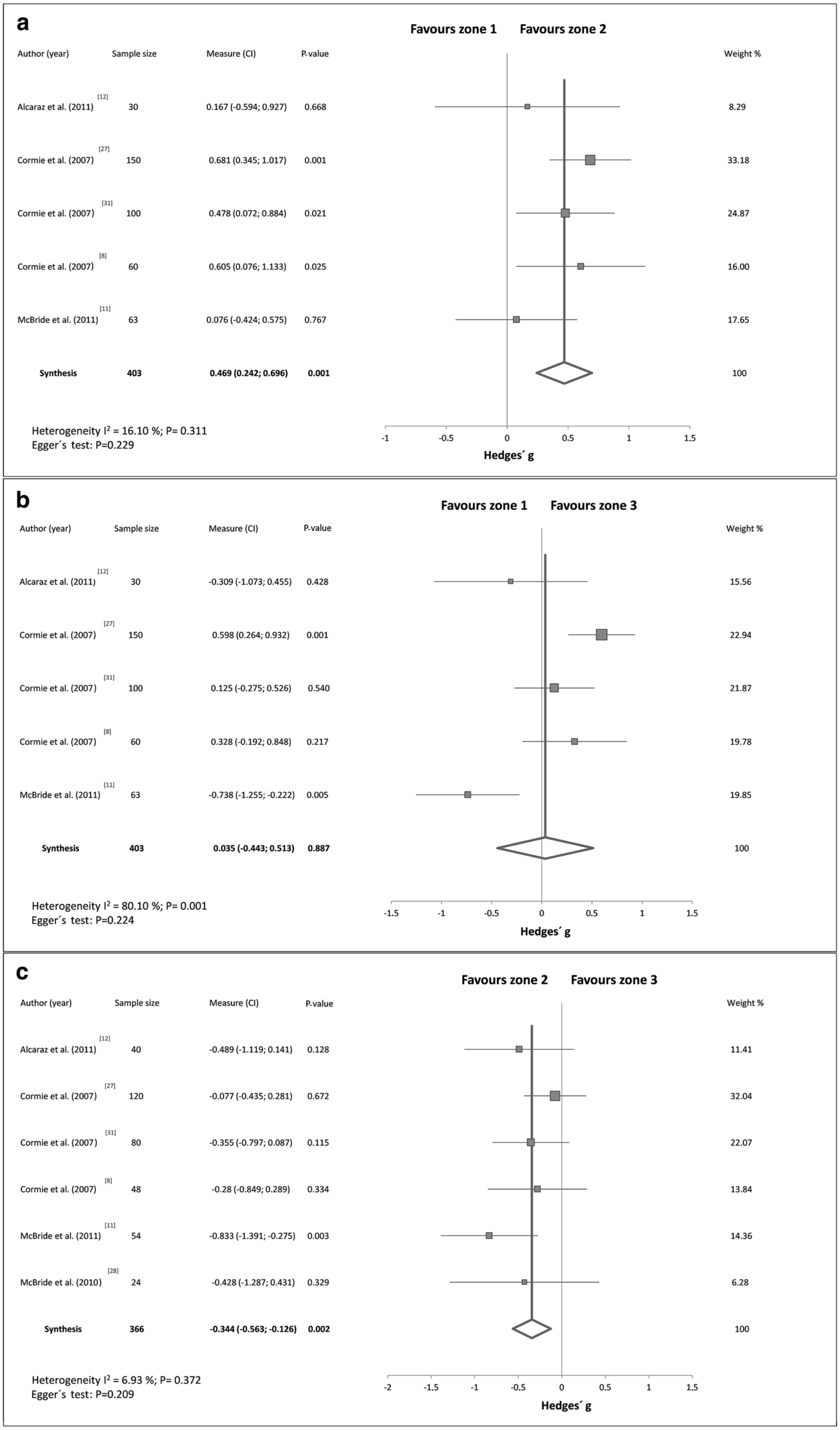

Fig. 2 Forest plots of effect sizes of squat exercise associated with **a** Zone 1 compared with Zone 2; **b** Zone 1 compared with Zone 3; and **c** Zone 2 compared with Zone 3. Results are expressed as Hedges' g and 95 % confidence intervals (CIs)

