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2 **Mechanical power production assessment during weightlifting**
3 **exercises. A systematic review**

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6 Power assessment during weightlifting exercises

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37

38 **Abstract**

39 The assessment of the mechanical power production is of great importance for researchers
40 and practitioners. The purpose of this review was to compare the differences in ground
41 reaction force (GRF), kinematic, and combined (bar velocity x GRF) methods to assess
42 mechanical power production during weightlifting exercises. A search of electronic
43 databases was conducted to identify all publications up to 31 May 2019. The peak power
44 output (PPO) was selected as the key variable. The exercises included in this review were
45 clean variations, which includes the hang power clean (HPC), power clean (PC) and
46 clean. A total of 26 articles met the inclusion criteria with 53.9% using the GRF, 38.5%
47 combined, and 30.8% the kinematic method. Articles were evaluated and descriptively
48 analysed to enable comparison between methods. The three methods have inherent
49 methodological differences in the data analysis and measurement systems, which
50 suggests that these methods should not be used interchangeably to assess PPO in Watts
51 during weightlifting exercises. In addition, this review provides evidence and rationale
52 for the use of the GRF to assess power production applied to the system mass while the
53 kinematic method may be more appropriate when looking to assess only the power
54 applied to the barbell.

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56 **Key words**

57 Peak power output, force platform, power clean, kinetics, kinematics

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63 **Introduction**

64 The assessment of mechanical power production is of great interest for researchers and
65 practitioners. Peak power output (PPO), defined as the highest instantaneous mechanical
66 power output is the variable most commonly reported during the biomechanical
67 assessment of sporting tasks (Garhammer, 1993). This is based on the notion that the PPO
68 is highly related to sports performance during dynamic athletic tasks (Cronin & Hansen
69 2005; Young, 2006), is a reliable and valid measure to differentiate between sports profile
70 based on the training background (Baker, 2001; Comfort, Graham-Smith, Matthews, &
71 Bamber, 2011; McBride, Triplett-McBride, Davie, & Newton, 1999), and therefore, may
72 be appropriate to monitor during the training process.

73

74 Weightlifting exercises such as the clean, power clean (PC) and hang power clean (HPC),
75 have been suggested by researchers as effective training tools to improve the ability to
76 exert high levels of power outputs and enhance sport performance of dynamic athletic
77 tasks (Chiu & Schilling 2005; Hori, Newton, Nosaka, & Stone, 2005; Janz, Dietz, &
78 Malone, 2008; Suchomel, Comfort, & Lake, 2017). The potential for dynamic
79 correspondence and the ability to train power across the load-velocity continuum are
80 likely why the clean, PC, and HPC are widely implemented in strength and conditioning
81 programs to enhance sport performance not only in weightlifters, but also in the general
82 sporting population (Hori et al., 2005; Suchomel et al., 2017; Tricoli, Lamas, Carnevale,
83 & Ugrinowitsch, 2005).

84

85 The assessment of PPO has been widely studied by researchers using the clean variations.
86 For example, the use of applied video-analysis using a work-energy approach has
87 specifically been reported in weightlifting competitions to determine successful

88 performance predictors of the clean, and to describe the technical differences of skilled
89 vs. non-skilled weightlifters (Garhammer & Newton, 2013; Garhammer & Oarhammer,
90 1985). In contrast, in controlled laboratory and field testing conditions, three main
91 methods have commonly been utilised to obtain mechanical power production: 1) power
92 applied to the system mass (SM: individual's body mass + external load), obtained from
93 the ground reaction force (GRF); 2) power applied to the barbell, obtained from the
94 kinematics of the barbell; and 3) power applied to the SM, obtained from the kinematics
95 of the barbell and GRF (known as the combined method) (Cormie, McBride, &
96 McCaulley, 2007a; Hori, Newton, Nosaka, & McGuigan, 2006).

97

98 Researchers have suggested that practitioners may be interested in either the PPO applied
99 to the barbell or to the SM, depending on sport-specific skills (Hori et al., 2006, 2007;
100 McBride, Haines, & Kirby, 2011) and the objective of the research (Lee, DeRosia, Lamie,
101 & Levine, 2017; Lee, DeRosia, & Lamie, 2018). For example, it has been suggested that
102 weightlifters or throwers may be particularly interested in the PPO applied to the barbell
103 using the kinematic method, as their performance predictor is how much power is applied
104 to an object (i.e. barbell, javelin, ball, hammer), whereas the general sport population may
105 be more interested in the power applied to the SM to assess performance of the lower-
106 body accelerating the external load and the body mass as a whole (Hori et al., 2008;
107 McBride et al., 2011). Although Hori et al. (2006, 2007) recommended that the GRF
108 method should be used as the 'gold standard' to assess power applied to the SM, the
109 combined method has become popular as an alternative to assess power production during
110 lower-body dynamic tasks (Cormie et al., 2007a; Cormie, Deane, & McBride, 2007b;
111 Dugan, Doyle, Humphries, Hasson, & Newton, 2004). However, the combined method
112 has been criticised by some researchers for having a questionable rationale and a lack of

113 agreement concerning the GRF method (Hori et al., 2006, 2007; Mundy, Lake, Carden,
114 Smith, & Lauder, 2016). Therefore, the lack of consensus between researchers makes it
115 difficult to compare results among studies where different methods have been used.

116

117 The purpose of this review was therefore, to compare the three methods commonly
118 employed to assess power production during weightlifting exercises. Furthermore, a
119 secondary goal was to establish practical applications and guidelines for researchers and
120 practitioners in the use of the current methodologies to assess mechanical power
121 production. The findings of various studies are integrated to provide dependability
122 evidence upon which to base the mechanical power output assessment settings. It has
123 been hypothesised that the GRF, kinematic and combined methods show marked
124 differences in power production (watts) during weightlifting exercises.

125

126 **Methods**

127 ***Review protocol***

128 A review protocol for this paper was developed using the PRISMA guidelines for
129 systematic reviews and meta-analyses (Moher et al., 2016; Shamseer et al., 2015). This
130 was used in the planning and development of the systematic review to assure the quality
131 of the review process.

132

133 ***Search strategy and inclusion criteria***

134 A search of electronic databases was conducted to identify all publications on mechanical
135 power production assessment during the clean variations up to 31 May 2019. The
136 literature search was undertaken using 22 different key-words: ‘mechanical power’, ‘peak
137 power’, ‘power production’, ‘power assessment’, ‘power development’, ‘power-load

138 curve', 'peak power output', 'mechanical power output', 'weightlifting exercises',
139 'clean', 'clean and jerk', 'power clean', 'hang power clean', 'linear position transducer',
140 'displacement-time', 'combined method', 'force platform', 'accelerometer', 'high-speed
141 video camera', 'ground reaction force', 'kinematic', 'kinetic'. Search terms were
142 combined by Boolean logic (AND, OR), with no restrictions on date or language, in
143 MEDLINE (SPORTDiscus), PubMed, Google Scholar, and Web of Science. The search
144 spectrum has also been extended to 'related articles' and the bibliographies of all retrieved
145 studies. For the sake of guaranteeing accurate outputs (articles selected), two independent
146 reviewers (initial evaluators: MS, PJM) screened citations of potentially relevant
147 publications. The total number of citations were gathered and duplications excluded. The
148 final outputs obtained from this process were categorised as 'potential abstracts and titles
149 identified and selected'. When abstracts indicated potential inclusion, the specific
150 inclusion criteria was applied for the process of including and excluding articles. A third-
151 party consensus meeting was held (mediator: PSB) if the two reviewers were not able to
152 reach agreement upon inclusion of an article (Moher et al., 2016; Shamseer et al., 2015).

153

154 Studies were included in this review if the following criteria were met: a) full-text, journal
155 articles; b) research focused on the clean, PC or HPC; c) research reported the PPO in
156 text, tables, or figures measured across a single load or a power-load spectrum of absolute
157 values (kg) or relative to the 1RM (%1RM); d) research employed the GRF, kinematic or
158 combined method for analysis and explained clearly the measurement system and how
159 the variables were analysed.

