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The effect of high volume power training on repeated high intensity performance and the assessment of repeat power ability: a systematic review

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Abstract

Background- High volume power training (HVPT) involves high volumes of high velocity resistance training, with the aim to improve repeated high intensity efforts (RHIE). Repeat power ability (RPA) is the ability to repeatedly produce maximal or near maximal efforts. Assessments of RPA using external loading may determine the ability to perform repeat high intensity efforts (RHIEs) typical of many sports and therefore provide useful information on the effectiveness of training.

Objectives- 1) Identify the different HVPT protocols; 2) Examine the acute responses and chronic adaptations to different HVPT protocols; 3) Identify different lower body RPA assessment protocols and highlight similarities, differences and potential limitations between each protocol, and; 4) describe the reliability and validity of RPA assessments.

Methods- An electronic search was performed using SportDiscus, PubMed, CINAHL and Embase for studies utilising HVPT protocols and assessments of RPA. Eligible studies included peer reviewed journal articles published in English.

Results- Twenty studies met the inclusion criteria of the final review. Of the eight longitudinal studies, three were rated as fair and five were rated as poor methodological quality, respectively. In contrast, all 12 cross-sectional studies were considered to have a low risk of bias. Preliminary evidence suggests that HVPT can enhance RHIE, RPA, anaerobic capacity, anaerobic power and aerobic performance. HVPT generally consists of 2-3 sessions per week, utilising loads of 30-40% 1 repetition maximum (RM), for 3-5 sets of 10-20 repetitions, with inter set rest periods of 2-3 minutes. RPA assessments can be valid and reliable and may provide useful information on an athlete's ability to perform RHIE and the success of HVPT programmes.

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Conclusions- HVPT can be used to improve a number of physical qualities including RPA and RHIE; while a variety of RPA assessments provide valid and reliable information regarding the athlete's ability to perform RHIEs. Considering the heterogeneity in the HVPT protocols currently used and the relatively low volume and quality of longitudinal publications in this area, further studies are needed to identify the effects of a variety of HVPT methods on RPA, RHIE and other performance outcomes and to identify the most valid and reliable RPA outcomes to use in such studies**.**

Key Points

During HVPT, maximal power output can be achieved at the beginning of each set followed by within-set reductions in power with additional repetitions.

HVPT appears to be a time effective training modality in improving a number of physiological capacities including maximal anaerobic power, anaerobic capacity and repeated high intensity sporting actions. However, studies are limited and implications for performance of elite athletes unclear.

Dependent on the variable of interest, some RPA tests appear to be valid and reliable measures of the effectiveness of HVPT and the ability of athletes to perform RHIEs.

1 Introduction

1.1 Training for repeated high intensity efforts

The ability to perform repeated, lower body dominated, high intensity efforts (RHIE) with minimal rest during accelerating, changing direction, sprinting, jumping, and physical contact situations like striking, tackling or wrestling are important physical qualities for many sports (1,2). These different high intensity sporting actions can be characterised by the high relative physical effort required to accomplish the task and the rate and magnitude of fatigue experienced as a result of the task (3–5). A wide range of technology, for example global positioning systems and tri-axial accelerometers, can be used to describe RHIE sporting actions where thresholds can be established to quantify the level of intensity achieved (6,7).

Strength training using external resistance, is commonly used to promote morphological and/or neurological adaptations in skeletal muscles and enhance the intensity of muscular actions; with high intensity training loads, greater than 80-85% 1RM (one repetition maximum), with a range of prescription schemes and volumes often utilised (8). During strength training, intensity is typically described by how the resistance load compares to the athlete’s directly assessed or estimated 1RM (9,10). However, such simple measures of intensity are unable to be used when the goal is to maximise power over a range of submaximal loads, where peak power output can be defined as the maximum rate of work produced per unit time or the greatest product of instantaneous force and velocity (11). One approach to quantify intensity when performing power training may be to base the intensity of training on the load at which peak power output is obtained by the athlete for a given exercise (11,12).

Power training is a sub classification of high intensity strength training where the goal is to lift a range of loads as fast as possible (12,13). Traditional power training incorporates both non-ballistic and ballistic lifts and also weightlifting exercises (12). Non-balllistic lifts are traditional strength training lifts, like the back squat and the bench press, performed with low to moderate loads and lifted at maximal velocity

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(14). In ballistic lifts the system mass (the lifter and the load) or the object (for example a barbell) are projected into flight, as in a squat jump and bench throws respectively (14). The weightlifting exercises, the clean, the snatch, the jerk, and their derivatives are also used in traditional power training (12,15). Traditional power training commonly consists of working sets of between one to six repetitions and are generally characterised by relatively lengthy inter-set rest periods, of between two to five minutes (11,16–18). Cluster loading, with the use of inter-set rest periods lasting from 5-100 seconds, are used in traditional power training to maintain power-output across sets with multiple repetitions (19–24).

An alternative power training option, high volume power training (HVPT), typically consisting of higher volumes of work and potentially limited rest in comparison to traditional power training, may be an effective training method to enhance the ability to perform RHIE sporting actions (25). This is perhaps similar to recent approaches using high intensity training to elicit cardiovascular improvements (26). Different variations of HVPT have been used in the field and have also been described in coaching manuals, text books and in the description of the training of participants in peer reviewed publications (16,25,27,28). Although this method of power training has been described it is not commonly utilised in physical development training programmes and this warrants further investigation into this training method.

A description of the training protocols and prescription guidelines for HVPT will be examined in this review. The effect of different lower limb HVPT protocols on enhancing the ability to repeatedly produce maximal or near maximal efforts against external loads and the concomitant effect on RHIEs in a sporting context are also examined in this review.

Traditional training to enhance RHIEs often involves training methods focusing on the development of the cardiorespiratory system and the neuromuscular system in relative isolation (29). For example, the development of the cardiorespiratory system can be done in isolation, through either continuous steady-

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state training or through high intensity interval training methods. Aerobic capacity can therefore be enhanced and the aerobic driven recovery between high intensity bouts improved (4,30,31). It is important to note however, that aerobic capacity has been found to be at best moderately correlated to repeated sprint ability (32). The importance of aerobic capacity in affecting repeated sprint ability seems to be dependent on the type of repeated effort/volume/distance/rest intervals used to assess it (33–37).

The development of the neuromuscular system in order to improve RHIEs can also be done in isolation, through sprint training, plyometrics and strength training. These forms of training may improve the ability of the lower limbs to produce force rapidly (12,13). The increase in the ability to produce force more rapidly, may enhance power output and speed in every effort of a RHIE bout (38,39). Anaerobic power has been found to be the strongest predictor of repeated sprint efforts that are low in volume and duration and short in recovery time (36,38). Despite these findings, strength, aerobic capacity and repeated sprint ability have all been shown to be poor individual predictors of RHIE (40). The discrepancy between these findings is likely due to differences in volume, sprint distance, recovery time and the varied mechanical demands, like change of direction, grappling and tackling, associated with the assessment of RHIEs (36). As such, training interventions that are more specific to RHIEs have been recommended (2).

Beyond a threshold level of strength and fitness, muscular endurance may be more associated with RHIE sporting actions than maximal strength or aerobic fitness (40). This may be why strength training focused on the development of muscular endurance, with high repetition volumes, relatively slow muscle actions and short rest periods has previously been found to enhance RHIEs (41,42). However, considering RHIEs by definition are high intensity sporting actions, then the development of muscular endurance of the lower body using high velocity, high intensity muscular actions may provide a more effective strength training solution to improve RHIEs.

1.2 Assessing the ability to repeat high power outputs

In order to understand the effect of training on the development of a particular physical quality, in this case the ability of the lower body to repeatedly produce high levels of mechanical power, a reliable and valid assessment must first be established. It is suggested that the ability to perform RHIEs is due to the ability to maintain relatively high levels of maximal power output. Again, maximal power output is the optimal product of force and velocity, where in a practical sense, it is the greatest instantaneous power in a movement where the goal is to achieve maximal velocity at release, takeoff or impact (12,43). This review introduces the term repeat power ability (RPA) as the ability to repeatedly produce maximal or near maximal efforts against external resistance training loads.