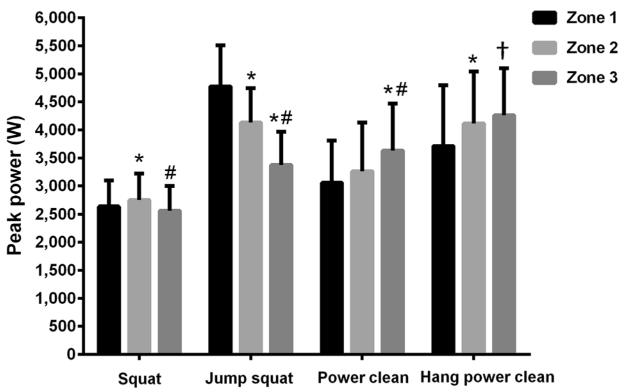

Fig. 3 Peak power across the loading zones in the squat, jump squat, power clean, and hang power clean. Values are means ± standard deviation. *Significantly different to Zone 1 at the same exercise ($P < 0.05$); #significantly different to Zone 2 at the same exercise ($P < 0.05$); †not significantly different to Zone 1 at the same exercise ($P = 0.09$)

3.2.3 Loading Zones During Power Clean Exercise

3.2.3.1 Zone 1 Versus Zone 2 The association of Zone 1 versus Zone 2 during power clean exercise was investigated in five studies [8, 11, 14, 27, 31] and 360 effect sizes. Peak power output during power clean exercise was no different for Zone 1 and Zone 2, with a pooled effect size (Hedges' g) of 1.19 (95 % CI −1.12 to 0.49, $P = 0.225$) and no evidence of publication bias ($P = 0.316$) and no heterogeneity among studies ($I^2 = 37.89$ %, $Q = 6.44$, $P = 0.168$) (Figs. 3, 5a).

3.2.3.2 Zone 1 Versus Zone 3 The association of Zone 1 versus Zone 3 during power clean exercise was investigated in five studies [8, 11, 14, 27, 31] and 361 effect sizes. Peak power output during power clean exercise was higher in Zone 3 than in Zone 1, with a pooled effect size (Hedges' g) of 0.637 (95 % CI 0.41–0.87, $P = 0.001$) and no evidence of publication bias ($P = 0.351$) or no heterogeneity among studies ($I^2 = 0.00$ %, $Q = 3.46$, $P = 0.483$) (Figs. 3, 5b).

3.2.3.3 Zone 2 Versus Zone 3 The association of Zone 2 versus Zone 3 during power clean exercise was investigated in six studies [8, 11, 13, 14, 27, 31] and 555 effect sizes. Peak power output during power clean exercise was higher in Zone 3 than in Zone 2, with a pooled effect size (Hedges' g) of 0.49 (95 % CI 0.32–0.66, $P = 0.001$) and no evidence of publication bias ($P = 0.379$) or no heterogeneity among studies ($I^2 = 0.00$ %, $Q = 4.54$, $P = 0.473$) (Figs. 3, 5c).

3.2.4 Loading Zones During Hang Power Clean Exercise

3.2.4.1 Zone 1 Versus Zone 2 The association of Zone 1 versus Zone 2 during hang power clean exercise was investigated in four studies [18, 43–45] and 201 effect sizes. Peak power output during hang power clean exercise was higher in Zone 2 than in Zone 1, with a pooled effect size (Hedges' g) of 0.52 (95 % CI 0.06–0.99, $P = 0.028$) and no evidence of publication bias ($P = 0.308$) and no heterogeneity among studies ($I^2 = 54.63$ %, $Q = 6.61$, $P = 0.085$) (Figs. 3, 6a).

3.2.4.2 Zone 1 Versus Zone 3 The association of Zone 1 versus Zone 3 during hang power clean exercise was investigated in four studies [18, 43–45] and 170 effect sizes. Peak power output during hang power clean exercise was trending higher in Zone 3 than in Zone 1, with a pooled effect size (Hedges' g) of 0.85 (95 % CI −0.12 to 1.83, $P = 0.087$) and no evidence of publication bias ($P = 0.783$) with heterogeneity among studies ($I^2 = 23.05$ %, $Q = 23.05$, $P = 0.001$) (Figs. 3, 6b).

3.2.4.3 Zone 2 Versus Zone 3 The association of Zone 2 versus Zone 3 during hang power clean exercise was investigated in four studies [18, 43–45] and 255 effect sizes. Peak power output during hang power clean exercise was no different for Zone 3 than in Zone 2, with a pooled effect size (Hedges' g) of 0.31 (95 % CI −0.17 to 0.79, $P = 0.206$) and no evidence of publication bias ($P = 0.734$) with heterogeneity among studies ($I^2 = 70.24$ %, $Q = 10.08$, $P = 0.018$) (Figs. 3, 6c).