160

161

162 *Quality assessment*

163 A specific and previously validated quality assessment tool that fits this study has not
164 been found in the literature. However, in a recent systematic review of biomechanical
165 research methods in cross-sectional studies (Hindle et al. 2019) researchers have
166 developed a checklist that seems suitable for evaluating the risk of bias for the eligible
167 articles of this study (Table 1). Each study was read and ranked from 0 to 16, with a larger
168 number indicating better quality. For each question, a 1 was awarded if the study met the
169 standard. If insufficient description or data were not provided to analyse a specific
170 question, a 0 was awarded. The process of evaluation was undertaken by two researchers
171 (initial evaluators: MS, PJM) who ranked the articles blinded. Then, a third researcher
172 (mediator: PSB) compared the scores of each researcher. If there was no consensus, the
173 three researchers involved (MS, PJM and PSB) discussed the study to provide a definite
174 score. Eventually, the total risk of bias score was calculated for each article and
175 categorised using a previous method (Davids and Roman 2014; Hindle et al. 2019) which
176 classifies articles scoring $\geq 67\%$ as having low risk of bias, articles scoring in the range of
177 34-66% as having a satisfactory risk of bias, and articles scoring $\leq 33\%$ as having a high
178 risk of bias. Only articles scoring a low or satisfactory risk of bias were included in the
179 review (Davids and Roman 2014; Hindle et al. 2019).

180

181 ***Table 1 about here***

182

183 *Description of the methods*

184 The methods were selected based on the guidelines provided by Hori et al. (2006, 2007)
185 for the assessment of power production during weightlifting exercises: 1) The GRF
186 method; 2) the kinematic method, and 3) the combined method. In addition, the common
187 process of data analysis, equations and approaches are provided in the description (see

188 Figure 1). Essential concerns regarding the procedures of each method are also addressed
189 in later sections.

190

191 *The GRF method*

192 The GRF method represents the force applied to the SM, following *Newton's third law*
193 using a force platform (FP) (Cavagna, 1975). Acceleration of the SM is calculated by first
194 subtracting system weight ($SM * g$, where $g = -9.81\text{m}\cdot\text{s}^{-2}$) from GRF, to provide the
195 exerted force (net force), before this is divided by SM based on *Newton's second law*.
196 SM velocity is calculated from the integration of the SM acceleration data with respect to
197 time (Cavagna, 1975; Chiu, 2018). Power applied to the SM is obtained as the product of
198 velocity of the SM and corresponding vertical GRF directly, this process of integration
199 based on the known GRFs is termed the forward dynamics approach (Cavagna, 1975;
200 Hori et al., 2006). Researchers and practitioners must be aware that with this method,
201 power may be calculated by multiplying force and velocity of the SM in the three axes
202 (x, y, z), however, only the vertical component (z) is typically reported for power
203 calculations during weightlifting exercises (Comfort, Fletcher, & McMahon, 2012).

204

205 *The kinematic method*

206 The kinematic method has been commonly used by researchers and practitioners with
207 two different methods to obtain barbell kinematics depending on the technology used
208 (Chiu, 2018; Hori et al., 2006). The first method corresponds to the calculation of the
209 displacement-time differentiation using motion capture high speed video-cameras
210 (McBride et al., 2011), a single or dual linear position transducer (LPT) (Cormie, et al.
211 2007b) or optoelectronic motion capture systems (Rossi et al., 2007), where barbell
212 velocity is calculated from the rate of change of displacement divided by time. Barbell

213 acceleration is then calculated by differentiating velocity-time data between two
214 consecutive time points (known as double differentiation of displacement-time data)
215 (Cormie, et al. 2007b; Hori et al. 2006). The second method is based on new technologies
216 such as accelerometers attached to the barbell (Sato, Sands, & Stone 2012; Thompson &
217 Bemben, 1999), which provide acceleration of the barbell directly, where no process of
218 differentiation is needed, although one must integrate the signal to get barbell velocity.
219 In this matter, the average barbell acceleration value is multiplied by the time interval
220 between data points (based on the sampling rate) to yield instantaneous barbell velocity
221 at each data point (Thompson & Bemben, 1999). Once the barbell acceleration is obtained
222 either directly (accelerometers) or by the double differentiation process (displacement-
223 time), barbell force is then calculated by multiplying the barbell mass by the acceleration
224 data + barbell weight (barbell mass x g) at each time point. Power is therefore calculated
225 by multiplying force (individual's body mass excluded) and integrated velocity data (Hori
226 et al., 2006, 2007). This process is the inverse dynamic approach, which estimates force
227 output from barbell kinematics (Chiu, 2018). Similarly to the GRF method, calculations
228 of total power which correspond to the sum of three axes ([x-force * x-velocity] + [y-
229 force * y-velocity] + [z-force * z-velocity]) may be done depending on the measurement
230 system utilised (e.g. high speed video-cameras), although only the vertical component (z)
231 is usually reported for power calculations (Ammar et al., 2018a; Kipp, Harris, & Sabick,
232 2013; Lake, Lauder, & Smith, 2010).

233

234

Fig 1 About here

235

236 *The combined method*

237 Using the combined method power is calculated as the product of GRF (from the FP to
238 represent the force applied to the SM) and barbell velocity (from high-speed video
239 cameras or LPTs). Using this method, force and velocity are obtained directly,
240 minimising data manipulation (Cormie et al. 2007a; Cormie et al. 2007b; Hori et al. 2006,
241 2007).

242

243 *Data analysis*

244 To address the primary objectives of this systematic review, the data from the included
245 articles were subdivided into three zones following previous research (Soriano, Jiménez-
246 Reyes, Rhea, & Marín, 2015). Loads ranged from 0 to 30 % of 1RM were categorised as
247 Zone 1 (lighter loads), >30 to <70 % of 1 RM categorised as Zone 2 (moderate loads),
248 and ≥ 70 % of 1RM categorised as Zone 3 (heavier loads). Furthermore, when two or
249 more loads were within the same zone, the PPO was averaged to enable descriptive
250 comparisons between zones. A comparison between zones was chosen instead of a load
251 by load comparison based on the notion that although power production differences may
252 be observed between all loads, a difference statistically significant is not usually observed
253 (Cormie, McCaulley, Travis-Triplett, McBride, 2007c; Kilduff et al., 2007).
254 Measurement system details, sampling rate, and relative reliability (intraclass correlation
255 coefficient, [ICC]) were reported when available.

256

257 **RESULTS**

258 *Literature search and quality assessment*

259 A flow diagram of the literature search is shown in Figure 2. According to the above-
260 defined inclusion criteria, 26 independent studies were identified. The GRF method and
261 the combined method are the most commonly utilised methods to assess PPO for clean

262 variations, with 53.9% and 38.5% of the total articles included in this review,
263 respectively. The kinematic method was used in 30.8% of articles included. Results from
264 the quality scores and risk of bias are provided in Table 1. In general, the articles reviewed
265 provided a well-defined and validated data collection methods, utilised appropriate
266 statistical analysis and presented the results adequately. The risk of bias assessment
267 conducted on the articles selected showed 21 articles classified as having a low risk of
268 bias ($\geq 67\%$), while 5 articles were classified as having a satisfactory risk of bias (34-
269 66%).

270

271 ***Fig 2 about here***

272

273 *Descriptive Analyses*

274 *Mechanical power production*

275 The PPO values and the optimal load for maximal power production are descriptively
276 reported for the clean, PC and HPC in Table 2. In brief, the PPOs reported for the GRF
277 method during the clean variations were within a range of 1301 – 3587 W for Zone 1,
278 1321 – 4226 W for Zone 2, and 1554 – 4391 W for Zone 3. The PPOs reported for the
279 combined method were descriptively higher than those reported for the GRF and the
280 kinematic method for Zone 1 (3884 – 4030 W), Zone 2 (3980 – 5618 W) and Zone 3
281 (3679 – 6629 W). The kinematic method displayed lower PPOs than the GRF and
282 combined method for Zone 1 (984 – 2203 W), Zone 2 (1680 – 2838 W) and the Zone 3
283 (1717 – 3493 W). The results of this review showed that the load that maximises power
284 output during clean variations was consistently observed in Zone 3 (heavier loads),
285 independent of the methods and measurement systems employed (Table 2).