The distinction between the maintenance of high levels of power output with and without external load is important. Not only does movement velocity decrease with an increase in load but fatigue-related reductions in power and force have also been found to occur earlier as external load increases (16,44,45). There is likely a greater metabolic cost in repeated maximal efforts with additional loads. The physical demands of a number of sports, like rugby union, rugby league, American football, Judo and mixed martial arts, require RHIEs against external loads like the mass of an opposing player (40,46,47). The high force demands associated with change of direction and acceleration tasks might also be best represented with the addition of external loads (48,49). An assessment protocol for RPA that does not utilise external loads may lack the specificity or sensitivity for many high intensity sporting demands.

The importance of this systematic review is to examine the quality and quantity of available research on HVPT protocols and RPA assessments. The results of this systematic review may either warrant the inclusion or exclusion of HVPT protocols and RPA assessments in physical development, routine monitoring and physical testing of athletic populations respectively. This systematic review will: 1) examine the acute responses to HVPT protocols; 2) examine the chronic adaptations to this method of power training; 3) identify the different lower body RPA assessment protocols and highlight the

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similarities, differences and the potential limitations between each protocol; 4) describe the reliability and validity of each RPA assessment protocol.

2. Methods

2.1 Search strategy and inclusion criteria

A systematic review of the literature was conducted in order to find applicable studies utilising different HVPT protocols and also studies examining acute and chronic physiological adaptations to this type of training. RPA type assessments and the different procedural approaches were also investigated in this systematic review. The scientific databases searched were PubMed, Embase, SPORTDiscus and CINAHL and the search criteria included the terms: power endurance, power training, ballistic, explosive, high volume, resistance, training, conditioning, power output, anaerobic capacity, power capacity, maximal power, repeat power, decrement, power and fatigue. The full search strategy for the PubMed search was ("power endurance" OR "power training" OR ballistic OR explosive OR ("high volume" AND resistance)) AND (training OR conditioning) AND ("power output*" OR "anaerobic capacity" OR "power capacity" OR "maxim* power" OR (repeat* AND power) OR (decrement* AND power) OR fatigue). The database search was initially conducted on the 25th of November 2015 and then an updated search was conducted on the 7th of April 2019.

To be included in this review, the studies had to use resistance training exercises of the lower body with external loads. Studies that included upper body exercises were only included if lower body exercises were also performed. Importantly the study had to state that the exercises were performed with maximal intent to move the resistance or system mass as fast as possible or words to that effect. Both HVPT and RPA protocols required ≥ 8 repetitions per set and where multiple sets were used, inter-set recovery needed to be ≤ 3 minutes. In the absence of quantification of internal or external loads, at least a clear outline of the training or assessment protocol along with the outcome or results of the intervention was

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required to meet the inclusion criteria. There were no restrictions on the year of publication; however, the studies needed to be full articles printed in English. All studies involved adults, except for that of Gonzalo-Skok *et al*. (50), who examined elite young basketball players aged 16-18 years.

The rationale for study inclusion and exclusion based on the body part trained or assessed was determined by the locomotive demands of most able-bodied land-based sports and activities, meaning that exercises and assessments had to involve the use of the lower limbs to be included in this review. The requirement for the studies to utilise resistance training external loads was due to; 1) the development of power in traditional power training is commonly achieved using ballistic or weightlifting exercises with moderate to high external loads; 2) many sports require the production of high forces against external loads; 3) the application of external loads cause an earlier onset of fatigue and reductions in power and force; and 4) the application of external load differentiates this form of exercise or assessment from more traditional cardiorespiratory forms of training. The execution intent of the exercise was important so to differentiate between training and assessment protocols that were muscular endurance focused, where the intention may be to complete a number of repetitions or as many repetitions as possible within a time limit, versus HVPT and RPA assessment protocols that are focused on executing each repetition at maximal velocity. The inclusion of studies based on the number of repetitions and inter-set rest periods was to ensure there was a clear differentiation between a traditional power training protocol and a HVPT protocol. By only including studies that outlined the training or assessment protocols in detail and provided either quantification of internal or external load or the outcomes and results of the intervention, an initial screen of applicable research related to this review was established.

2.2 Study quality assessment and risk-of- bias assessment

The first and last author (initials AN and JK) of this review each independently assessed the risk of bias and research quality of each longitudinal study using the Physiotherapy Evidence Database (PEDro) scale.

The PEDro checklist was deemed not to be entirely suitable for the cross-sectional studies included. Therefore, a risk of bias assessment, developed by Hindle *et al.* (51) and based upon several other checklists was used, for all cross-sectional studies included (52–54). The longitudinal studies were evaluated against the 11 items described in the PEDro scale criteria and the cross-sectional studies were evaluated against the 16 items described in the risk of bias assessment developed by Hindle *et al.* (51). If there were any disagreements between the two assessors a consensus meeting was conducted, and the disagreements were resolved.

Briefly, both the PEDro scale and the risk of bias assessment (Hindle *et al*. (51)) include items that describe the internal validity and interpretability of the relevant study design. The sum of the PEDro scale items have been shown to be a valid measure of the study's methodological quality (55,56) and the checklist in the risk of bias assessment developed by Hindle *et al*. (51) has been based on a number of systematic reviews that include literature with similar study designs. All items within the two scales were scored as 0 or 1 for studies with a low or high ROB and research quality, respectively. The item was scored as 0 if no clear information was provided regarding the item or if it was unclear whether the criterion for an item was met. Longitudinal studies scoring 9-10, 6-8, 4-5 and 0-3 on the PEDro scale were classified as excellent, good, fair and poor, respectively (57) and cross sectional studies scoring ≥ 67%, 34-66% and ≤ 33% considered as having a low, satisfactory and high risk of bias respectively (Hindle *et al*. (51)).

2.3 Data analysis

The HVPT variables, exercise modality, load, volume, recovery and number of training sessions, were the primary variables of interest from a training prescription perspective. Outcome measures such as maximal power and force, average power, % decrement of power or speed and blood lactate accumulation were also primary variables of interest from both an RPA assessment and HVPT perspective. Statistical data

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reporting the reliability and validity of RPA assessments were also of interest for this review. Due to the conflicting and heterogeneous nature of the variables assessed, effect sizes were not able to be calculated.

3 Results

The results of this search were 626, 366, 406, 244 articles from PubMed, Embase, SPORTDiscus and CINAHL respectively. Nineteen articles were initially selected for this review; after the reference list of each of these articles was further examined an additional study was added to bring the total number of articles reviewed to 20. Figure 1 displays a flow chart of the article selection process used in this review.

[INSERT FIGURE 1]

Table 1 displays the results of the PEDro scale assessment for the longitudinal studies and Table 2 displays the results of the risk of bias assessment for the cross-sectional studies. Of the eight longitudinal studies included, only three studies were deemed to be of fair methodological quality, with five studies deemed to be of poor quality (29,50,58–63). The mean PEDro scale score for the longitudinal studies was 3.25 out of 10 suggesting that, on average, the current longitudinal research on HVPT and RPA is of poor methodological quality. Of the 12 cross-sectional studies included, all of these studies were considered to be of low risk of bias (16,64–74). The mean risk of bias assessment score for the cross-sectional studies was 78.25% suggesting that, on average, the current cross-sectional research on HVPT and RPA is of low risk of bias.

Across the longitudinal studies, the strengths were a) 85% of subjects receiving 1 key measurement; b) statistical significance reported for one key outcome and c) the inclusion of drop outs in the statistical analysis (intention to treat). The weaknesses were a) the lack of the use of a concealed allocation; and b) the lack of blinding of assessors, subjects and coaches.

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Across the cross-sectional studies the strengths were a) the objectives/purpose of the study is clearly defined; b) the design of the study adequately tests the hypothesis; c) the statistical methods used were well described; d) the statistical tests used to analyse the data were appropriate; e) the results were well described; f) the information provided in the paper is sufficient to allow a reader to make an unbiased assessment of the findings of the study; g) confounding factors were identified. The weaknesses were a) the criteria for the inclusion of subjects were not clearly described; b) a description of how the study size was arrived at was not provided; c) sponsorships/conflicts of interest were not acknowledged.