4 Discussion

The results of this meta-analysis support the concept of exercise-specific optimal loads for power training [8]. Figure 3 provides a valuable overview of the optimal zones to maximize power production for the different exercises examined in this analysis. Each exercise presents the athlete with a unique biomechanical challenge, and, therefore, the different intensity zones to optimize power output also change. It becomes clear that a single relative intensity cannot be broadly applied to all exercises as an optimal training load for power.

The differences in optimal load between the squat, jump squat, power clean, and hang power clean are notable and of great applied value. Each, at different loads, may target a separate aspect of the force–velocity relationship. Jump squats at lighter loads (0–30 % of 1RM) elicited greater

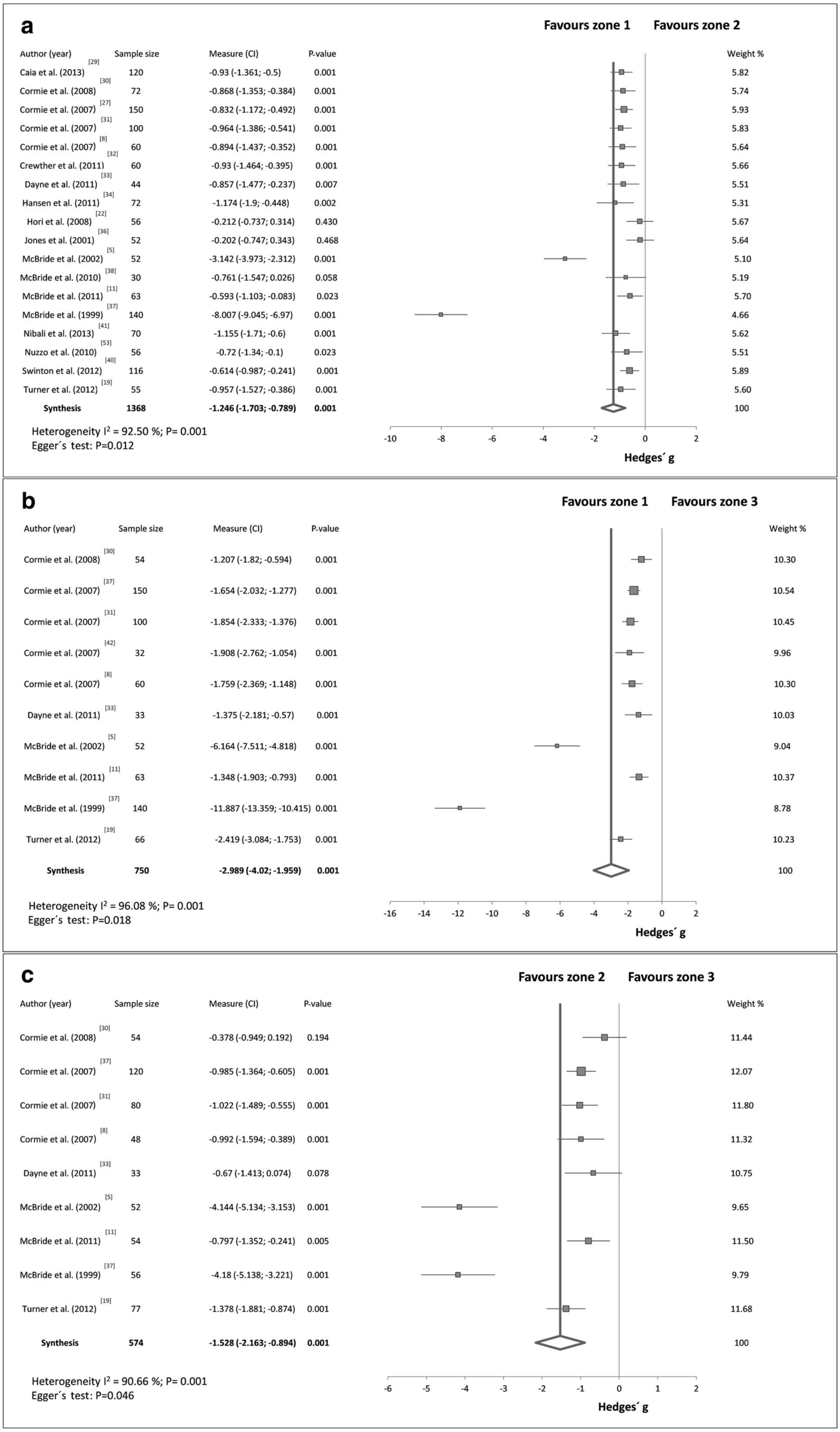

Fig. 4 Forest plots of effect sizes of jump squat exercise associated with **a** Zone 1 compared with Zone 2; **b** Zone 1 compared with Zone 3; and **c** Zone 2 compared with Zone 3. Results are expressed as Hedges' g and 95 % confidence intervals (CIs)

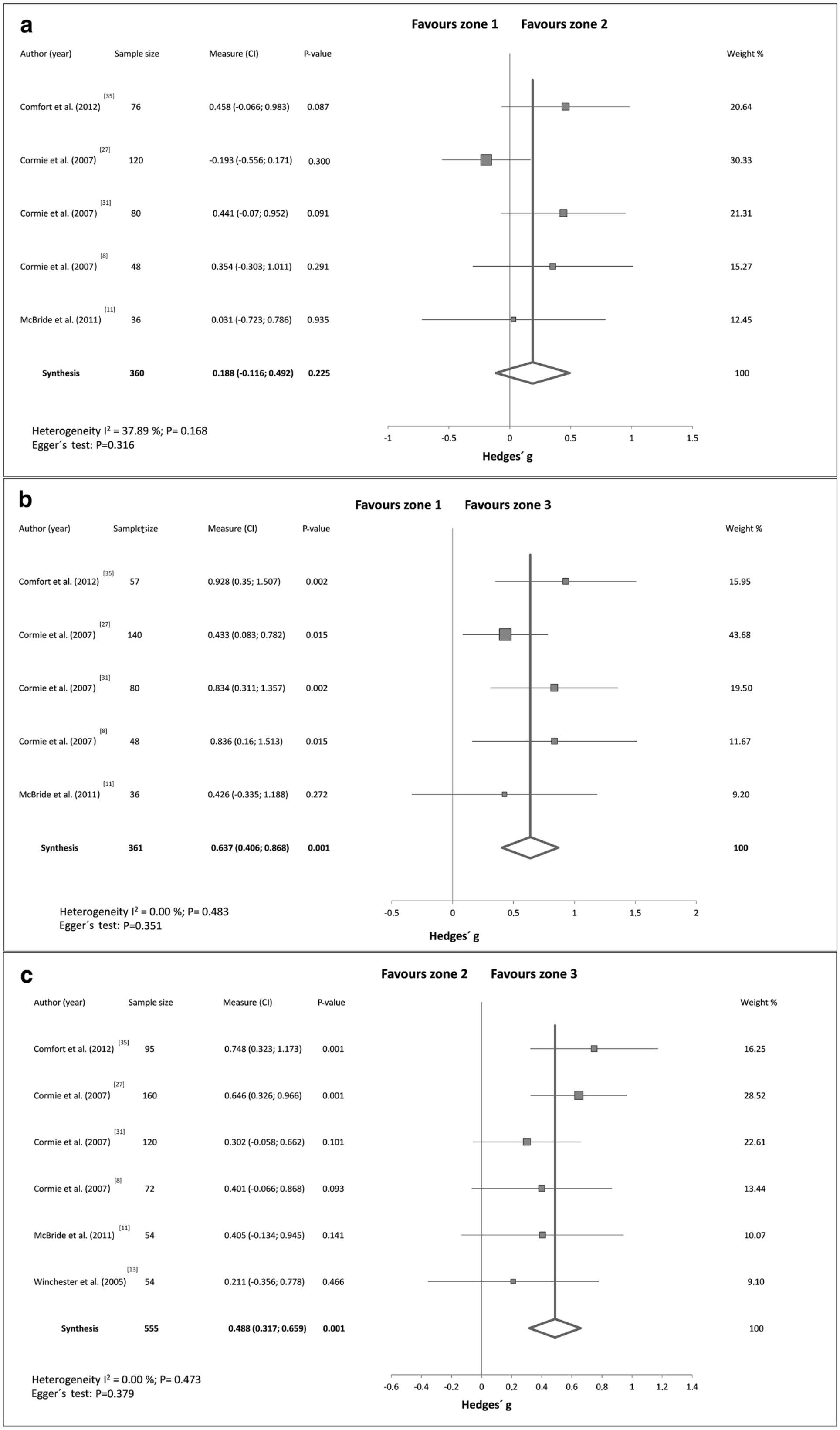

Fig. 5 Forest plots of effect sizes of power clean exercise associated with **a** Zone 1 compared with Zone 2; **b** Zone 1 compared with Zone 3; and **c** Zone 2 compared with Zone 3. Results are expressed as Hedges' g and 95 % confidence intervals (CIs)