286

287

Table 2 about here

288

289 *Measurement system, sampling rate and relative reliability*

290 A detailed description of the articles measurement system, sampling rate, and reliability
291 values is provided in Table 3. In summary, there are inherent methodological differences
292 to each method regarding the equipment and data analysis. The only measurement system
293 used to evaluate power production in the GRF method was a FP, the sampling rate was
294 over 200Hz, and the reliability reported was generally high across the studies (ICC
295 >0.83). The kinematic method employed four different measurement systems: a) 1 LPT,
296 b) 2 LPT in a triangular fashion, c) high speed video-cameras, and d) a 3-axis
297 accelerometer. The sampling rate was 100 Hz for the accelerometers, and ≥ 100 Hz for
298 the LPTs and high-speed video cameras. The reliability values for the kinematic method
299 were high (ICC >0.90) independent of the measurement system. In the combined method,
300 the measurement systems were variable across studies including a) 1 LPT + FP, b) 2 LPT
301 + FP, and c) high-speed video cameras + FP. The sampling rate was ≥ 200 Hz, and the
302 reliability values were high (ICC >0.90). Additionally, Table 3 shows the different
303 advantages and disadvantages associated with the use of each method, and measurement
304 system utilised.

305

306

Table 3 about here

307

308 **Discussion and implications**

309 The purpose of this systematic review was to examine the literature related to the
310 assessment of the PPO during clean variations, to compare the differences between the
311 GRF, kinematic, and combined methods regularly used to assess PPO in research and

312 field testing and to establish practical applications and guidelines of the current
313 methodologies. The information included in this review provides researchers and
314 practitioners with a summary of the evidence on this topic, helping to guide research and
315 enhance future professional practices.

316

317 The results of this review show that the GRF, kinematic and combined methods display
318 inherent methodological differences in the data analysis and measurement systems (Table
319 2, Table 3, and Figure 3), and therefore, these methods should not be used interchangeably
320 in order to assess the changes in the PPO during clean variations over time. Moreover,
321 the descriptive differences of power outputs in Watts between methods should be
322 interpreted with caution since the power development may be influenced by other factors
323 along with the methods and measurement systems employed (e.g. training status, sex,
324 warm-up procedures, exercises, load, etc.) (Baker, 2001, 2002; Cormie et al., 2011;
325 Garhammer, 1980; McMillian, Moore, Hatler, & Taylor, 2006; Needham, Morse, &
326 Degens, 2009).

327

328 Since the pioneering work of Hori et al. (2007, 2006) a systematic review of the literature
329 discussing the methods commonly used during weightlifting exercises was necessary for
330 several reasons. First, the systematic approach was necessary to clarify the topic for
331 researchers and practitioners according to the current findings and position statements.
332 Second, based on the distribution percentages reported in this review, the three methods
333 have been widely used and therefore, a final statement describing the potential ‘gold
334 standard’ method was necessary to enable comparison between studies. Third, the wide
335 equipment that is available and the possibilities for different measurement system are
336 often subject to controversy for many researchers and practitioners, and therefore, the

337 clarification regarding this matter along with the main advantages and disadvantages of
338 each system provides valuable information. Fourth, after reading this review, researchers
339 and practitioners will be able to interpret with caution the data previously published
340 during weightlifting exercises and more specifically the clean variations, avoiding
341 misinterpretation when comparing the results between studies. Fifth, researchers and
342 practitioners may choose the method that best fits their equipment and measurement
343 system availability as well as to the specific condition (e.g. controlled laboratory, field
344 testing) whilst being aware of any potential limitations. Finally, this updated review may
345 facilitate recommendations and guidelines for future research regarding the assessment
346 of mechanical power production during weightlifting exercises.

347

348 *Power applied to the barbell vs. power applied to the SM.*

349 To the authors' knowledge, little research has been conducted during weightlifting
350 exercises and more specifically, during the clean variations comparing the kinematic and
351 GRF method. In line with the results of this review, McBride et al. (2011) found that
352 during the PC, the optimal load for the GRF method was close to the kinematic method
353 (80 and 90%, respectively). However, the power production in Watts differed markedly
354 (1611 + 505 vs. 2145 + 407 W, respectively), although authors did not compare it
355 statistically. Similarly, Kipp et al. (2013) found that the PPO was maximised at 75 and
356 85% for the kinematic and GRF methods during the clean. Although there was no
357 statistical comparison, the PPO values showed meaningful differences between the GRF
358 (3572 ± 1431 W) and the kinematic method (1802 ± 1452 W). Moreover, Hori et al.
359 (2007) did compare the PPOs statistically and found that the GRF was significantly
360 greater than the kinematic method (3076 ± 638 W vs. 1644 ± 295 W; $p < 0.01$) for the

361 HPC. It was explained that the reason the kinematic method underestimated the PPOs
362 during the HPC was because the individual's body mass was not taken into account.

363

364 Since the kinematic method only accounts for the power applied to the barbell and does
365 not consider the acceleration of the individual centre of mass (CM) (see Figure 1), bigger
366 differences between the kinematic and GRF methods are expected when power is
367 measured during exercises that include large movement of the individual CM, such as
368 weightlifting exercises and derivatives (Hori et al., 2006, 2007). Furthermore, Hori et al.
369 (2007) determined that although a strong correlation was found between the kinematic
370 and GRF methods for evaluating the PPO ($r=0.70$; $p<0.01$), their results still suggested
371 that the barbell measures do not completely reflect the actual power output developed by
372 the individual's lower body accelerating the SM through the propulsion phase, as it is not
373 reflected totally in the correlation. Such a difference between the kinematic and the GRF
374 method during the propulsion phase, may be easily identified in Figure 3 of unpublished
375 data from our laboratory. Furthermore, researchers recently have revealed the big
376 contribution of the lower-limbs in accelerating the SM by establishing correlations
377 between the lower-body net joint torques and power applied to the SM during clean
378 variations (Kipp et al., 2012, 2013; Lee et al., 2017). However, it should be noted that
379 correlation is not agreement from a statistical perspective, and therefore, irrefutable
380 conclusions based on correlations may not be adequate (Bland & Altman, 1995; Bland &
381 Altman, 1986; Mullineaux, Barnes, & Batterham 1999).

382

383 Based on the results of this review, researchers and practitioners are encouraged to use
384 the GRF method to assess PPO during clean variations if the objective is to obtain
385 information regarding the performance of the lower-body and therefore, to evaluate the

386 individual's ability to accelerate the SM (Lake et al., 2012). However, although the power
387 applied to the SM may be more representative of whole-body mechanical power
388 production, monitoring the power applied to the barbell using displacement-time-,
389 velocity or acceleration-based equipment may be more representative of weightlifting or
390 throwing performance, and it may also be useful for practitioners in terms of time-
391 efficient data analysis, and less-costly choice (Hori et al., 2006, 2007; Flores et al., 2017;
392 Lee et al., 2018; McBride et al., 2011; Sato et al., 2012).

393

394 *Power applied to the SM: GRF vs. combined method*

395 Previous research has suggested that the combined method should be used when
396 measuring power output in multidimensional, free weight movements (Cormie et al.
397 2007c; Cormie et al., 2007b). Weightlifting exercises present these characteristics and
398 previous research has used this method widely to assess the power production and optimal
399 load during the clean and PC (Cormie et al. 2007a; Marriner et al., 2018; Winwood et al.,
400 2015). The combined method has been compared to other methods and established as the
401 'gold standard' on the basis of the high reliability and a questionable rationale (Cormie
402 et al., 2007a; Cormie et al., 2007b; Cormie et al., 2007c; Dugan et al. 2004). However, it
403 was currently proven that the GRF method is the true 'gold standard' and most valid
404 method for assessing the PPO of the SM (Mundy et al. 2016). The validity of the
405 calculation of power production using the GRF method and therefore, the force and
406 velocity of the SM is based on the impulse-momentum relationship, which describes and
407 explains prerequisites for performance during dynamic lower-body tasks, being precise
408 and mathematically irrefutable (Winter et al., 2016).