[INSERT TABLE 1 and 2 HERE]

The results of the systematic review revealed twenty studies in total that both described and utilised or explicitly examined HVPT protocols or RPA assessments. Of the twenty studies included in this review, 14 studies described a variety of different HVPT protocols (see Table 3), with the acute effect of HVPT reported in nine of the 14 HVPT studies (59,65–67,70–74). Four of these studies examined the change in power output throughout the training session (65,70,71,74). In each of these studies there was no difference found in maximal power output between sets, despite significant declines in power output found within each sets. Two additional studies attempted to report the acute effect of HVPT at various time points post training (67,72). These studies found maximal force output to recover by 7 minutes post HVPT while time-dependent force qualities were still depressed up to 30 minutes post HVPT respectively.

[INSERT TABLE 3 HERE]

The chronic effect of HVPT training was assessed in five HVPT studies (50,58,60,61,63), with the results of these studies summarised in Table 4. Of the five training studies presented, only one examined the effect of training on RPA (49). Between these studies, there was considerable heterogeneity in terms of the training performed and performance variables assessed. All five HVPT studies examined the effect of HVPT on some form of sporting performance where movements like change of direction, hopping, sprinting or jumping were performed (50,58,60,61,63). Only one of the HVPT studies examined the chronic effects of HVPT on single maximal intensity efforts, RPA and RHIEs collectively (60).

[INSERT TABLE 4 HERE]

The results of this review also indicate seven studies that attempted to measure RPA (16,29,60,62,64,68,69). Within these seven studies there was heterogeneity found in terms of the assessment protocols and parameters used to measure RPA. A summary of these studies is provided in Table 5. Three of these seven studies identified the reliability of the RPA assessment (29,64,68), with one of these studies also having analysed the validity of the assessment used (68). For each of the reliability studies, a high degree of test-retest reliability was found (with Intraclass correlation coefficient's [ICC's] ranging from 0.730-0.987) despite the different RPA assessments used. In terms of validity of RPA assessments, power output in the Kansas Squat Test demonstrated validity with respect to the maximum test power and the mean test power of 30 second Wingate assessment (*r* = 0.775 and 0.752 respectively) (68).

[INSERT TABLE 5 HERE]

4 Discussion

4.1 High volume power training protocols

4.1.1 Exercise modality

There was considerable heterogeneity with respect to the exercise modalities utilised within the studies reporting physiological responses to HVPT; with these including the speed squat, power clean, clean pull, countermovement jump (CMJ), speed bench press and speed biceps curl (with one study also including multiple 10 s stationary cycle sprints within the HVPT protocol). Unfortunately, the range of modalities

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used makes the research difficult to compare due to the variation in non-ballistic, ballistic and weightlifting exercises used in the studies. In studies involving non-ballistic exercises, where the system mass or object do not gain flight, such as the speed squat, speed bench press and biceps curl, there is a substantialy greater deceleration phase of the barbell in the second half of the concentric portion of the lift in comparison to ballistic exercise alternatives (75). The deceleration of the barbell in non-ballistic exercise is proportionate to the momentum generated in the propulsion phase, where in the early concentric part of a lift the force imparted on the barbell is greater than the gravitational force (76,77). This is particularly true with lighter load, non-ballistic exercises where higher barbell velocities cause a greater percentage of the range of motion to be spent in deceleration and a smaller percentage of the range of motion spent in propulsion (77). The propulsion and deceleration in non-ballistic exercise variations is likely to impart very different biomechanical and physiological requirements in comparison to ballistic exercises (75,78,79), thereby resulting in improved acute responses and chronic adaptations when using ballistic exercises (80,81).

In comparing force-time characteristics between ballistic and non-ballistic half squats, Suchomel *et al*. (78) found higher peak force and impulse across a range of light to heavy loads during the ballistic condition. Likewise, it appears that ballistic exercise variants allow higher peak velocities and longer propulsive phases in comparison to non-ballistic derivatives (77,79). A combination of higher peak forces, greater impulse, higher movement velocities and longer propulsive phases are likely to impose higher levels of acute fatigue in relation to non-ballistic variants (81).

With reference to the Olympic weightlifting exercises (e.g. the clean and snatch), the execution of these lifts require the control of many degrees of freedom in comparison to more traditional lifts like the squat or the squat jump were the barbell follows a more linear path (82). The use of derivatives of these exercises, for example the mid-thigh pull, can reduce the number of degrees of freedom requiring control and the resulting technical demand, whilst still providing a high force and a high velocity stimulus that is

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considered just as effective as the full variants of the lift (83,84). The ability to reduce the degrees of freedom within an exercise used for HVPT may minimise the various technical strategies that could be utilised to increase the work performed and maintain power output as a result of fatigue (85–87). When performing HVPT using 3 sets of 9 repetitions of the power clean, Date *et al*. (66) found blood lactate accumulation of 7.43±2.94 mmol·L^{-1}, indicating significant skeletal muscle substrate utilisation. Some support of this view of how increased technical demands may acutely effect HVPT performance, can be found in the resuts of Hatfield *et al*. (70) and Volek *et al*. (88). Higher blood lactate accumulation, between 9.6±3.3 mmol·L^{-1}and 16.1±3.9 mmol·L^{-1} respectively, were found while using a HVPT protocol consisting of 4 sets of 12 repetitions and 5 sets of 10 repetitions of continuous CMJs. It is important to note the difficulty in comparing acute physiological responses between different HVPT exercises and the way they are executed, with or without rest between repetitions, along with the range of volumes, external loads and inter-set rest periods used.

4.1.2 Load

The load utilised in HVPT can also create some difficulty in comparing the research. Date *et al*. (66) and Romero *et al*. (63) used loads of between 60-75% 1RM for the power clean and clean pull respectively, whereas studies involving the speed squat utilised loads between 30-60% 1RM (60,67,71,73,74,89). The load utilised in non-ballistic lifts, like the speed squat, have a substantial effect on the propulsive phase and ensuing barbell deceleration of a lift. Smaller propulsive phases and greater levels of deceleration are found with lighter loads in order to counteract the higher velocities that can be attained (90,91). During ballistic exercise, higher external loads have been shown to have a greater effect on fatigue levels. During a six-repetition set of jump squats, Thomassen and Comfort (92) found a 60% 1RM load to have a significant decrease in power output by the sixth repetition. However, there was no significant decrease in power output by the sixth repetition when using a 40% 1RM load (92). It is also important to note that although there is a range of % 1RM loads utilised in HVPT, the % 1RM loads have been derived from a range of exercises and therefore the absolute loads may differ substantially (93).

4.1.3 Volume and frequency

In the longitudinal training studies found, two to three sessions per week was the most common frequency of training (50,58–61,63). Training frequency of two to three sessions per week seemed to be the most common training strategy for other traditional strength training methods that focused on developing either strength, muscle hypertrophy or power (9,94–96). Depending on the magnitude of fatigue and corresponding time an athlete may need to recover, HVPT frequency may need to be perioidsed and individualised. For example, highly fatiguing protocols may need a minimum of 72 hours recovery between sessions, with less fatiguing protocols only requiring 48 hours between sessions (9). Consideration around other elements of weekly training will also dictate the frequency of HVPT; with perhaps less fatiguing protocols being more suited closer to competition periods or important technical training sessions.

Most of the training studies found utilised six to ten week training blocks, with only the Bosco *et al*. (58) study investigating a more general overview of a 20-week training period. This was similar to most training studies, where training periods between four to twelve weeks were common (97). If HVPT can be utilised effectively as a brief training intervention, for example peaking into competitions, then perhaps a six to ten week training block is an appropriate prescription guideline. It is important to note, however, that there are recommendations that neuromuscular training studies must include at least 40 to 50 training sessions across several months, in order to appropriately quantify the training effects (97). This suggests that more studies may need to examine HVPT interventions over 40 to 50 training sessions across several months to better determine if this type of training should be considered a useful longitudinal method of training.