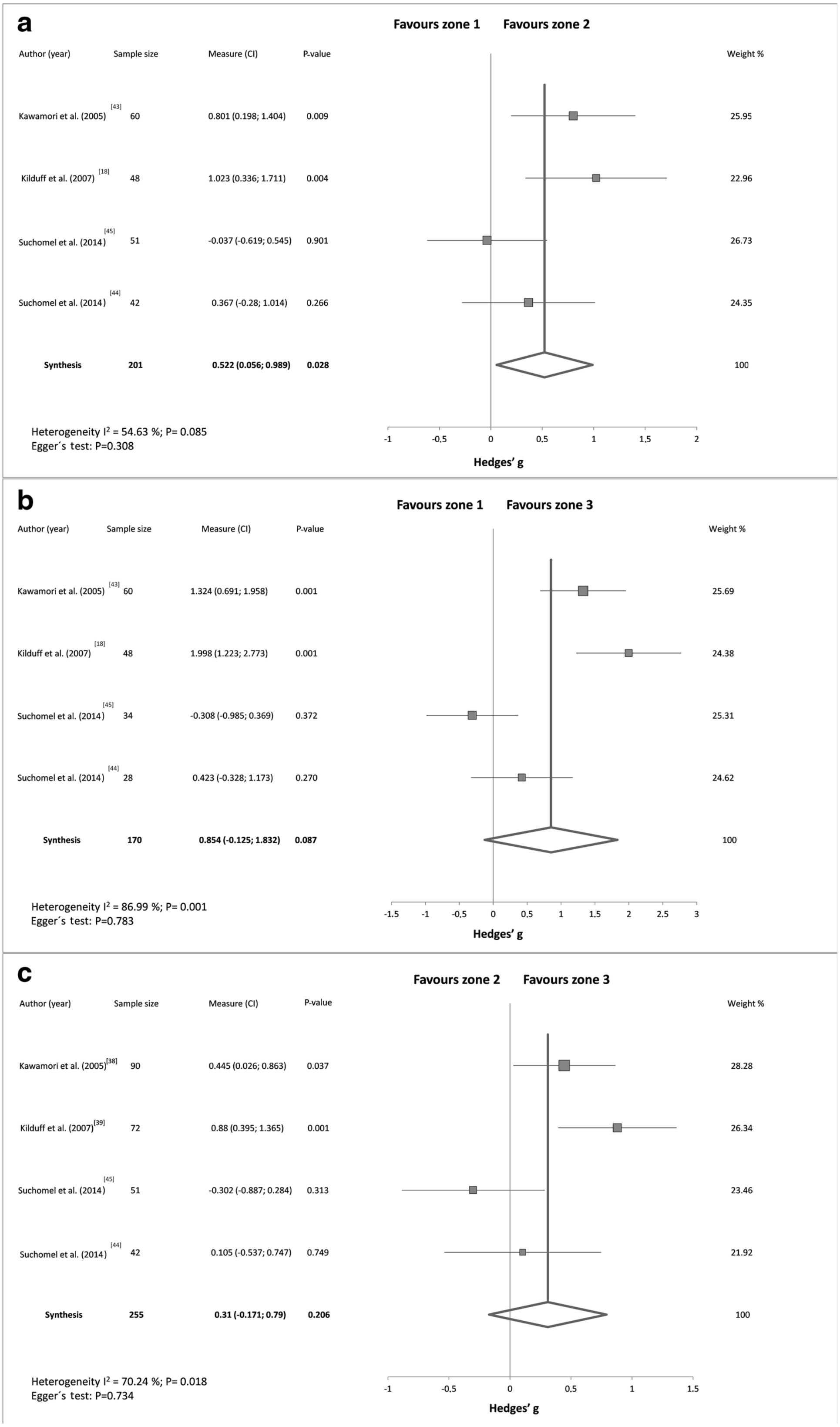

Fig. 6 Forest plots of effect sizes of hang power clean exercise associated with **a** Zone 1 compared with Zone 2; **b** Zone 1 compared with Zone 3; and **c** Zone 2 compared with Zone 3. Resultsare pressed as Hedges' g and 95 % confidence intervals (CIs)