409

410 A few studies have compared the differences between the combined and the GRF method
411 within studies (Cormie et al., 2007b; Hori et al., 2007; Kipp et al., 2013). For example,
412 Kipp et al. (2013) analysed the clean exercise and found that the highest power production
413 was observed at 75% 1RM clean for both the GRF and combined methods. However, the
414 PPO reported differed markedly between each method (3572 ± 1431 vs. 5702 ± 1166 W,
415 respectively). Similarly, Cormie et al. (2007b) showed that both methods agreed to
416 identify the optimal load at 80% 1RM PC across a wide load-power spectrum (30 to 90%
417 1RM); however, the power production was descriptively higher for the two modalities of
418 the combined method according to the measurement system (FP + 2 LPT: 4842 ± 882 W,
419 FP + 1LPT: 4925 ± 920 W) in comparison to the GRF method (3474 ± 542 W). These
420 results are in line with Hori et al. (2007) who found that although there was a high
421 correlation between the PPO for the HPC between the GRF and combined methods ($r =$
422 0.97 ; $p < 0.01$), PPO was generally overestimated while using the combined method
423 ($p < 0.01$).

424

425 Defenders of the combined method claim that the PPO may have less error due to the
426 direct assessment of force and velocity, avoiding the error related to data manipulation
427 and the inability to account for barbell movement (horizontal and vertical) and the
428 subsequent derivations (acceleration, velocity) that occurs independently of the body
429 (Cormie et al., 2007b; Cormie et al. 2007c). Such findings along with a high relative
430 reliability explain why the use of the combined method to obtain power production has
431 been proposed as a suitable and the preferred method for researchers to assess the power
432 applied to the SM (Cormie et al., 2007b; Cormie et al. 2007c; Dugan et al. 2004).
433 However, current research has shown that the combined and GRF methods do not agree
434 in measuring power production during dynamic lower-body tasks, and therefore, both

435 methods should not be used interchangeably (Hansen, Cronin, & Newton 2011a; Hansen,
436 Cronin, & Newton 2011b; Lee et al., 2018; Mundy et al., 2016). Moreover, the same
437 amounts of manipulations are done using the GRF method and further, integrating
438 acceleration-time data naturally reduces signal noise (Beckham, Suchomel, & Mizuguchi
439 2014; Cavagna, 1975), whereas the differentiation associated with the barbell kinematics
440 of the combined method increases signal noise (Lake et al., 2012; Mundy et al. 2016).
441 Critics of the combined method for assessing whole-body power production state that the
442 combined method assumes the velocity of the barbell as the velocity of the SM and
443 therefore, the power outputs will be systematically overestimated in comparison to the
444 GRF method as can be seen in Figure 3 (Hori et al., 2006, 2007; Lake et al., 2012; Mundy
445 et al., 2016). It should be noted that the assumption that barbell velocity corresponds to
446 SM velocity has never been verified and may not be at all valid for weightlifting exercises
447 (Kipp et al., 2013; Lee et al., 2017). In addition, the kinetic contribution of the lower
448 extremities has been more related to the whole-body power production during
449 weightlifting exercises using the velocity of the SM from the GRF than from the velocity
450 of the barbell (Kipp et al., 2013; Lee et al., 2017, 2018).

451

452 In addition to the disagreement in measuring power production due to differences in the
453 analysis, the combined method presents more disadvantages in comparison to the GRF
454 method in the high equipment costs, and space needed. These findings suggest that both
455 researchers and practitioners, whenever possible, should use the GRF method to estimate
456 whole-body power production of a given athlete when attempting to assess the power
457 applied to the SM during weightlifting exercises. Note that the results of this review may
458 be speculated to occur in other kinds of weightlifting movements such as the snatch

459 variations, since similar kinematics and kinetics of the body and barbell have been
460 identified during the 1st and 2nd pull (Garhammer, 1991, 1993).

461

462 **Conclusion**

463 The findings of the articles reviewed provide valuable guidance for researchers and
464 practitioners to unify the knowledge and establish practical guidelines for assessing PPO
465 during weightlifting exercises. In particular, practitioners must be aware of that the GRF,
466 kinematic and combined methods cannot be used interchangeably to assess PPO in Watts
467 during weightlifting exercises because inherent and marked methodological differences
468 can be found (Table 2, Table 3, and Figure 3). The result of the analysis of the articles
469 reviewed are the reason to encourage researchers and practitioners to use the GRF using
470 a FP as the ‘gold standard’ to assess PPO applied to the SM during weightlifting exercises.
471 However, the kinematic method may be more appropriate when looking to assess only
472 the power applied to the barbell. There is a wide range of equipment and measurement
473 systems that researchers and practitioners can choose from and being aware of the
474 advantages and disadvantages of each will help inform decision making. Finally, the
475 authors encourage researchers to develop more research comparing the GRF, kinematic,
476 and combined methods to assess mechanical power production during the weightlifting
477 exercises to allow for statistically irrefutable conclusions

478

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482

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485

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Table 1 Quality and risk of bias evaluation

Article	1.1	1.2	1.3	2.1	2.2	2.3	2.4	3.1	3.2	3.3	3.4	4.1	4.2	4.3	4.4	4.5	Score (%)
Cormie et al. (2007a)	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	0	88 (L)
McBride et al. (2011)	1	1	1	1	1	0	0	1	1	1	1	1	0	1	1	0	75 (L)
Winchester et al. (2005)	1	1	1	1	0	0	0	1	1	1	1	1	0	1	1	0	69 (L)
Cormie et al. (2007c)	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	0	88 (L)
Suchomel et al. (2017)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	94 (L)
Kilduff et al. (2007)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	100 (L)
Suchomel et al. (2014a)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	94 (L)
Comfort et al. (2012)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	100 (L)
Flores et al. (2017)	1	1	0	1	0	0	0	1	1	1	1	1	0	1	1	0	63 (S)
Suchomel et al. (2014b)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	94 (L)
Kawamori et al. (2005)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	100 (L)
Marriner et al. (2017)	1	1	0	1	0	0	1	0	1	1	1	1	0	1	1	0	63 (S)
Marriner et al. (2018)	1	1	0	1	0	0	1	0	1	1	1	1	0	1	1	0	63 (S)
Kipp et al. (2013)	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	88 (L)
Pennington et al. (2005)	0	1	0	0	0	0	1	1	1	1	1	1	0	1	1	0	56 (S)
Cormie et al. (2007b)	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	0	88 (L)
Hori et al. (2007)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	100 (L)
Jones et al. (2008)	0	1	0	0	1	1	1	1	1	1	1	1	0	1	1	0	69 (L)
Hardee et al. (2012)	0	1	0	1	1	1	1	1	1	1	1	1	0	1	1	0	75 (L)
Ammar et al. (2018a)	1	1	1	1	1	0	0	1	1	1	1	1	0	1	1	0	75 (L)
Ammar et al. (2018b)	1	1	1	1	1	0	0	1	1	1	1	1	0	1	1	0	75 (L)
Comfort et al. (2013)	0	1	0	1	1	1	1	1	1	1	1	1	0	1	1	1	81 (L)
Comfort et al. (2011)	0	1	0	1	1	1	1	1	1	1	1	1	0	1	1	1	81 (L)
Oranchuck et al. (2018a)	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	88 (L)
Oranchuk et al. (2018b)	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	88 (L)
Winwood et al. (2015)	0	1	0	0	1	0	0	1	1	1	1	1	0	1	1	0	56 (S)