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In an article outlining the physical preparation for sevens rugby, a number of HVPT protocols ranging from 1 to 3 series of 4 sets, 4 to 12 sets in total, were described (25). Although Bosco *et al*. (58) also reported the use of up to 10 sets, protocols consisting of 3-5 sets seem to be most common in the literature. The common number of sets found in HVPT seems to be consistent with other traditional strength training volumes (9,94). Considering the objectives of HVPT, the number of repetitions per set showed a large variation between studies, this may be due to the variety of loads and exercises used in HVPT or this could be an indication that more research is required to understand the effect of repetitions per set in HVPT.

The within set repetition schemes range from 8 to 25 with most of the protocols utilising repetitions from 12 to 20 (58–60,67,70–72,74). When focused solely on the lower body exercises, the HVPT studies had a total repetition range per session of between 27 to 80 repetitions, with only Bosco *et al*. (58) describing ranges from 100 to 200 repetitions. These within set repetition ranges and total repetition ranges were similar to that found in muscle hypertrophy and muscular endurance training protocols (9,94). The total number of sets performed also seemed to be similar between traditional power training and HVPT, however, it is the repetitions per set that causes a substancial discrepancy in total repetitions between both methods of training (9,12,13).

4.1.4 Inter and intra set rest

Inter-set recovery seems to be fairly consistent between HVPT protocols with all, except three of the protocols found, utilising a 2-3-minute recovery (50,59,61,65–67,70–74). This recovery range is within the margins of recovery periods utilised in traditional power training (12). Although higher repetition ranges are used in HVPT in comparison to traditional power training, it seems as though a two-minute inter-set rest period is often enough recovery to restore physiological systems responsible for maximal power output (70,71,88). As the utilisation of shorter inter-set rest periods, for example ≤ 1 minute, has not been well investigated within the HVPT literature, future research should investigate whether athletes can be trained to tolerate such short rest periods in an attempt to improve RPA and associated physiological capacities. Although Schuster *et al*. (25) describe inter-set rest periods of 2 minutes, 1 minute and also 30 seconds for their HVPT protocols, they do not provide any empirical evidence to support these recommendations. Reducing the length of the inter-set rest periods is an approach that can considerably effect the acute training response and the likely chronic physiological adaptation that may occur (71). Within a periodisation structure, a gradual reduction in inter-set rest periods over several weeks or even months may be one viable approach to maximising the training effect when using HVPT to improve RPA in athletic populations.

Romero-Arenas *et al*. (63) utilised a HVPT protocol consisting of very short inter-set rest periods, performed in a circuit format. In this study the training effect between what was described as a traditional power training protocol, with relatively high volume (approximately 80-200 repetitions), was compared directly to a volume matched HVPT protocol. Each protocol required 10 seconds of all-out work for each of the four exercises, but the work to rest ratio and the set to set configuration differed. In the traditional power training protocol, the completion of up to 5 sets for each of the four exercises was conducted consecutively with 90 s rest between each set. In the HVPT protocol, a continuous circuit was conducted whereby after completing 10 seconds of all out work on one exercise, 15 s rest was provided before performing the next exercise and so on. Although completing HVPT with very short rest periods, as in circuit based formats, is likely to provide a substantial cardiorespiratory stress (41,42), the limited recovery may acutely decrease power output in consecutive sets (98). With an acute fatigue induced reduction in power output, the chronic neuromuscular adaptations may be reduced (63). Therefore, care should be taken in the prescription of inter-set rest periods, with acute performance measures, e.g. power output periodically recorded to ensure the likelihood of positive long-term cardiorespiratory and neuromuscular adaptations.

Besides inter-set recovery, another method used to maintain power output in HVPT is the use of cluster sets. Cluster sets may be used at the start of a HVPT training block with the intra-set rest periods gradually decreasing as the athlete adapts and is better able to maintain power-output. In one of the HVPT protocols described by Schuster *et al*. (25), a 5 second intra-set rest period was provided after every 5 repetitions of a 15 repetition set. This cluster set format was said to reduce fatigue when HVPT is performed in the lead in to a rugby sevens competition, but no empirical evidence is provided to support this suggestion (25). Although two of the eligible studies utilised cluster set formats (in the form of 5-20 seconds intra-set recovery dispersed throughout the set) (59,99), no data has been provided in order to show the chronic effects of such HVPT protocols.

With careful planning cluster set schemes may well be used to good effect in the progression and periodization of HVPT (59). In the initial stages of introducing HVPT, the use of cluster sets may provide a viable method that would allow power output to be maintained throughout the set. For example, Garcia-Ramos *et al*. (69) showed that the decline in power output to pre-established thresholds can be attenuated, resulting in ~100-150% more repetitions when each repetition of speed squats is interspersed with 6 s of rest. As the athlete starts to adapt to the total volume of work during HVPT, intra-set rest can be gradually reduced throughout the training block, until there is no longer any intra-set rest provided (59).

Gonzalo-Skok *et al*. (50) utilised cluster sets in their successful application of HVPT, however, they chose to keep intra-set rest periods consistent throughout the training block, whilst instead providing progression in the form of increased volume of work. In this study, a single set of 25 repetitions, where every 5 repetitions were separated by 20 s of rest, was progressed to two sets of 25 repetitions after an initial three-week training period. It is unknown which of these progressions (reducing inter-set rest periods or increasing volume of training) is more effective, but it is suggested that there is potential to use each of these progressions throughout an annual periodised training plan. It is important to note, however, that Apanukul *et al*. (60) did not utilise any form of progressive overload in their eight-week training study. Instead Apanukul *et al*. (60) applied a consistent 30% 1RM loading to 3 sets of 20 repetitions

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of speed squats; despite this they were still able to significantly enhance RPA, power and agility measures. This finding may suggest that a consistent prescription of HVPT, over an 8-week period, may provide a sufficiently large physiological stress to cause significant adaptations, without having to provide progressive overload *per se* for athletes who were initially naive to HVPT. This may however require the athletes to consistently try to accelerate the loads as rapidly as possible across all repetitions in training.

An in-depth understanding of these methods and findings are important when deciding on implementing a particular HVPT protocol, especially with respect to how a HVPT protocol may be prescribed in relation to other training and recovery elements. For example, technical and tactical training, speed and agility or injury prevention sessions all need to be concurrently performed in the weekly training schedule. If the training stress and concomitant fatigue associated with HVPT are so high that other forms of training are compromised or the risk of injury increases, then HVPT may not be considered a feasible form of training. It is therefore important to understand the acute physiological responses to HVPT and the ensuing impact on recovery and regeneration between training elements and competition.

4.2 The acute effects of high volume power training

4.2.1 Power output

As suggested previously, of the fourteen studies found, nine of these studies provide some physiological or biomechanical data pertaining to the acute HVPT responses (59,65–67,70–74). The other five studies have been included as they incorporated potential HVPT training variables that may be considered in the planning or prescription of HVPT (50,58,60,61,63).

It is important to consider some methodological limitations in the measurement of power output during a number of these HVPT studies. Firstly, as a consequence of fatigue in vertical jumping, power output and jump height may be maintained, at least in part, by utilising a different jump strategy, for example by increasing squat depth or countermovement displacement (85–87). None of the HVPT studies included in

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this review quantified potential changes in joint or segment kinematics throughout a HVPT session, meaning it is unclear if the maintenance of power output within or between HVPT sets may have been a result of a change in kinematics.

It is also important to consider the equipment used to measure power output and how power output is calculated during HVPT. Overestimations in power output have been shown to occur when using barbell displacement time data in comparison to using the system centre of mass (100). Barbell displacement time data was used in each of the HVPT studies that measured power output, therefore it is important to consider that power output will have been overestimated in these studies. However, it could be argued that such errors are systematic in nature, meaning the magnitude of change with fatigue should be relatively unaffected.

