Mechanical power production assessment during weightlifting exercises. A systematic review

Power assessment during weightlifting exercises

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Abstract

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

Key words

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

Introduction

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

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

The assessment of PPO has been widely studied by researchers using the clean variations. For example, the use of applied video-analysis using a work-energy approach has specifically been reported in weightlifting competitions to determine successful performance predictors of the clean, and to describe the technical differences of skilled vs. non-skilled weightlifters (Garhammer & Newton, 2013; Garhammer & Oarhammer, 1985). In contrast, in controlled laboratory and field testing conditions, three main methods have commonly been utilised to obtain mechanical power production: 1) power applied to the system mass (SM: individual´s body mass + external load), obtained from the ground reaction force (GRF); 2) power applied to the barbell, obtained from the kinematics of the barbell; and 3) power applied to the SM, obtained from the kinematics of the barbell and GRF (known as the combined method) (Cormie, McBride, & McCaulley, 2007a; Hori, Newton, Nosaka, & McGuigan, 2006).

Researchers have suggested that practitioners may be interested in either the PPO applied to the barbell or to the SM, depending on sport-specific skills (Hori et al., 2006, 2007; McBride, Haines, & Kirby, 2011) and the objective of the research (Lee, DeRosia, Lamie, & Levine, 2017; Lee, DeRosia, & Lamie, 2018). For example, it has been suggested that weightlifters or throwers may be particularly interested in the PPO applied to the barbell using the kinematic method, as their performance predictor is how much power is applied to an object (i.e. barbell, javelin, ball, hammer), whereas the general sport population may be more interested in the power applied to the SM to assess performance of the lower-body accelerating the external load and the body mass as a whole (Hori et al., 2008; McBride et al., 2011). Although Hori et al. (2006, 2007) recommended that the GRF method should be used as the ‘gold standard’ to assess power applied to the SM, the combined method has become popular as an alternative to assess power production during lower-body dynamic tasks (Cormie et al., 2007a; Cormie, Deane, & McBride, 2007b; Dugan, Doyle, Humphries, Hasson, & Newton, 2004). However, the combined method has been criticised by some researchers for having a questionable rationale and a lack of agreement concerning the GRF method (Hori et al., 2006, 2007; Mundy, Lake, Carden, Smith, & Lauder, 2016). Therefore, the lack of consensus between researchers makes it difficult to compare results among studies where different methods have been used.

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

Methods

Review protocol

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

Search strategy and inclusion criteria

A search of electronic databases was conducted to identify all publications on mechanical power production assessment during the clean variations up to 31 May 2019. The literature search was undertaken using 22 different key-words: ‘mechanical power’, ‘peak power’, ‘power production’, ‘power assessment’, ‘power development’, ‘power–load curve', 'peak power output', 'mechanical power output', 'weightlifting exercises', 'clean', 'clean and jerk', 'power clean', 'hang power clean', 'linear position transducer', 'displacement-time', 'combined method', 'force platform', 'accelerometer', 'high-speed video camera', 'ground reaction force', 'kinematic', 'kinetic'. 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. The search spectrum has also been extended to 'related articles' and the bibliographies of all retrieved studies. For the sake of guaranteeing accurate outputs (articles selected), two independent reviewers (initial evaluators: MS, PJM) screened citations of potentially relevant publications. The total number of citations were gathered and duplications excluded. The final outputs obtained from this process were categorised as 'potential abstracts and titles identified and selected'. When abstracts indicated potential inclusion, the specific inclusion criteria was applied for the process of including and excluding articles. A third-party consensus meeting was held (mediator: PSB) if the two reviewers were not able to reach agreement upon inclusion of an article (Moher et al., 2016; Shamseer et al., 2015).