Method for assessing risk of bias based on (Hindle et al. 2019): (1.1) study design is clearly stated; (1.2) the objectives/purposes of the study are clearly defined; (1.3) the design of the study adequately tests the hypothesis; (2.1) the criteria for the inclusion of participants are clearly described; (2.2) the characteristics of the population are clearly described; (2.3) the study sample is representative of the population intended to the study; (2.4) a description of how the study size was arrived at is provided; (3.1) the testing methods are clearly described; (3.2) the measurement tools used are valid and reliable; (3.3) the statistical methods used are well described; (3.4) the statistical tests used to analyse the data are appropriate; (4.1) the results are well described; (4.2) the information provided in the article is sufficient to allow a reader to make an unbiased assessment of the findings of the study; (4.3) confounding factors are identified; (4.4) sponsorships/conflicts of interest are acknowledged; (4.5) any limitations to the study are identified. Note: the risk of bias score for an article (given as a percentage) is calculated through the addition of the score from each criteria being met divided by the maximum possible score across all criteria (16), and multiplied by 100. The risk of bias was interpreted based on (Davids and Roman 2014) where: *L* Low risk of bias ($\geq 67\%$), *S* satisfactory risk of bias (34-66%), *H* high risk of bias ($\geq 33\%$).

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Table 2 Descriptive characteristics of journal articles selected

Study	Sample Characteristics	Exercise and loading conditions	Data analysis and measurement system	Results
Cormie et al. (2007a)	n = 12 healthy athletes Age: 20.0 ± 1.40 years Sex: M Height: 179 ± 5.00 cm BM: 90.1 ± 15.0 kg 1RM PC: 113 ± 13.2 kg 1RM/BM: 1.30 S-P experience: nd	PC 30, 40, 50, 60, 70, 80, 90% 1RM PC	The CM FP 2 LPT	Zone 1: PC: ~4030 W Zone 2: PC: ~4493 W Zone 3: PC: ~4786 W (OL: 80% 1RM PC)
McBride et al. (2011)	n = 9 healthy subjects Age: 25.0 ± 2.10 years Sex: M Height: 175 ± 6.00 cm Body mass: 81.0 ± 7.20 kg 1RM PC: 97.1 ± 6.40 kg 1RM/BM: 1.20 S-P experience: ≥24 months	PC 30, 40, 50, 60, 70, 80, 90 % 1RM PC	1) The GRF method 2) The kinematic method FP High-speed video cameras	1) The GRF method Zone 1: PC: ~1301 W Zone 2: PC: ~1321 W Zone 3: PC: ~1554 W (OL: 80% 1RM PC) 2) The kinematic method: Zone 1: PC: ~1199 W Zone 2: PC: ~1680 W Zone 3: PC: ~2103 W (OL: 90% 1RM PC)

Winchester et al. (2005)	n = 18 healthy American football players Age: 22.2 ± 2.10 years Sex: M Height: nd BM: nd 1RM PC: nd 1RM/BM: nd S-P experience: ≥12 months	PC 50, 70, 90% 1RM PC	The CM FP High-speed video camera	Zone 2: PC: ~3430 W Zone 3: PC: ~3679.15 W (OL: 70% 1RM PC)
Cormie et al. (2007c)	n = 12 healthy athletes Age: 20.0 ± 1.40 years Sex: M Height: 179 ± 5.00 cm BM: 90.1 ± 15.0 kg 1RM PC: 113 ± 13.2 kg 1RM/BM: 1.30 S-P experience: nd	PC 30, 40, 50, 60, 70, 80 and 90% 1RM PC	The CM; FP 2 LPT	Zone 1: PC: ~3884 W Zone 2: PC: ~4305 W Zone 3: PC: ~4619 W (OL: 80% 1RM PC)
Suchomel et al. (2017)	n = 13 healthy track and field athletes Age: 21.2 ± 1.10 years Sex: M Height: 181 ± 6.00 cm BM: 86.1 ± 18.0 kg 1RM HPC: 110 ± 2.40 kg 1RM/BM: 1.30 S-P experience: ≥24 months	HPC 30, 45, 65 and 80% 1RM HPC	The GRF method FP	Zone 1: HPC: ~3220 W Zone 2: HPC: ~3857 W (OL: 65% 1RM HPC) Zone 3: HPC: ~3883 W

Kilduff et al. (2007)	n = 12 professional rugby players Age: 25.0 ± 4.00 years Sex: M Height: 186 ± 6.00 cm BM: 102 ± 11.4 kg 1RM HPC: 107 ± 13.0 kg 1RM/BM: 1.04 S-P experience: ≥24 months	HPC 30, 40, 50, 60, 70, 80, 90% 1RM HPC	The GRF method FP	Zone 1: HPC: ~3246 W Zone 2: HPC: ~3867 W Zone 3: HPC: ~4390.5 W (OL: 80% 1RM HPC)
Suchomel et al. (2014a)	n = 17 healthy athletes Age: 22.0 ± 1.30 years Sex: M Height: 181 ± 6.30 cm BM: 87.1 ± 16.0 kg 1RM PC: 111 ± 20.4 kg 1RM/BM: 1.30 S-P experience: ≥24 months	HPC 30, 45, 65 and 80% 1RM HPC	The GRF method FP	Zone 1: HPC: ~3857 W Zone 2: HPC: ~4226 W (OL: 65% 1RM HPC) Zone 3: HPC: ~4185 W
Comfort et al. (2012)	n = 19 healthy collegiate athletes Age: 22.0 ± 1.40 years Sex: M Height: 174 ± 8.00 cm BM: 79.0 ± 9.00 kg 1RM PC: 85.0 ± 7.40 kg 1RM/BM: 1.10 S-P experience: ≥12 months	PC 30, 40, 50, 60, 70 and 80% 1RM PC	The GRF method FP	Zone 1: PC: ~2150 W Zone 2: PC : ~2379 W Zone 3: PC: ~2935 W (OL: 70% 1RM PC)

Flores et al. (2017)	<p>G1 n = 11 international elite weightlifters Age: 24.1 ± 6.00 years Sex: M Height: 175 ± 8.10 cm BM: 89.0 ± 28.0 kg 1RM C: 164 ± nd kg 1RM/BM: 1.90 S-P experience: ≥24 months</p> <p>G2 n = 11 national competitive weightlifters Age: 25.1 ± 6.10 years Sex: M Height: 176 ± 5.00 cm BM: 83.0 ± 14.1 kg 1RM C: 129 ± nd kg 1RM/BM: 1.60 S-P experience: ≥24 months</p>	C 30, 40, 50, 60, 70, 80 and 90% 1RM C.	The kinematic method 3-axis acc	<p>G1 Zone 1: C: ~2032 W Zone 2: C: ~2838 W Zone 3: C: ~3493 W (OL: 90% 1RM C)</p> <p>G2 Zone 1: C: ~1670 W Zone 2: C: ~2461 W Zone 3: C: ~2880 W (OL: 90% 1RM C)</p>
Suchomel et al. (2014b)	<p>n = 14 healthy athletes Age: 22.0 ± 1.30 years Sex: M Height: 179 ± 6.00 cm BM: 82.0 ± 9.00 kg 1RM HPC: 105 ± 15.1 kg 1RM/BM: 1.30 S-P experience: ≥24 months</p>	HPC 30, 45, 65 and 80% 1RM HPC	The GRF method FP	<p>Zone 1: HPC: ~3527 W Zone 2: HPC: ~3915 W Zone 3: HPC: ~4015 W (OL: 80% 1RM HPC)</p>