Hatfield *et al*. (70) and Volek *et al*. (65) used the Plyometric Power System to measure the acute response to 4 sets of 12 and 5 sets of 10 repetitions of jumps squats, respectively. These studies demonstrated strong similarities with respect to the relative maintenance of mean power and increase in blood lactate responses across the sets. This finding shows the importance of the measurement device, metric and sample population used when comparing the results of HVPT. Although only Hatfield *et al*. (70) actually analysed the change in mean power from set to set, the maximal mean power in each set in both studies remained relatively unchanged throughout the HVPT protocol. This was despite the post blood lactate readings of 9.6 ± 3.3 mmol·L^{-1} and 16.1 ± 3.9 mmol·L^{-1}, respectively. The two minutes' inter-set recovery in both protocols may have provided enough recovery in order for both the metabolic and neuromuscular system to have recovered sufficiently to produce mean power outputs close to maximal levels. Incidentally, the difference in blood lactate readings may well be the result of the additional set that was performed in the Volek *et al*. (65) study. Nonetheless, the increase in blood lactate levels did not seem to affect maximal power outputs in consecutive sets. Future studies should investigate what characteristics may be required for athletes to maintain their mean power values over multiple sets while experiencing high metabolic demands, as indicated by the blood lactate values.

An objective of HVPT prescription may be to provide sufficient, but not excessive recovery between sets in order to produce maximal or near-maximal levels of power output at the commencement of the ensuing set(s). This would seem a reasonable training objective if improvements, or at least maintenance, of both maximal power output and RPA are the objective. Further, it appears that mean and peak power output can be maintained across multiple sets despite significant reductions in power output. Within set reductions in power-output can be as much as -23% when using 30-40% 1RM loads for up to 5 sets of 10-16 repetitions (65,70,71,74). Unfortunately, the effect of HVPT repetitions above 16 repetitions were not examined in any of the studies found. Therefore, it is unknown whether or not maximal power output can be maintained from set to set with the use of the higher repetition ranges.

4.2.2 Hormonal and immune response

Nune *et al*. (73) identified no significant differences in acute hormonal and immune responses between three different resistances training schemes (a HVPT type scheme, a strength-hypertrophy scheme and strength-endurance scheme). The findings from Nune *et al*. (73) provide potential evidence to suggest that a HVPT type scheme may induce no greater acute hormonal or immune response than traditional muscular strength, hypertrophy and endurance training schemes. Only the strength-hypertrophy scheme showed a significant increase in pre vs. post training cortisol levels, with no schemes showing any significant changes in testosterone or immunoglobulin A. It may be reasonable to suggest that the total training load volume in this HVPT session (approximately 2000 kg/90 repetitions in total) was not large enough to stimulate a significant hormone or immune response. The use of exercises involving smaller muscle mass, as in the bench press and bicep curl exercise, in comparison to the squat, are likely to require lower energy expenditure and metabolic demand that will result in a sub-maximal hormone and immune response (101). The fact that female athletes were used in this study may also have had an effect on

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potential testosterone response, with males having substantially greater testosterone levels than females (102). The hormone and immune response to HVPT protocols involving the use of large muscle mass for high volumes of work still needs to be elucidated as well as the relevance of acute hormonal responses in the potential long-term training adaptations (103). Hormonal markers that are suggested to be more indicative of metabolic challenge than testosterone include insulin-like growth factor 1+ and growth hormone, which may prove to be more sensitive in investigating HVPT responses (104).

4.2.3 Cardiorespiratory response

While it has been suggested that HVPT would produce a substantial metabolic demand and homeostatic challenge, there appear to be no studies that have identified these aspects in relation to HVPT protocols. Previous resistance training studies have shown that the type of exercise, the number of repetitions, the amount of inter-set rest and the load used can significantly affect exercise performance, energy expenditure and oxygen consumption (101,105,106). In order to prescribe and programme HVPT effectively, it is important to quantify and understand the physiological demands and their effect on fatigue and the ensuing recovery imposed by different HVPT protocols.

4.2.4 Recovery post HVPT

Conchola *et al*. (67) and Mackey *et al*. (72) were the only studies found to investigate the time course effects post HVPT. The HVPT protocol in each of these studies consisted of 5 sets of 16 repetitions of speed squats with a 40% 1RM load and directly compared to a volume matched hypertrophy-based protocol consisting of 5 sets of 8 repetitions with an 80% 1RM load. Conchola *et al*. (67) found a significant reduction in peak knee extensor torque immediately post HVPT (pre = 264.37 ± 53.14 vs. post = 226.06 ± 48.54 N·m). By 7 minutes' post HVPT, peak torque was no longer significantly different from pre HVPT levels (249.47 ± 36.52 N·m); indicating that the recovery of maximal force generating capacity of leg muscles can occur relatively quickly after this type of protocol.

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In contrast to these findings for peak torque, time-dependent neuromuscular qualities, like peak rate of torque development and maximal unloaded velocity were shown to have slower recovery characteristics (67,72). The rate of torque development 30 minutes' post HVPT was still significantly depressed in comparison to pre HVPT levels (pre = 2005.42 ± 405.31 vs. 30 minutes' post = 1735.48 ± 347.85 N·m/s) (67). Similarly, unloaded maximal velocity was also significantly reduced after 30 minutes (males pre = 491.48 ± 9.03 vs. 30 minutes post = 479.73 ± 16.70 deg·s^{-1} and females pre = 484.76 ± 7.78 vs. 30 minutes post = 479.73 ± 11.29 deg·s^{-1}). It is important to note that although the pre to post changes were significantly different, the relative change in mean scores were very small and therefore care should be taken in interpretting these findings. Although measures of rate of torque development and velocity recovery were only taken for a 30-minute period post HVPT, it is interesting to note that the same recovery trends were also found in the matched hypertrophy-based session.

As hypertrophy training is common place in many sport and physical preparation programmes, the findings of similar fatigue time courses in HVPT and hypertrophy training programmes is important for establishing how HVPT might fit into weekly training plans. For example, the planning of the training week to optimise recovery between a HVPT session and a speed or high intensity technical session may be the same as that used for hypertrophy training. However, with only a 30-minute post-exercise time period assessed in these studies, the time needed to fully recover lower body neuromuscular function remains somewhat unknown. As rate of force development and maximal shortening velocity are important physical qualities in sport performance (107), their full recovery for skill and speed based conditioning training sessions is paramount. It is essential that future studies in this area include additional observations conducted over multiple days, in order to better quantify the physiological cost and recovery profile of such sessions. It may also be important to account for bimodal recovery patterns, which have been observed in high volume stretch shortening cycle activities; where following acute fatigue, a brief recovery period ensues before another depression in performance was observed (108).

4.3 The chronic effects of high volume power training and traditional training on measures of repeat power ability

Apanukul *et al*. (60) investigated the effect of specific HVPT on RPA in competitive male tennis players. Although the primary aims of the research were to examine the differences in traditional barbell lifting versus a pneumatic lifting device, the researchers applied a matched HVPT protocol to both groups, while a control group performed normal tennis training consisting of court-based skill and conditioning work. Over an eight-week training period, where two sessions a week of HVPT were completed, both experimental groups significantly increased RPA as measured by the average relative peak power for 30 continuous CMJs. This research provides evidence in support of the use of a specific HVPT modality to improve RPA. However, Apanukul *et al*. (60) did not compare the training effects between traditional and specific HVPT modalities. Thus, which training modality is more effective at increasing RPA is currently unknown. However, with the time cost of training in mind, it is of interest that HVPT can improve both maximal power and RPA by 22% and 21% respectively, across a total of sixteen HVPT sessions (60). It is clearly evident that both changes in maximal power and RPA can come at a relatively low time cost when using a specific HVPT modality.

4.4 The effects of high volume power training on performance and repeat high intensity efforts

Apanukul *et al*. (60) demonstrated that an eight-week block of HVPT not only significantly increased RPA but also maximal power output and a specific tennis change of direction test in comparison to a matched control group who only performed on court tennis training. As the change of direction test in this study took approximately 17 s to complete, such high intensity work for this period of time is likely to apply a substantial stress to glycolytic energy production (109). It is therefore unknown if the HVPT programme would improve shorter duration discrete change of direction tasks inherent to the game of tennis and other sports.