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

Quality assessment

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

Table 1 about here

Description of the methods

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

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

The GRF method

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

The kinematic method

The kinematic method has been commonly used by researchers and practitioners with two different methods to obtain barbell kinematics depending on the technology used (Chiu, 2018; Hori et al., 2006). The first method corresponds to the calculation of the displacement-time differentiation using motion capture high speed video-cameras (McBride et al., 2011), a single or dual linear position transducer (LPT) (Cormie, et al. 2007b) or optoelectronic motion capture systems (Rossi et al., 2007), where barbell velocity is calculated from the rate of change of displacement divided by time. Barbell acceleration is then calculated by differentiating velocity-time data between two consecutive time points (known as double differentiation of displacement-time data) (Cormie, et al. 2007b; Hori et al. 2006). The second method is based on new technologies such as accelerometers attached to the barbell (Sato, Sands, & Stone 2012; Thompson & Bemben, 1999), which provide acceleration of the barbell directly, where no process of differentiation is needed, although one must integrate the signal to get barbell velocity. In this matter, the average barbell acceleration value is multiplied by the time interval between data points (based on the sampling rate) to yield instantaneous barbell velocity at each data point (Thompson & Bemben, 1999). Once the barbell acceleration is obtained either directly (accelerometers) or by the double differentiation process (displacement-time), barbell force is then calculated by multiplying the barbell mass by the acceleration data + barbell weight (barbell mass x g) at each time point. Power is therefore calculated by multiplying force (individual's body mass excluded) and integrated velocity data (Hori et al., 2006, 2007). This process is the inverse dynamic approach, which estimates force output from barbell kinematics (Chiu, 2018). Similarly to the GRF method, calculations of total power which correspond to the sum of three axes ([x-force * x-velocity] + [y-force * y-velocity] + [z-force * z-velocity]) may be done depending on the measurement system utilised (e.g. high speed video-cameras), although only the vertical component (z) is usually reported for power calculations (Ammar et al., 2018a; Kipp, Harris, & Sabick, 2013; Lake, Lauder, & Smith, 2010).

Fig 1 About here

The combined method

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

Data analysis

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

RESULTS

Literature search and quality assessment

A flow diagram of the literature search is shown in Figure 2. According to the above-defined inclusion criteria, 26 independent studies were identified. The GRF method and the combined method are the most commonly utilised methods to assess PPO for clean variations, with 53.9% and 38.5% of the total articles included in this review, respectively. The kinematic method was used in 30.8% of articles included. Results from the quality scores and risk of bias are provided in Table 1. In general, the articles reviewed provided a well-defined and validated data collection methods, utilised appropriate statistical analysis and presented the results adequately. The risk of bias assessment conducted on the articles selected showed 21 articles classified as having a low risk of bias (≥67%), while 5 articles were classified as having a satisfactory risk of bias (34-66%).

Fig 2 about here

Descriptive Analyses

Mechanical power production

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

Table 2 about here

Measurement system, sampling rate and relative reliability

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

Table 3 about here

Discussion and implications

The purpose of this systematic review was to examine the literature related to the assessment of the PPO during clean variations, to compare the differences between the GRF, kinematic, and combined methods regularly used to assess PPO in research and field testing and to establish practical applications and guidelines of the current methodologies. The information included in this review provides researchers and practitioners with a summary of the evidence on this topic, helping to guide research and enhance future professional practices.

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

Since the pioneering work of Hori et al. (2007, 2006) a systematic review of the literature discussing the methods commonly used during weightlifting exercises was necessary for several reasons. First, the systematic approach was necessary to clarify the topic for researchers and practitioners according to the current findings and position statements. Second, based on the distribution percentages reported in this review, the three methods have been widely used and therefore, a final statement describing the potential ‘gold standard’ method was necessary to enable comparison between studies. Third, the wide equipment that is available and the possibilities for different measurement system are often subject to controversy for many researchers and practitioners, and therefore, the clarification regarding this matter along with the main advantages and disadvantages of each system provides valuable information. Fourth, after reading this review, researchers and practitioners will be able to interpret with caution the data previously published during weightlifting exercises and more specifically the clean variations, avoiding misinterpretation when comparing the results between studies. Fifth, researchers and practitioners may choose the method that best fits their equipment and measurement system availability as well as to the specific condition (e.g. controlled laboratory, field testing) whilst being aware of any potential limitations. Finally, this updated review may facilitate recommendations and guidelines for future research regarding the assessment of mechanical power production during weightlifting exercises.

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

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

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

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

Based on the results of this review, researchers and practitioners are encouraged to use the GRF method to assess PPO during clean variations if the objective is to obtain information regarding the performance of the lower-body and therefore, to evaluate the individual's ability to accelerate the SM (Lake et al., 2012). However, although the power applied to the SM may be more representative of whole-body mechanical power production, monitoring the power applied to the barbell using displacement-time-, velocity or acceleration-based equipment may be more representative of weightlifting or throwing performance, and it may also be useful for practitioners in terms of time-efficient data analysis, and less-costly choice (Hori et al., 2006, 2007; Flores et al., 2017; Lee et al., 2018; McBride et al., 2011; Sato et al., 2012).