Kawamori et al. (2005)	<p>n = 15 athletic and sports player subjects Age: 22.1 ± 2.00 years Sex: M Height: 180 ± 6.30 cm BM: 89.4 ± 15.0 kg 1RM HPC: 107 ± 19.0 kg 1RM/BM: 1.20 S-P experience: ≥6 months</p>	<p>HPC 30, 40, 50, 60, 70, 80 and 90% 1RM</p>	<p>The GRF method FP</p>	<p>Zone 1: HPC: ~2990 W Zone 2: HPC: ~3665 W Zone 3: HPC: ~4010 W (OL: 70% 1RM HPC)</p>
Marriner et al. (2017)	<p>G1 n = 8 recreationally trained subjects Age: 23.1 ± 2.30 years Sex: M Height: nd BM: 94.0 ± 11.0 kg 1RM PC: 103 ± 8.00 kg 1RM/BM: 1.10 S-P experience: ≥24 months</p> <p>G2 n = 8 recreationally trained subjects Age: 23.3 ± 3.80 years Sex: M Height: nd BM: 87.2 ± 10.0 kg 1RM PC: 102 ± 15.0 kg 1RM/BM: 1.17 S-P experience: ≥24 months</p>	<p>PC 50, 70 and 90% 1RM PC</p>	<p>The CM FP 1 LPT</p>	<p>G1 Zone 2: PC: ~3980 W Zone 3: PC: ~4296 W (OL: 70% 1RM PC)</p> <p>G2 Zone 2: PC: ~4150 W Zone 3: PC: ~4215 W (OL: 90% 1RM PC)</p>

Marriner et al. (2018)	n = 9 Age: 23.0 ± 4.30 years Sex: M Height: nd BM: 92.0 ± 12.0 kg 1RM PC: 101 ± 11.0 kg 1RM/BM: 1.10 S-P experience: ≥24 months	PC 50 and 70% 1RM PC	The CM FP 1 LPT	Zone 2: PC: ~3160 W Zone 3: PC: ~3960 W (OL: 70% 1RM PC)
Kipp et al. (2013)	n = 9 Age: nd Sex: M Height: 185 ± 1.00 cm BM: 106 ± 13.2 kg 1RM C: 126 ± 23.0 kg 1RM/BM: 1.20 S-P experience: nd	C 65, 75 and 85% 1RM C	1) The GRF method 2) The kinematic method 3) The CM FP High-speed video cameras	1) The GRF method Zone 2: C: ~3424 W Zone 3: C: ~3381 W (OL: 75% 1RM C) 2) The kinematic method Zone 2: C: ~1399 W Zone 3: C: ~1717 W (OL: 85% 1RM C) 3) The CM Zone 2: C: ~5618 W Zone 3: C: ~5650 W (OL: 75% 1RM C)
Pennington et al. (2005)	G1 n = 8 Age: 19.0 – 22.0 years Sex: M Height: 181 ± 3.00 cm BM: 87.0 ± 3.20 kg 1RM PC: 114 ± 9.20 kg 1RM/BM: 1.31	PC 30, 40, 50, 60, 70, 80, 90 and 100 % 1RM C	The kinematic method 1 LPT	Zone 1: PC: ~984 W Zone 2: PC: ~1350 W Zone 3: PC: ~1767 W (OL: 90-100% 1RM PC)

S-P experience: nd

G2

n = 12

Age: 19.0 – 22.0 years

Sex: M

Height: 188 ± 4.00 cm

BM: 113 ± 10.1 kg

1RM PC: 124 ± 11.3 kg

1RM/BM: 1.10

S-P experience: nd

Cormie et al. (2007b)

n = 10

Age: 20.0 ± 2.00 years

Sex: M

Height: 178 ± 5.00 cm

BM: 89.0 ± 15.1 kg

1RM PC: 113 ± 13.2 kg

1RM/BM: 1.30

S-P experience: ≥24 months

PC

30, 40, 50, 60, 70, 80 and 90% 1RM

1) The GRF method

2) The CM

FP

2 LPT

1) The GRF method

Zone 1:

PC: ~2609 W

Zone 2:

PC: ~2841 W

Zone 3:

PC: ~3335 W (OL: 80% 1RM PC)

2) The CM

Zone 1:

PC: ~3932 W

Zone 2:

PC: ~4333 W

Zone 3:

PC: ~4632 W (OL: 80% 1RM PC)

Hori et al. (2007)

N = 30 semi-professional

Australian football players

Age: 21.3 ± 3.00 years

Sex: M

Height: 182 ± 6.30 cm

BM: 84.0 ± 8.30 kg

1RM HPC: 75.3 ± 9.00 kg

HPC

70% 1RM HPC

1) The GRF method

2) The CM

3) The kinematic method

FP

1) The GRF method

Zone 3:

HPC: ~3076 W

2) The CM

Zone 3:

HPC: ~4017 W

	1RM/BM: 1.00 S-P experience: ≥ 3 months		1 LPT	3) The kinematic method Zone 3: HPC: ~ 1644 W
Jones et al. (2008)	n = 14 healthy subjects Age: 25.0 ± 6.20 years Sex: M Height: 184 ± 9.40 cm BM: 98.1 ± 21.0 1RM PC: 87.3 ± 17.0 kg 1RM/BM: 1.00 S-P experience: ≥ 24 months	PC 85% 1RM PC	The kinematic method 1 LPT	Zone 3: PC: ~ 2520 W
Hardee et al. (2012)	n = 10 amateur weightlifters Age: 24.0 ± 0.40 years Sex: M Height: 177 ± 1.00 cm BM: 80.4 ± 1.00 kg 1RM PC: $112 \pm nd$ kg 1RM/BM: 1.40 S-P experience: ≥ 24 months	PC 80% 1RM PC	2) The CM FP 2 LPT	Zone 3: PC: ~ 4564 W
Ammar et al. (2018a)	n = 9 elite weightlifters Age: 24.0 ± 4.00 years Sex: M Height: 176 ± 7.10 cm BM: 77.0 ± 9.00 kg 1RM C: 170 ± 15.0 kg 1RM/BM: 2.21 S-P experience: ≥ 24 months	C 85, 90, 95 and 100% 1RM C	The GRF method FP	Zone 3: C: ~ 2768 W

Ammar et al. (2018b)	n = 9 elite weightlifters Age: 24.4 ± 4.00 years Sex: M Height: 176 ± 6.40 cm BM: 77.2 ± 7.10 kg 1RM C: 170 ± 5.00 kg 1RM/BM: 2.20 S-P experience: ≥24 months	C 100% 1RM C	The GRF method FP	Zone 3: C: ~2663 W
Comfort et al. (2013)	n = 16 healthy subjects Age: 19.0 ± 2.30 years Sex: F Height: 167 ± 3.22 cm BM: 63.0 ± 5.00 kg 1RM PC: 52.0 ± 3.00 kg 1RM/BM: 0.82 S-P experience: ≥6 months	PC, HPC 60, 70, 80% 1RM PC	The GRF method FP	Zone 3: HPC: ~2588.8 W PC: ~2861 W
Comfort et al. (2011)	n = 16 healthy rugby players Age: 22.0 ± 2.00 years Sex: M Height: 182 ± 3.00 cm BM: 99.0 ± 8.00 kg 1RM PC: nd 1RM/BM: nd S-P experience: ≥24 months	PC, HPC 60 % 1RM PC	The GRF method FP	Zone 2: HPC: ~3184 W PC: ~2591 W
Oranchuck et al. (2018a)	n = 11 healthy rugby players Age: 28.1 ± 6.00 years Sex: M Height: 176 ± 6.40 cm BM: 85.0 ± 11.1 kg 1RM PC: 109 ± 17.2 kg	PC 75-79, 80-84, 85-89, 90-94, >95% 1RM PC	The kinematic method 2 LPT	Zone 3: PC: ~3174 W

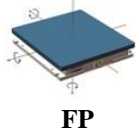


1RM/BM: 1.30
 S-P experience: ≥ 24 months

Oranchuk et al. (2018b)	n = 11 weightlifters and athletes Age: 28.1 ± 6.00 years Sex: M Height: 176 ± 6.40 cm BM: 85.0 ± 11.1 kg 1RM PC: 109 ± 17.2 kg 1RM/BM: 1.30 S-P experience: ≥ 3 months	PC 75-79, 80-84, 85-89, 90-94, >95% 1RM PC	The kinematic method 2 LPT	Zone 3: PC: ~ 3156 W
Winwood et al. (2015)	n = 6 strongman athletes Age: 24.0 ± 4.00 years Sex: M Height: 182 ± 9.40 cm BM: 113 ± 29.0 kg 1RM C&J: 117 ± 20.4 kg 1RM/BM: 1.10 S-P experience: ≥ 24 months	C 70% C&J	The CM FP High speed video-camera	Zone 3: C: ~ 6629 W

M men, *BM* body mass, *1RM* one repetition maximum, *PC* power clean, *CM* combined method *S-P* strength-power training, *PPO* peak power output, *F* force, *V* velocity, *FP* force platform, *LPT* linear position transducer, *OL* optimal load, *SM* system mass, *nd* no data, *HPC* hang power clean, *C* clean, *3-axis acc* accelerometer, *G1* groups one, *G2* group two, *F* female.