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In another investigation of the performance effect of HVPT, Gonzalo-Skok *et al*. (50) examined the effect of two HVPT sessions per week on running and jumping ability over a six-week period. In addition to the training completed by the control group, which included general exercises for injury prevention and on court basketball practice, the experimental group performed a progressive HVPT protocol. In this study, HVPT significantly improved hop distance, a measure of lower limb power, by approximately 8% and RHIE ability by approximately 2%. Similar improvements in both repeated sprint ability and repeated change of direction ability were also found for the HVPT group in this study, with no improvements in any of the measures found for the control group.

Bosco *et al*. (58) examined the effect of ~20 weeks of specific strength and HVPT on 12 international alpine skiers. Unfortunately, all participants in this study used a combination of both traditional strength training, where loads of between 70-100% 1RM were utilised in the squat and leg press exercises, and HVPT, where both unloaded and loaded jumps, ranging from 20-50 kg, were used for up to 10 sets of 20 repetitions. The combination of these two training approaches was highly effective in improving a variety of jump power and anaerobic capacity measures by between ~23-60% and ~15-16%, respectively. However, conclusions cannot be made on the relative effectiveness of traditional strength training or HVPT, in contributing to these adaptations. It is also important to note again that the data presented in Bosco *et al*. (58) is more of a description of training and physical capacities at different time points rather than a training study *per se*.

Balsalobre-Fernandez *et al*. (61) performed weighted squat jumps in their investigation of the effects of HVPT in high level track and field hurdlers. Although a thorough description of the training status of these participants was not provided, baseline half squat strength was ~2.3 times body weight, and this would indicate a substantial strength training background. Despite there being no traditional strength training performed during the study period, significant improvements in half squat strength along with jump power and acceleration performance were observed over a 10 week training period. While changes in

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track times were not assessed in this study, the significant improvements in squat strength and jump power are noteworthy given the high level training base of the subjects and the fact that only 2 sessions a week were conducted, each with a short training session duration of approximately 15 minutes. Although no assessments of cardiorespiratory or RHIE performance were conducted in this study, the combination of HVPT and track and field hurdle training had a significant effect on neuromuscular performance.

In a recent study examining the training effects of HVPT with short inter-set rest periods (15 s in a circuit format) versus moderate rest periods (90 s), several neuromuscular and cardiorespiratory adaptations were also observed (63). Significant increases in maximal power, anaerobic capacity and aerobic performance were found in both the circuit format group and the moderate rest period group after six weeks of training consisting of three sessions per week. This is the only study to have measured the change in maximal aerobic speed after a HVPT intervention and its results suggest that HVPT can improve aerobic as well as anaerobic performance. Surprisingly, these adaptations also occurred with total training session durations as short as 5-8 minutes in the circuit training group.

In elite sporting environments, training time can often be scarce with only a few available training sessions to optimise recovery and regeneration and to prepare athletes both technically and tactically and for the physical components of the sport. If HVPT can simultaneously enhance a number of different physiological systems, this training method may provide a time efficient training alternative for many sports. Although care must be taken when comparing the results from a cohort of healthy men (63) to high level athletes, these findings may warrant further investigations of the effect of HVPT on a number of physical qualities.

These studies provide evidence that HVPT can collectively enhance power, RPA, anaerobic performance, aerobic performance, explosive sporting tasks like change of direction ability and RHIE tasks including repeated change of direction and repeated sprint tasks. The effect of HVPT on RHIE like those found in collision and grappling type sports (mentioned in section 1.1) still need to be established. As each of these studies utilised quite different exercise prescriptions additional comparative training studies need to be conducted so to better understand how variations in the acute training stimuli contribute to chronic training adaptations.

4.5 Measuring repeat power ability

The 60 s Bosco jump test was the first repeated jump power assessment devised to measure anaerobic power and capacity and was developed because other popular assessments did not replicate the ballistic characteristics of the lower limbs' and stretch shortening cycle actions found in many sports (110). The 60 seconds Bosco jump test requires participants to perform 60 s worth of continuous maximal effort CMJs on a force platform or jump mat without additional load. When performing the Bosco jump test, between 55-65 jumps are typically performed in the 60 s time frame and for each 15 s segment the average power output is calculated (110). It is important to note that power in the original work was not directly assessed in the Bosco jump test, but instead it was derived from jump height, based on flight time and gravitational acceleration using a jump mat. This should be taken into account when comparing RPA assessments between protocols that measure or calculate power with other devices like force plates and/or rotary encoders (111).

More recently, repeated jump assessments have incorporated the use of external loads to replicate the external loading demands that occur in many sports; to impose a greater stress on the neuromuscular and cardiorespiratory systems; and to more closely resemble the externally loaded training modalities often used to improve power output (16,64,68). Alemany *et al*. (64), Baker and Newton (16), Patterson *et al*. (29) and Patterson et al. (62) all developed RPA assessments where they used barbell loaded CMJs, either using a continuous (repeated jumps with no between jump rest) or discontinuous (with brief rest periods between jumps) protocol. Although Patterson *et al*. (29,62) used a free bar, all other studies used a Smith

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machine, including Fry *et al*. (68) and Garcia-Ramos *et al*. (69) in their speed squat protocols. The Smith machine controls the vertical tracking of the bar and in doing so assists in reducing the technical demands placed on the athlete and the potential for measurement error associated with any horizontal motion during the vertical jump. Only two studies used a maximal power reference (29,62), whereby a maximal power reference value was obtained before performing their RPA assessment. Collecting this maximal power reference before the RPA test is important as it allows the researcher to quantify the true decline in power output during each RPA assessment. A maximal power reference can also inform the assessor and athlete of any potential pacing strategies that may have been utilised in order to conserve energy for later parts of the RPA test. Therefore, establishing this maximal power reference should be considered an important part of an RPA protocol to ensure a maximal effort at the commencement of the assessment.

Unfortunately, the differences between the RPA assessment protocols used in these studies are more apparent than their similarities (refer to Table 5.). There seems to be no consensus between the loads (with 30%, ~52% and ~67% 1RM, an absolute load of 60 kg [approximately 35% 1RM], 70% 1RM system mass and 40% body mass all used), number of repetitions/duration (with 30, 15, 10 repetitions, 2 minutes or 2.5 minutes used), jump or squat depth (self-selected, posterior thigh parallel to ground or a 90˚ knee angle used), repetition timing (self-selected, 6 s or 2.5 s between repetitions), measurement devices (jump mat, integrated force plate and velocity transducer or either force plate only or velocity transducer only) and the measurement indices used (average relative mean power, % average relative mean power, average mean power, average peak power, average mean velocity and average peak velocity and a fatigue index). With such large variation in assessment and analysis procedures, it is difficult to identify which factors may influence the reliability and validity of the RPA assessments described in the studies. It is suggested that, in order to minimise measurement error, greater control around jump kinematics is required along with establishing the most appropriate measurement device and measurement variable(s) to explain and help quantify RPA.

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4.6 Reliability and validity of assessments of repeat power ability

Although power output is calculated and not directly measured, the 60 s Bosco jump test was originally found to be (and still is) a reliable and valid relatively low-cost assessment of anaerobic power and capacity in unloaded jump conditions (112,113). More recently, Fry *et al*. (68) investigated the reliability and validity of an externally loaded RPA type assessment, named the Kansas Squat Test, which consists of one set of 15 speed squats with each repetition performed every 6 s. It is important to note that in traditional barbell exercises such as speed squats, a significant deceleration occurs toward the end of the range of motion (up to 40% of the concentric portion of the lift) (114). Therefore, the study of Fry *et al*. (68) who examined the RPA qualities of speed squats is somewhat different to the other studies utilising jumping activities. Specifically, a ballistic lifting alternative, such as a squat jump, that again allows the barbell to be accelerated through a greater portion of the movement, will result in significantly greater forces, velocities and power values to be produced, especially in the second half of the concentric phase (75,114).