Power applied to the SM: GRF vs. combined method

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

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

Defenders of the combined method claim that the PPO may have less error due to the direct assessment of force and velocity, avoiding the error related to data manipulation and the inability to account for barbell movement (horizontal and vertical) and the subsequent derivations (acceleration, velocity) that occurs independently of the body (Cormie et al., 2007b; Cormie et al. 2007c). Such findings along with a high relative reliability explain why the use of the combined method to obtain power production has been proposed as a suitable and the preferred method for researchers to assess the power applied to the SM (Cormie et al., 2007b; Cormie et al. 2007c; Dugan et al. 2004). However, current research has shown that the combined and GRF methods do not agree in measuring power production during dynamic lower-body tasks, and therefore, both methods should not be used interchangeably (Hansen, Cronin, & Newton 2011a; Hansen, Cronin, & Newton 2011b; Lee et al., 2018; Mundy et al., 2016). Moreover, the same amounts of manipulations are done using the GRF method and further, integrating acceleration-time data naturally reduces signal noise (Beckham, Suchomel, & Mizuguchi 2014; Cavagna, 1975), whereas the differentiation associated with the barbell kinematics of the combined method increases signal noise (Lake et al., 2012; Mundy et al. 2016). Critics of the combined method for assessing whole-body power production state that the combined method assumes the velocity of the barbell as the velocity of the SM and therefore, the power outputs will be systematically overestimated in comparison to the GRF method as can be seen in Figure 3 (Hori et al., 2006, 2007; Lake et al., 2012; Mundy et al., 2016). It should be noted that the assumption that barbell velocity corresponds to SM velocity has never been verified and may not be at all valid for weightlifting exercises (Kipp et al., 2013; Lee et al., 2017). In addition, the kinetic contribution of the lower extremities has been more related to the whole-body power production during weightlifting exercises using the velocity of the SM from the GRF than from the velocity of the barbell (Kipp et al., 2013; Lee et al., 2017, 2018).

In addition to the disagreement in measuring power production due to differences in the analysis, the combined method presents more disadvantages in comparison to the GRF method in the high equipment costs, and space needed. These findings suggest that both researchers and practitioners, whenever possible, should use the GRF method to estimate whole-body power production of a given athlete when attempting to assess the power applied to the SM during weightlifting exercises. Note that the results of this review may be speculated to occur in other kinds of weightlifting movements such as the snatch variations, since similar kinematics and kinetics of the body and barbell have been identified during the 1st and 2nd pull (Garhammer, 1991, 1993).

Conclusion

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

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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 (≥67%), *S* satisfactory risk of bias (34-66%), *H* high risk of bias (≥33%).

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)	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 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	C 30, 40, 50, 60, 70, 80 and 90% 1RM C.	**The kinematic method** 3-axis acc	G1 Zone 1: C: ~2032 W Zone 2: C: ~2838 W Zone 3: C: ~3493 W (OL: 90% 1RM C) G2 Zone 1: C: ~1670 W Zone 2: C: ~2461 W Zone 3: C: ~2880 W (OL: 90% 1RM C)
Suchomel et al. (2014b)	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	HPC 30, 45, 65 and 80% 1RM HPC	**The GRF method** FP	Zone 1: HPC: ~3527 W Zone 2: HPC: ~3915 W Zone 3: HPC: ~4015 W (OL: 80% 1RM HPC)

Kawamori et al. (2005)	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	HPC 30, 40, 50, 60, 70, 80 and 90% 1RM	**The GRF method** FP	Zone 1: HPC: ~2990 W Zone 2: HPC: ~3665 W Zone 3: HPC: ~4010 W (OL: 70% 1RM HPC)
Marriner et al. (2017)	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 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	PC 50, 70 and 90% 1RM PC	**The CM** FP 1 LPT	G1 Zone 2: PC: ~3980 W Zone 3: PC: ~4296 W (OL: 70% 1RM PC) G2 Zone 2: PC: ~4150 W Zone 3: PC: ~4215 W (OL: 90% 1RM PC)

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

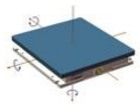
	1RM/BM: 1.00 S-P experience: ≥3 months		1 LPT	**3) The kinematic method** Zone 3: HPC: ~1644 W
Jones et al. (2008)	n = 14 healthy subjects Age: 25.0 ± 6.20 years Sex: M Height: 184 ± 9.40 cm BM: 98.1 ± 21.0 1RM PC: 87.3 ± 17.0 kg 1RM/BM: 1.00 S-P experience: ≥24 months	PC 85% 1RM PC	**The kinematic method** 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 ± 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.