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Table 3 Description of the measurement systems, sampling rate and relative reliability

Method	Peculiarities of the analysis			Advantages	Disadvantages
	Studies	Sampling rate (Hz)	ICC		
GRF method  FP	McBride et al. (2011)	1000	0.88	1. Highly reliable for measuring power production 2. Valid for power measurements based on the SM where the $V_{(0)}$ is known, and the total SM is taken into account 3. Direct forces (impulse, PF, RFD) along with power output may be selected for a more complete study of the lift 4. Landing forces and load absorption may be selected for studying	1. Exercises from the floor (PC, clean) and from blocks should be measured with caution when the objective is to assess the power applied to the SM. A common strategy is that the lifter stands on the FP holding the bar 1 cm above the floor 2. Low sampling rates may negatively influence the measurement 3. Expensive and destined to controlled laboratory conditions 4. Requires previous qualified experience for calibration, data collection, processing and analysis
	Suchomel et al. (2017)	500	0.93-0.99		
	Kilduff et al. (2007)	500	0.96		
	Suchomel et al. (2014a)	500	0.88-0.96		
	Comfort et al. (2012)	1000	0.83		
	Suchomel et al. (2014b)	500	0.88-0.96		
	Kawamori et al. (2005)	600	0.98		
	Hori et al. (2007)	200	0.90		
	Cormie et al. (2007b)	1000	0.88		
	Kipp et al. (2013)	1250	>0.90		
	Ammar et al. (2018a)	1000	nd		
	Ammar et al. (2018b)	1000	nd		
	Comfort et al. (2011)	1000	>0.92		
Comfort et al. (2013)	1000	>0.89			
Kinematic method  1 LPT  2 LPT	Pennington et al. (2005)			I. Reliable measure of power production in the vertical plane for 1 LPT and vertical and horizontal planes for 2 LPTs, high-speed video-cameras and Acc II. Sensible to differentiate between athletes of different status III. Relatively inexpensive (e.g. 1 LPT, Acc)	I. Inability to account for horizontal displacement (1 LPT) II. The effect that side dominance has on barbell power symmetry must be taken into account (e.g. 1 LPT, Acc attached on one side of the barbell), as well as the barbell rotation.
	Hori et al. (2007)	100	0.97		
	Jones et al. (2008)	200	0.67		
		100	0.97		
	Oranchuck et al. (2018a)				
	Oranchuk et al. (2018b)	500	0.97		
	500	0.97			



McBride et al. (2011) 240 nd
 Kipp et al. (2013) 250 >0.90

Flores et al. (2017) 100 0.96

IV. Direct measure of velocity and power applied to the barbell by most of the software on the market

V. It is possible to estimate the power symmetry by averaging both sides of the barbell using two markers on each side (e.g. high-speed video-cameras)

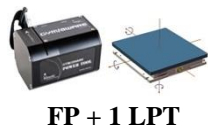
VII. Easy-to-use on a daily basis for practitioners (1 LPT and Acc)

III. Highly expensive and relatively expensive, requires calibration, previous experience and destined to controlled laboratory conditions (e.g. high-speed video-cameras and 2 LPT, respectively)

IV. Barbell velocity cannot be used to estimate whole body power production or power applied to the SM

V. The data manipulation based on the double differentiation (1 LPT, 2 LPT, high speed video-cameras) may lead to error of the power production

Combined method



Marriner et al. (2017) 500 0.89
 Marriner et al. (2018) 500 + 50 0.89
 Hori et al. (2007) 200 0.89
 Cormie et al. 2007b 1000 0.99

Cormie et al. (2007b) 1000 0.98
 Cormie et al. (2007a) 1000 0.98
 Cormie et al. (2007c) 1000 0.98
 Hardee et al. (2012) 1000 0.98

Winchester et al. (2005) 600 + 60 nd
 Kipp et al. (2013) 1250 + >0.90
 Winwood et al. (2015) 250 nd
 1000 +
 300

1) Direct measure of force (VGRF) and velocity of the barbell

2) High reliability for power production

3) Direct forces from the FP (kinetics) and kinematics of the barbell may be recorded along with the power production for a full study of the lift

1) Expensive setup, requires calibration, previous experience and destined to controlled laboratory conditions (FP + 1 LPT, FP + 2LPT, FP + high-speed video-cameras)

2) Inability to account for horizontal displacement (FP + 1 LPT)

3) Barbell velocity cannot be assumed to estimate the whole body power production (power applied to the SM)

4) Equipment requirements are double of necessary to estimate whole body power production

ICC intraclass correlation coefficient, *GRF* ground reaction force, *FP* force platform, *nd* no data *SM* system mass, $V_{(0)}$ initial velocity, *VGRF* vertical ground reaction force, *PF* peak force, *RFD* rate of force development, *PPO* peak power output, *LPT* linear position transducer, *Acc* 3-axis accelerometer, *CM* center of mass.

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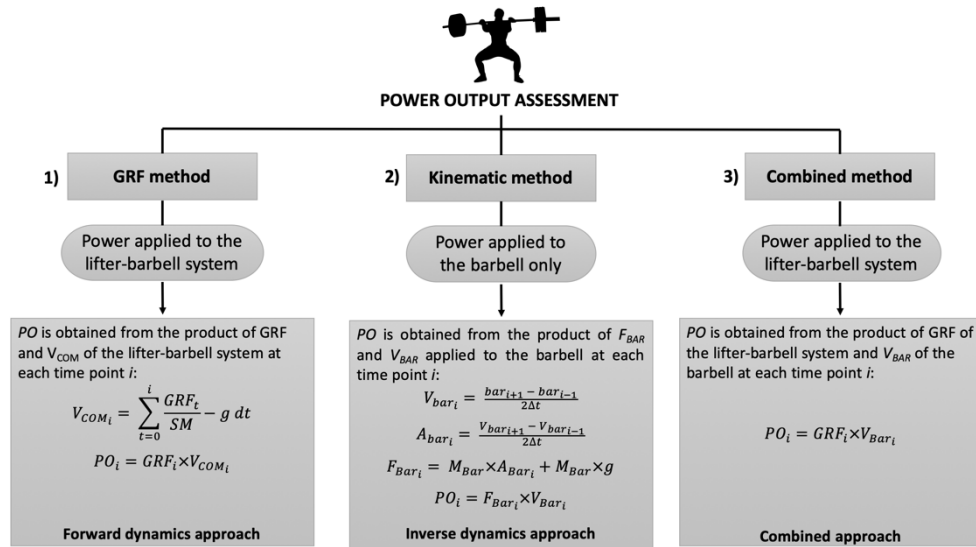


Fig 1 A description of the methods to assess power output during weightlifting exercises. *GRF* ground-reaction force, *SM* system mass, *PO* power output, V_{COM} velocity of the centre of mass, i time point based on sampling frequency, t time, g gravity (-9.81), dt difference in time, V_{bar} barbell velocity, bar barbell, A_{bar} barbell acceleration, F_{bar} barbell force, M_{bar} barbell mass.