peak power output than moderate or heavy loads, reflecting the ballistic nature of the exercise. Power cleans and hang power cleans require heavier loads (>70 % of 1RM) to elicit peak power production, perhaps focusing more on the force production components. In addition, more power is produced in a hang power clean than in a regular power clean, and the difference between the jump squat and squat is most pronounced in Zone 1. In theory, lighter loads in an exercise such as the jump squat may result in selective motor unit recruitment, increased firing frequency, and synchronization of active motor units targeting the early-phase rate of force development [30, 46, 47]. Heavier loads used in explosive exercises such as the power clean and hang power clean may produce adaptations in both early and late phases due to higher loads and longer contraction time through further stimulus of adaptations in neural drive and peripheral muscle properties [48].

Mixed methods appear to optimize the training environment by presenting the neuromuscular system with stresses that allow for a more complete adaptation to occur across the entire force–velocity curve [7, 49].

Thus, the use of different exercises with various optimal loads may serve to more fully develop power potential among athletes. Further research may provide better guidance on periodization schemes for altering program variables such as exercise selection and optimal load, in an effort to fully develop each aspect of the force–velocity curve.

One final point of interest in the data is the lower peak power exhibited during the squat exercise in all three zones, compared to the power clean and the hang power clean, with little differences between each zone. The squat may serve as a key exercise in building foundational strength to support rate of force development in later training cycles in a periodized plan or for expression during power exercises. The squat is an exercise with demonstrated value in the development of strength [50] but may best serve as a transitional exercise to other power lifts rather than being employed for the sake of peak power production. However, the use of the squat to elicit peak power, without the use of accommodated resistance, may not result in high rate of force development. According to our data, the jump squat, power clean, and hang power clean exercises are more effective to achieve peak power performance with heavier loads than the squat. The use of accommodated resistance may alter this power response to the squat. Previous research demonstrated a significant impact on speed of movement during the squat and improved chronic adaptations in lower-body power when squat training is performed with accommodated resistance. Further research is warranted to examine the relationship between acute power output during the squat with various forms of accommodated resistance [51].

The jump squat at lower loads demonstrated the highest amount of peak power output (Fig. 6) compared to the other three exercises examined. It is also notable that the hang power clean demonstrated higher acute peak power than the power clean at all levels of intensity. While the current meta-analysis does not provide direct information regarding power adaptation over time, these data may help in the selection of exercises and loads most likely to result in acute peak power during individual workouts. Further research would be needed to examine whether or not such exercise and load selection results in improved chronic power adaptations. Additional research would also be helpful in examining many other exercises, at different loads, to further assist coaches in selecting the best exercise for peak power development.

5 Conclusions

Our meta-analysis of results from the published literature provides evidence for exercise-specific optimal loads for power production. This meta-analysis provides valuable guidance for strength and conditioning professionals seeking to prescribe the most effective loads during training. Moderate loads (from >30 to <70 % of 1RM) appear to provide the optimal load to power production in the squat exercise. Lighter training loads (≤30 % of 1RM) appear to provide the optimal load for peak power production in the jump squat. Heavier loads (≥70 % of 1RM) result in greater peak power production in the power clean and hang power clean. Optimal loads for peak power production are exercise specific, which suggests that future research evaluating many different exercises is warranted.

Acknowledgments This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors. The authors declare they have no competing interests.

Conflicts of interest None.

References

1. Cronin JB, Hansen KT. Strength and power predictors of sports speed. J Strength Cond Res. 2005;19(2):349–57.
2. Loturco I, Artioli GG, Kobal R, et al. Predicting punching acceleration from selected strength and power variables in elite karate athletes: a multiple regression analysis. J Strength Cond Res. 2014;28(7):1826–32.
3. Wilson GJ, Newton RU, Murphy AJ, et al. The optimal training load for the development of dynamic athletic performance. Med Sci Sports Exerc. 1993;25(11):1279–86.
4. Hoffman JR, Ratamess NA, Cooper JJ, et al. Comparison of loaded and unloaded jump squat training on strength/power performance in college football players. J Strength Cond Res. 2005;19(4):810–5.