Despite the deceleration of the barbell during the speed squats, Fry *et al*. (68) established reliability and validity of the test protocol, with ICC's of 0.937, 0.811 and 0.754 for mean test power, single repetition power and relative fatigue, respectively. Likewise, significant relationships with maximum test power and mean power between their RPA test and the Wingate test (r = 0.775 and 0.752, respectively) were also found. The validity of the test in comparison to a gold standard anaerobic capacity assessment, the 30 second Wingate, provides strong evidence in support of repeated high velocity resistance training assessments to measure anaerobic power and capacity. Yet when comparing the relationship in relative fatigue between the Wingate and the Kansas Squat Test RPA, the correlation was low (r = 0.174). This finding suggests that each test may be measuring different aspects of anaerobic performance and fatigue. A difference in muscle mechanics between the Wingate and the Kansas Squat Test assessment may well be one reason why there is a disparity in the power decrement between the two tests.

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Fry *et al*. (68) suggest that the difference in fatigue may be related to the Kansas Squat Test relying more heavily on the phosphagen system in comparison to the Wingate test. This is perhaps evident with the Wingate test showing higher blood lactate concentration (8.94 ± 0 versus 5.96 ± 0.39 mmol·L^{-1}) which is suggestive of a greater reliance on the fast-glycolytic system. However, the different contraction modes, concentric only in the Wingate and eccentric-concentric in the RPA assessment, may have also contributed to the metabolic and fatigue relationship differences between the two assessments. The stretch-shortening cycle actions performed in a 60 second Bosco jump test (where 60 seconds of continuous maximal jumps are performed) (113), were suggested to account for difference in anaerobic power and capacity when compared to the 30 second Wingate test (112). It is therefore suggested that the validity of a potential RPA assessment may be affected by both mechanical and metabolic demands when compared to the criterion measure selected.

Results of Fry *et al*. (68) need to be interpreted with caution as the deceleration of the barbell in the speed squat ascent is likely to present a very different mechanical stress in comparison to a ballistic movement (as established in section 4.1.1). The ground reaction forces experienced upon landing in ballistic loaded jump conditions could also impose a very different mechanical stress that alters the degree of coordination required on landing and the overall level of fatigue. Currently, differences between the mechanical stresses imposed by the deceleration of the barbell in a speed squat and the ground reaction forces upon landing in a loaded jump are unknown. The difference in mechanical stress provided in each of these conditions is likely to contribute to differences in the rate and extent of fatigue and therefore RPA between conditions. However, despite the potential differences in fatigue between speed squats and squat jumps, in terms of specificity to sporting tasks it is considered more appropriate to use ballistic exercise tasks like jumping in order to assess sport related power output and RPA (12,80).

Alemany *et al*. (64) also assessed the reliability of an RPA assessment of ballistic CMJs on four separate occasions with the use of a Smith machine, where vertical tracking of the barbell was able to be controlled.

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The assessment involved 1 set of 30 repetitions with a load equivalent to a 30% 1RM. The coefficients of variation (CV) for CMJ mean power, peak power, mean velocity, peak velocity and work were 4.4%, 3.2%, 3.4%, 3.4% and 5.7% respectively. ICCs for CMJ measures in session 1 to sessions 2, 3 and 4 ranged from 0.73-0.97. No significant difference in ICCs from session 1-2 vs 1-4 were found, therefore high reliability for the test was established. This is the only study of RPA assessments to have used an absolute measure of reliability (CV), therefore little is known about the absolute reliability of RPA assessments. The relative lack of absolute measures of reliability mean that it is difficult to determine the magnitude of change required to be confident of a real change in RPA caused by training or injury.

Patterson *et al*. (29) also investigated the reliability of a 2.5-minute RPA assessment involving a maximal CMJ performed every 2.5 seconds with a barbell load equivalent to 40% of the participant's body weight. Patterson *et al*. (29) found a high degree of test-retest reliability for the average relative mean power for the whole test and for the average relative mean power for each 30 s segment of the test (ICC's were 0.955, 0.931, 0.958, 0.960, 0.900, 0.881, respectively). Although CMJs using a free bar were performed in this assessment, the authors did provide some control of potential jump variables by including a 2.5 s pause between jumps and by also controlling countermovement depth to a 90˚ knee angle. Again, similar to Alemany *et al*. (64), Patterson *et al*. (29) did not provide a measure of the extent of fatigue or power decrement in this study, however in more recent research by Patterson *et al*. (62) a fatigue index was calculated in order to describe the power decrement more accurately. It is important to note that although the RPA assessment used by Patterson *et al*. (29) was found to be a reliable measure of anaerobic power and anaerobic capacity, anaerobic capacity over 4 seasons was not significantly correlated (r = -0.35) with ski racing performance (62).

Collectively the results of the six studies examining the reliability and/or validity of RPA assessments suggest that such assessments have adequate relative reliability, but little data exist for their absolute

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reliability and validity. This suggest that additional research needs to be performed to determine the most reliable and valid measures of RPA, especially for the quantification of fatigue indices.

With regards to HVPT, future research should address the acute and chronic effects of a combination of different training variables, for example load, volume, interset rest time and also the chronic effect of using cluster sets. The acute or chronic effects of HVPT on the cardiorespiratory system is also an area requiring further research.

5 Conclusions

Considering the importance of RHIEs in many sports, there appears to be a relative lack of research on HVPT, the acute responses to this form of exercise and the chronic effect of this form of training on RPA and RHIEs.

Although a number of different HVPT protocols have been described in the literature, prescription generally consisted of speed squats, CMJs or Squat Jumps for 2-3 sessions per week. Common loading protocols consisted of 30-40% 1RM for 10-20 repetitions of 3-5 working sets, with inter-set rest periods of between 2-3 minutes. When using HVPT with the weightlifting derivatives, loads are generally higher (~60-65% 1RM) and repetition ranges are slightly lower (~9 repetitions per set). Further longitudinal studies are required to establish training prescription guidelines for weightlifting exercises, including whether repetitions are to be done continuously or with brief rest periods between repetitions.

Based on the somewhat limited literature, HVPT may be an effective training method in enhancing RPA, RHIEs, anaerobic power and capacity and aerobic performance. However, there is a lack of research on the chronic effect of HVPT in elite sporting cohorts with extensive training backgrounds and relatively high baseline levels of cardiorespiratory fitness and strength.

Although several assessments of RPA have demonstrated adequate reliability and/or validity, there is a relative lack of research on these assessments. Currently, the Kansas Squat Test may be suited to the training environment; however, the muscle actions used in this test may not be representative of ballistic sporting actions. It still remains unclear whether RPA is a unique physical quality, what constitutes the best way to measure or quantify RPA and the impact of RPA on sporting performance like RHIEs.

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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Compliance and Ethical Standards

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Conflict of Interest

Alex Natera, Marco Cardinale and Justin Keogh declare they have no conflict of interest relevant to the context of this review.