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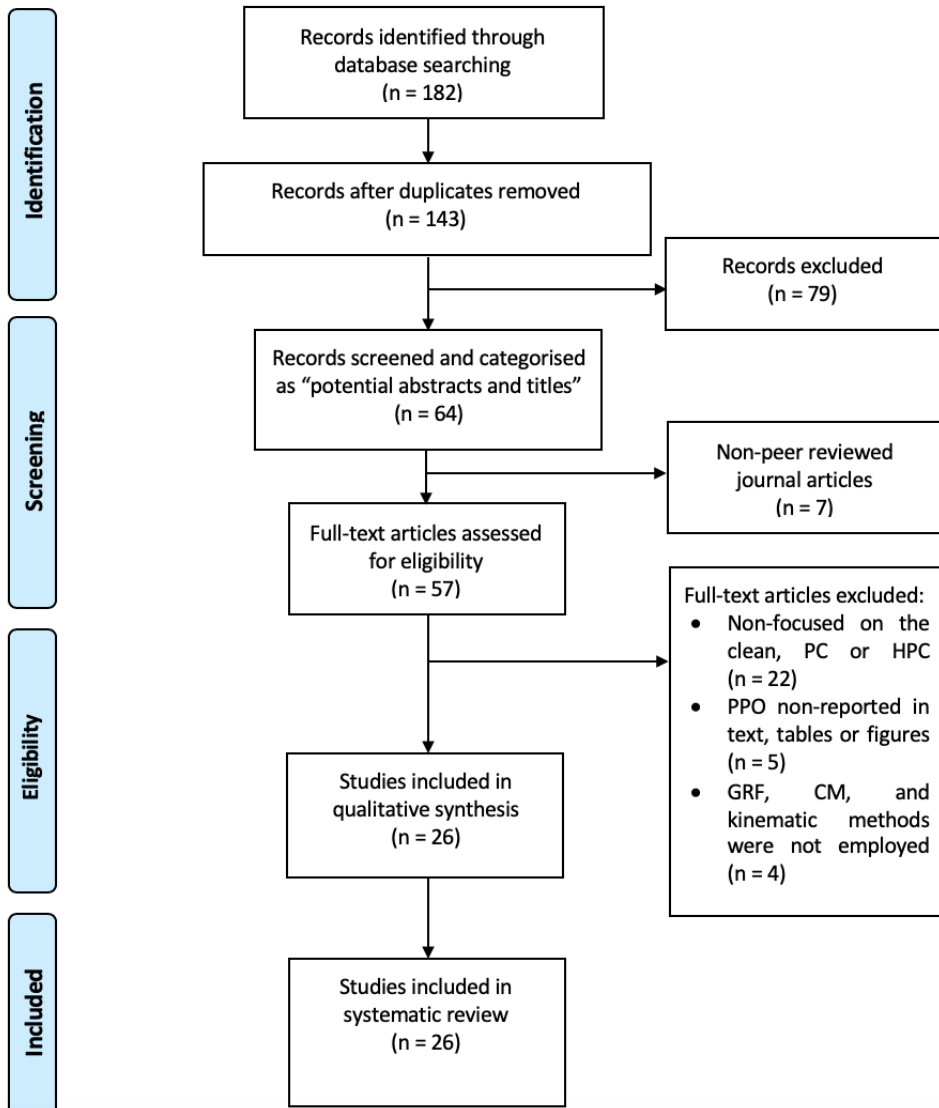


Fig 2 Flow diagram of the study selection process. *PC* power clean, *HPC* hang power clean, *PPO* peak power output, *GRF* ground reaction force, *CM* combine method

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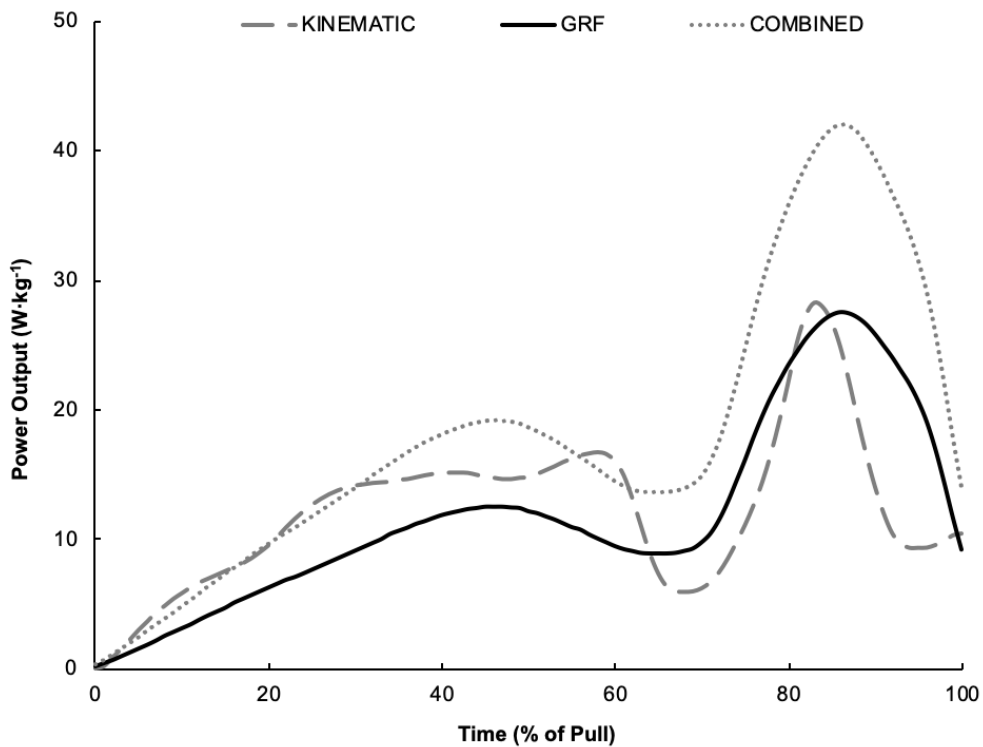


Fig 3 A graphical description of unpublished data from our laboratory of a PC (80%1RM PC) developed by a skilled subject. The lifter was assessed employing the kinematic, GRF and combined methods simultaneously. The horizontal axis represents the relative time of performing the lift from the starting position to the catch phase. The vertical axis corresponds to the power output relative to the body mass developed by the lifter. Note that the three common stages of the lift as the first pull, transition and second pull phase may be clearly differentiated through the three methods. The dashed line corresponds to the kinematic method; the solid line corresponds to the GRF method; and the dotted line corresponds to the combined method.

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941 **LIST OF FIGURE CAPTIONS**

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943 **Fig 1.** A description of the methods to assess power output during weightlifting exercises.
944 *GRF* ground-reaction force, *SM* system mass, *PO* power output, *V_{COM}* velocity of the
945 centre of mass, *i* time point based on sampling frequency, *t* time, *g* gravity (-9.81), *dt*
946 difference in time, *V_{bar}* barbell velocity, *bar* barbell, *A_{bar}* barbell acceleration, *F_{bar}* barbell
947 force, *M_{bar}* barbell mass.

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949 **Fig 2.** Flow diagram of the study selection process. *C* clean, *PC* power clean, *HPC* hang
950 power clean, *PPO* peak power output, *GRF* ground reaction force, *CM* combine method.

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952 **Fig 3.** A graphical description of unpublished data from our laboratory of a PC (80% 1RM
953 PC) developed by a skilled subject. The lifter was assessed employing the kinematic,
954 GRF and combined methods simultaneously. The horizontal axis represents the relative
955 time of performing the lift from the starting position to the catch phase. The vertical axis
956 corresponds to the power output relative to the body mass developed by the lifter. Note
957 that the three common stages of the lift as the first pull, transition and second pull phase
958 may be clearly differentiated through the three methods. The dashed line corresponds to
959 the kinematic method; the solid line corresponds to the GRF method; and the dotted line
960 corresponds to the combined method.

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