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

Method		**Peculiarities of the analysis** Studies	Sampling rate (Hz)	ICC	**Advantages**	**Disadvantages**
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**	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		
	 **2 LPT**	Oranchuck et al. (2018a)				
		Oranchuk et al. (2018b)	500	0.97		
			500	0.97		

	 **High Speed Video Cameras**	McBride et al. (2011) Kipp et al. (2013)	240 250	nd >0.90	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
	 **3 axis-Acc**	Flores et al. (2017)	100	0.96		
Combined method	 **FP + 1 LPT**	Marriner et al. (2017) Marriner et al. (2018) Hori et al. (2007) Cormie et al. 2007b	500 500 + 50 200 1000	0.89 0.89 0.89 0.99	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
	 **FP + 2 LPT**	Cormie et al. (2007b) Cormie et al. (2007a) Cormie et al. (2007c) Hardee et al. (2012)	1000 1000 1000 1000	0.98 0.98 0.98 0.98		
	 **FP + High speed video-cameras**	Winchester et al. (2005) Kipp et al. (2013) Winwood et al. (2015)	600 + 60 1250 + 250 1000 + 300	nd >0.90 nd		

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.

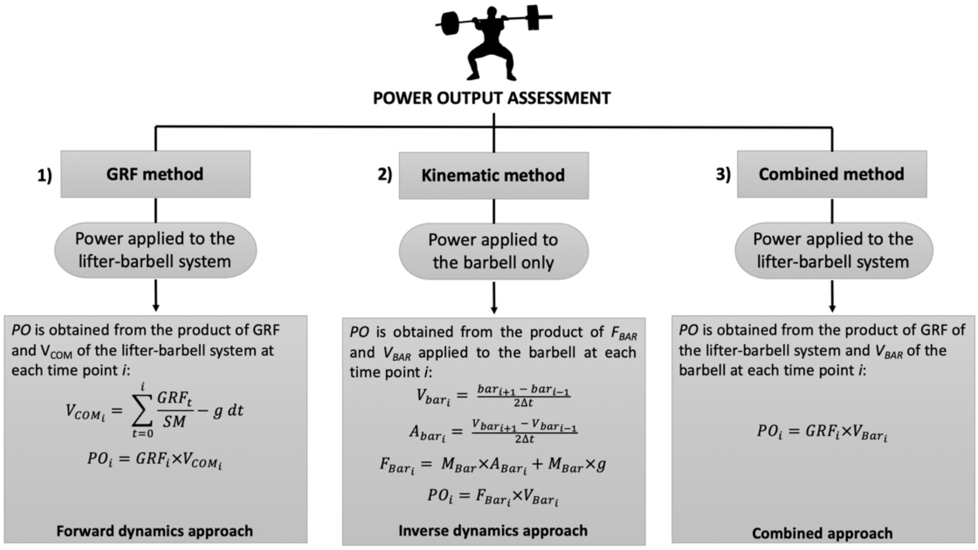


Fig 1 A description of the methods to assess power output during weightlifting exercises. *GRF* ground-reaction force, *SM* system mass, *PO* power output, V_{COM} velocity of the centre of mass, *i* time point based on sampling frequency, *t* time, *g* gravity (-9.81), *dt* difference in time, V_{bar}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