5. McBride JM, Triplett-McBride T, Davie A, et al. The effect of heavy- vs. light-load jump squats on the development of strength, power, and speed. J Strength Cond Res. 2002;16(1):75–82.
6. Toji H, Kaneko M. Effect of multiple-load training on the force–velocity relationship. J Strength Cond Res. 2004;18(4):792–5.
7. Cormie P, McCaulley GO, McBride JM. Power versus strength–power jump squat training: influence on the load–power relationship. Med Sci Sports Exerc. 2007;39(6):996–1003.
8. Cormie P, McCaulley GO, Triplett NT, et al. Optimal loading for maximal power output during lower-body resistance exercises. Med Sci Sports Exerc. 2007;39(2):340–9.
9. Izquierdo M, Hakkinen K, Gonzalez-Badillo JJ, et al. Effects of long-term training specificity on maximal strength and power of the upper and lower extremities in athletes from different sports. Eur J Appl Physiol. 2002;87(3):264–71.
10. Dugan EL, Doyle TL, Humphries B, et al. Determining the optimal load for jump squats: a review of methods and calculations. J Strength Cond Res. 2004;18(3):668–74.
11. 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.
12. Alcaraz PE, Romero-Arenas S, Vila H, et al. Power–load curve in trained sprinters. J Strength Cond Res. 2011;25(11):3045–50.
13. Winchester JB, Erickson TM, Blaak JB, et al. Changes in bar-path kinematics and kinetics after power-clean training. J Strength Cond Res. 2005;19(1):177–83.
14. Comfort P, Fletcher C, McMahon JJ. Determination of optimal loading during the power clean, in collegiate athletes. J Strength Cond Res. 2012;26(11):2970–4.
15. Nuzzo JL, Cormie P, McBride JM. Advances in strength and conditioning research. In: Duncan M, Lyons M, editors. Power in resistance exercise. New York: Nova Science Publishers Inc.; 2009. p. 123–45.
16. Kawamori N, Haff GG. The optimal training load for the development of muscular power. J Strength Cond Res. 2004;18(3):675–84.
17. Cronin J, Sleivert G. Challenges in understanding the influence of maximal power training on improving athletic performance. Sports Med. 2005;35(3):213–34.
18. Kilduff LP, Bevan H, Owen N, et al. Optimal loading for peak power output during the hang power clean in professional rugby players. Int J Sports Physiol Perform. 2007;2(3):260–9.
19. Turner AP, Unholz CN, Potts N, et al. Peak power, force, and velocity during jump squats in professional rugby players. J Strength Cond Res. 2012;26(6):1594–600.
20. Rhea MR. Synthesizing strength and conditioning research: the meta-analysis. J Strength Cond Res. 2004;18(4):921–3.
21. Harman EA, Rosenstein MT, Frykman PN, et al. The effects of arms and countermovement on vertical jumping. Med Sci Sports Exerc. 1990;22(6):825–33.
22. Hori N, Newton RU, Andrews WA, et al. Does performance of hang power clean differentiate performance of jumping, sprinting, and changing of direction? J Strength Cond Res. 2008;22(2):412–8.
23. Harris NK, Cronin J, Taylor K-L, et al. Understanding position transducer technology for strength and conditioning practitioners. Strength Cond J. 2010;34:66–79.
24. Egger M, Davey Smith G, Schneider M, et al. Bias in meta-analysis detected by a simple, graphical test. BMJ. 1997;315(7109):629–34.
25. Higgins JP, Thompson SG, Deeks JJ, et al. Measuring inconsistency in meta-analyses. BMJ. 2003;327(7414):557–60.
26. Bax L, Yu LM, Ikeda N, et al. Development and validation of MIX: comprehensive free software for meta-analysis of causal research data. BMC Med Res Methodol. 2006;6:50.
27. Cormie P, McBride JM, McCaulley GO. Validation of power measurement techniques in dynamic lower body resistance exercises. J Appl Biomech. 2007;23(2):103–18.
28. McBride JM, Skinner JW, Schafer PC, et al. Comparison of kinetic variables and muscle activity during a squat vs. a box squat. J Strength Cond Res. 2010;24(12):3195–9.
29. Caia J, Doyle TL, Benson AC. A cross-sectional lower-body power profile of elite and subelite Australian football players. J Strength Cond Res. 2013;27(10):2836–41.
30. Cormie P, McBride JM, McCaulley GO. Power–time, force–time, and velocity–time curve analysis during the jump squat: impact of load. J Appl Biomech. 2008;24(2):112–20.