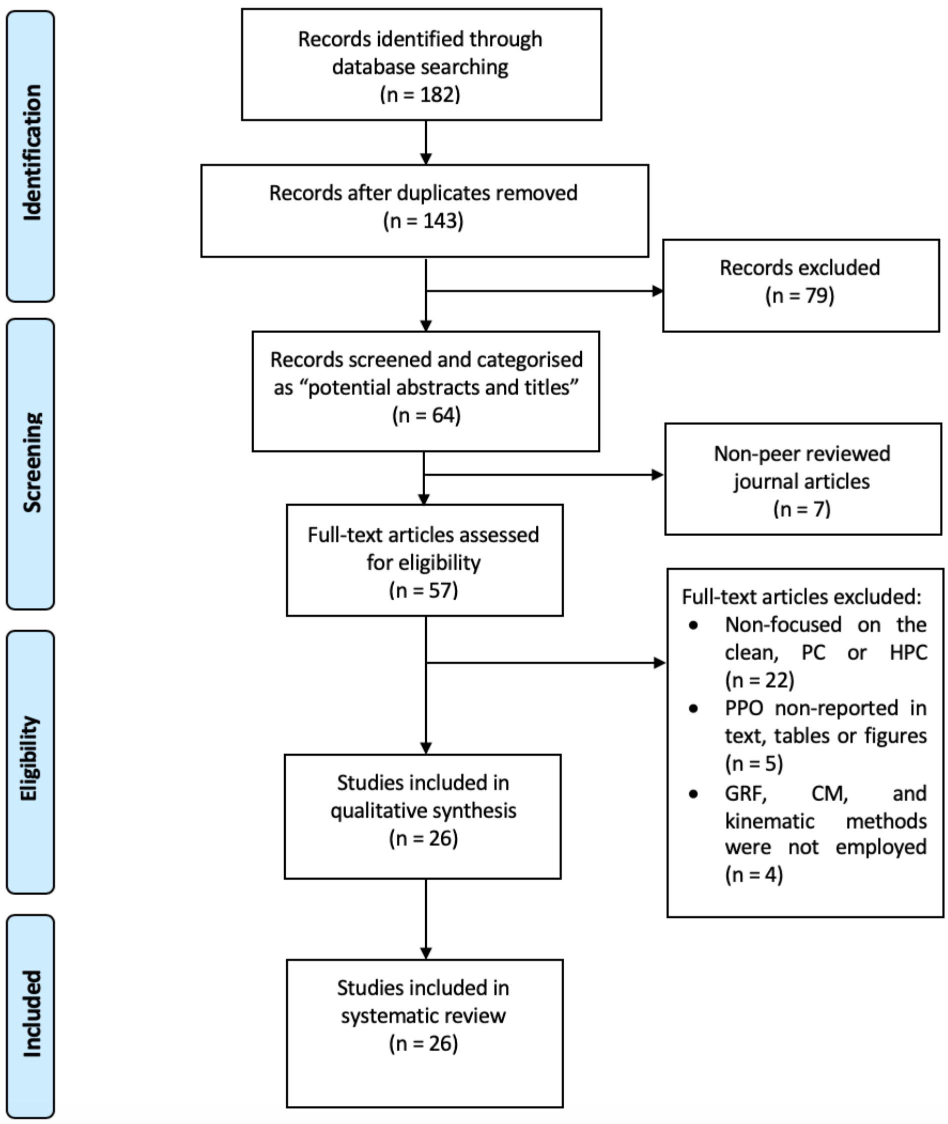


Fig 2 Flow diagram of the study selection process. *PC* power clean, *HPC* hang power clean, *PPO* peak power output, *GRF* ground reaction force, *CM* combine method

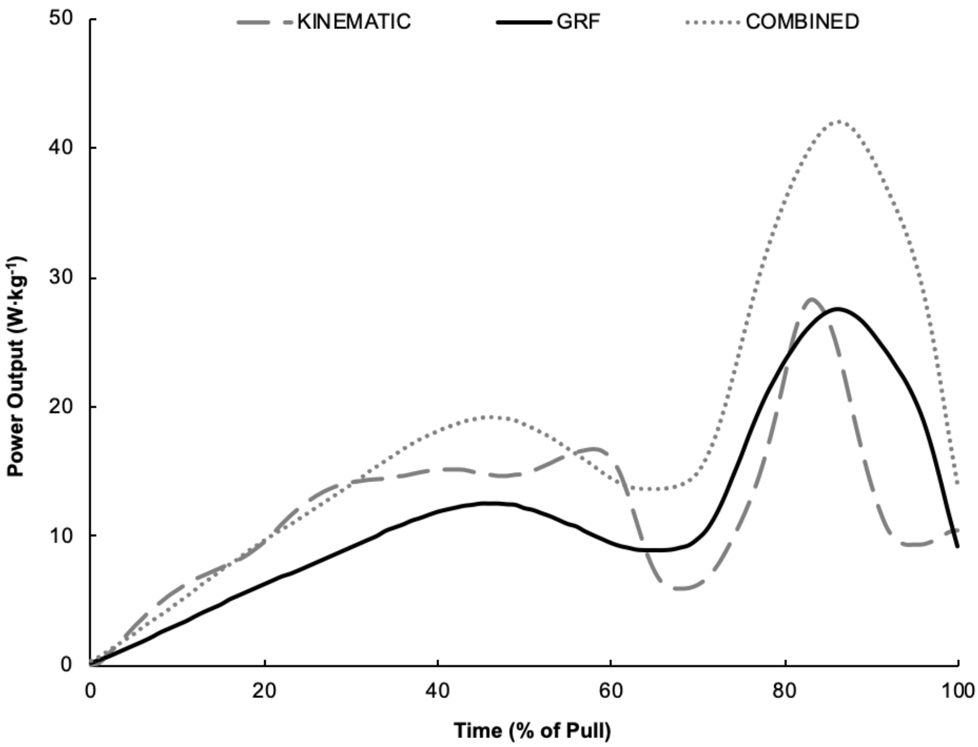


Fig 3 A graphical description of unpublished data from our laboratory of a PC (80%1RM PC) developed by a skilled subject. The lifter was assessed employing the kinematic, GRF and combined methods simultaneously. The horizontal axis represents the relative time of performing the lift from the starting 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.

LIST OF FIGURE CAPTIONS

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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