31. Cormie P, McBride JM, McCaulley GO. The influence of body mass on calculation of power during lower-body resistance exercises. J Strength Cond Res. 2007;21(4):1042–9.
32. Crewther BT, McGuigan MR, Gill ND. The ratio and allometric scaling of speed, power, and strength in elite male rugby union players. J Strength Cond Res. 2011;25(7):1968–75.
33. Dayne AM, McBride JM, Nuzzo JL, et al. Power output in the jump squat in adolescent male athletes. J Strength Cond Res. 2011;25(3):585–9.
34. Hansen KT, Cronin JB, Pickering SL, et al. Does cluster loading enhance lower body power development in preseason preparation of elite rugby union players? J Strength Cond Res. 2011;25(8):2118–26.
35. Comfort P, Udall R, Jones PA. The effect of loading on kinematic and kinetic variables during the mid-thigh clean pull. J Strength Cond Res. 2012;26(5):1208–14.
36. Jones K, Bishop P, Hunter G, et al. The effects of varying resistance-training loads on intermediate- and high-velocity-specific adaptations. J Strength Cond Res. 2001;15(3):349–56.
37. McBride JM, Triplett-McBride T, Davie A, et al. A comparison of strength and power characteristics between power lifters, olympic lifters, and sprinters. J Strength Cond Res. 1999;13(1):58–66.
38. McBride JM, Kirby TJ, Haines TL, et al. Relationship between relative net vertical impulse and jump height in jump squats performed to various squat depths and with various loads. Int J Sports Physiol Perform. 2010;5(4):484–96.
39. Nuzzo JL, McBride JM. The effect of loading and unloading on muscle activity during the jump squat. J Strength Cond Res. 2013;27(7):1758–64.
40. Swinton PA, Stewart AD, Lloyd R, et al. Effect of load positioning on the kinematics and kinetics of weighted vertical jumps. J Strength Cond Res. 2012;26(4):906–13.
41. Nibali ML, Chapman DW, Robergs RA, et al. Influence of rest interval duration on muscular power production in the lower-body power profile. J Strength Cond Res. 2013;27(10):2723–9.
42. Cormie P, Deane R, McBride JM. Methodological concerns for determining power output in the jump squat. J Strength Cond Res. 2007;21(2):424–30.
43. Kawamori N, Crum AJ, Blumert PA, et al. Influence of different relative intensities on power output during the hang power clean: identification of the optimal load. J Strength Cond Res. 2005;19(3):698–708.
44. Suchomel TJ, Beckham GK, Wright GA. The impact of load on lower body performance variables during the hang power clean. Sports Biomech. 2014;13(1):87–95.
45. Suchomel TJ, Wright GA, Kernozek TW, et al. Kinetic comparison of the power development between power clean variations. J Strength Cond Res. 2014;28(2):350–60.
46. Duchateau J, Hainaut K. Electrical and mechanical failures during sustained and intermittent contractions in humans. J Appl Physiol (1985). 1985;58(3):942–7.
47. Van Cutsem M, Duchateau J, Hainaut K. Changes in single motor unit behaviour contribute to the increase in contraction speed

after dynamic training in humans. J Physiol. 1998;513(Pt 1): 295–305.
48. de Oliveira FB, Rizatto GF, Denadai BS. Are early and late rate of force development differently influenced by fast-velocity resistance training? Clin Physiol Funct Imaging. 2013;33(4):282–7.
49. Haff GG, Whitley A, Potteiger JA. A brief review: explosive exercises and sports performance. Strength Cond J. 2001;23(3): 13–20.
50. Schoenfeld BJ. Squatting kinematics and kinetics and their application to exercise performance. J Strength Cond Res. 2010;24(12):3497–506.
51. Rhea MR, Kenn JG, Dermody BM. Alterations in speed of squat movement and the use of accommodated resistance among college athletes training for power. J Strength Cond Res. 2009;23(9):2645–50.
52. Kawamori N, Rossi SJ, Justice BD, et al. Peak force and rate of force development during isometric and dynamic mid-thigh clean pulls performed at various intensities. J Strength Cond Res. 2006;20(3):483–91.
53. Nuzzo JL, McBride JM, Dayne AM, et al. Testing of the maximal dynamic output hypothesis in trained and untrained subjects. J Strength Cond Res. 2010;24(5):1269–76.