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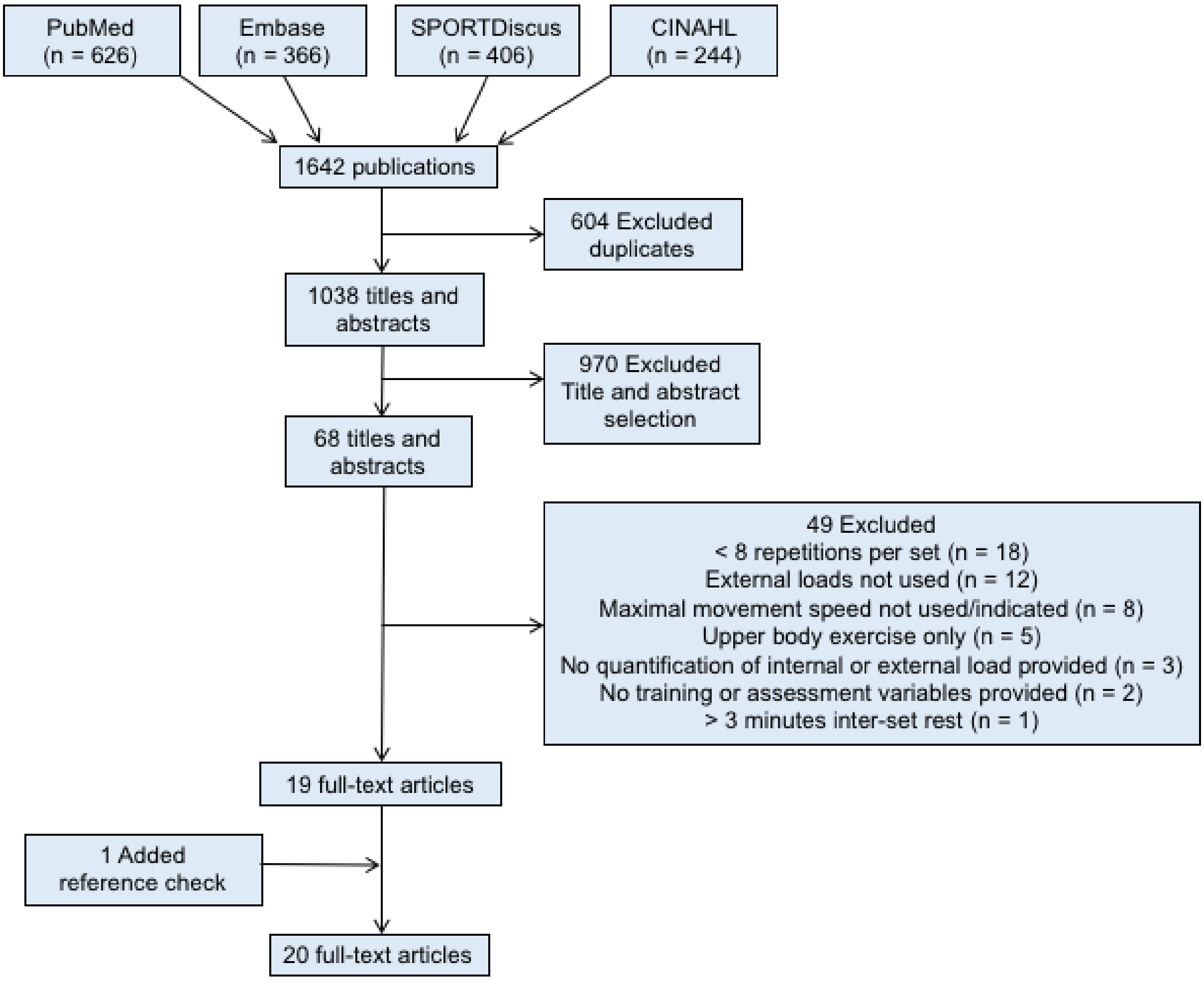

Fig 1 Flow chart of the article selection process

Table 1 Risk of bias and quality rating of included longitudinal studies

	PEDro criteria											
Study	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Totals (10 possible)**
Apanukul et al. (2015) (60)	Yes	1	0	1	0	0	0	0	0	1	1	5
Balsalobre-Fernandez et al. (2013) (61)	No	0	0	0	0	0	0	0	0	0	1	1
Bosco et al. (1994) (58)	Yes	0	0	0	0	0	0	0	0	1	0	1
Gonzalo-Skok et al. (2016) (50)	Yes	1	0	1	0	0	0	1	1	1	1	6
Mosey et al. (2011) (59)	No	0	0	0	0	0	0	1	1	0	0	2
Patterson et al. (2014) (29)	Yes	0	0	0	0	0	0	1	0	0	1	2
Patterson et al. (2019) (62)	Yes	0	0	0	0	0	0	1	1	0	1	3
Romero-Arenas et al. (2018) (63)	Yes	1	0	1	0	0	1	1	1	1	0	6

1 eligibility criteria specified, *2* random group allocation, *3* concealed allocation, *4* similar groups at baseline, *5* blinding of subjects, *6* blinding of coaches, *7* blinding of assessors, *8* 85% of subjects received 1 key measurement, *9* intention to treat, *10* statistical significance reported for 1 key outcome, *11* point measures and measures of variability reported.

Table 2 Risk of bias and quality rating of included cross-sectional studies

Study	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 (%)
Alemany et al. (2005) (64)	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	0	81% (L)
Baker and Newton (2007) (16)	0	1	1	0	1	1	0	1	1	1	1	1	1	1	0	0	69% (L)
Conchala et al. (2015) (67)	1	1	1	0	1	1	0	1	1	1	1	1	1	1	0	0	75% (L)
Date et al. (2013) (66)	1	1	1	1	0	0	0	1	1	1	1	1	1	1	0	1	69% (L)
Fry et al. (2014) (68)	1	1	1	0	1	1	0	1	1	1	1	1	1	1	0	1	81% (L)
Garcia-Ramos et al. (2016) (69)	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	88% (L)
Hatfield et al. (2006) (70)	1	1	1	0	1	0	1	1	1	1	1	1	1	1	0	0	69% (L)
Hester et al. (2014) (71)	0	1	1	1	1	1	0	1	1	1	1	1	1	1	0	0	75% (L)
Mackey et al. (2018) (72)	1	1	1	0	1	1	0	0	0	1	1	1	1	1	1	1	75% (L)
Nunes et al. (2011) (73)	1	1	1	0	1	1	0	1	1	1	1	1	1	1	1	1	88% (L)
Tufano et al. (2016) (74)	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	94% (L)
Volek et al. (1997) (65)	1	1	1	0	1	1	0	1	1	1	1	1	1	1	0	0	75% (L)

Method for assessing risk of bias: (1.1) study design is clearly stated; (1.2) the objectives/purpose of the study is clearly defined; (1.3) the design of the study adequately tests the hypothesis; (2.1) the criteria for the inclusion of subjects is clearly described; (2.2) the characteristics of the population is 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 paper 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 criterion being met divided by the maximum possible score across all criteria (16), multiplied by 100. *L* low risk of bias (67–100%), *S* satisfactory risk of bias (34–66%), *H* high risk of bias (0–33%)

Table 3 A summary of HVPT protocols and where reported, the acute responses to HVPT

Authors	Participants	Type	Session per week/ No. of weeks	Sets	Repetitions/duration	Load	Inter-set rest	Intra-set rest	Measurement tool/s	Response/Result
Apanukul et al. (2015) (60)	30 competitive M tennis players	Speed Squat	2 sessions per week/ 8 weeks	3	20 repetitions	30% 1RM	4 minutes	0		
Balsalobre-Fernandez et al. (2013) (61)	7 high -level M hurdlers	Squat Jumps	2 sessions per week/10 weeks	5	8 repetitions	~55% 1RM	3 minutes	0		
Bosco et al. (1994) (58)	12 international Alpine Skiers	Loaded and unloaded jumps (additional strength training-no aerobic training)	3 sessions per week/ 20 weeks	10	10-20 repetitions	20-50 kg				
Conchala et al. (2015) (67)	17 resistance trained men	Speed squat	Single session	5	16 repetitions	40% 1RM	2 minutes	0	Biodex isokinetic dynamometer	↓PT Post0 264±53 to 226±49 (N·m) ↓RTDpeak Post0, Post7, Post15 and Post30 (2005±405 to 1516±406, 1753±450, 1770±420, 1735±348 N·m·s^{-1} respectively) ↓RTDnorm Post0 1710±311 to 1321±359
Date et al. (2013) (66)	10 resistance trained men	Power clean	Single session	3	9 repetitions	70-75% 3RM	2 minutes	0	Lactate Plus analyser	↑La to 7.43±2.94 mmol·L^{-1} ↑La% 365.35±260.2
Gonzalo-Skok et al. (2016) (50)	22 M elite young basketball players	Explosive Leg Press	2 sessions per week/ 6 weeks	Week 1-3 = 1 Week 4-6 = 2	25 repetitions	MaxP Load: 120.3 ± 22.1 kg	3 minutes	20 s		
Hatfield et al. (2006) (70)	8 recreationally active men	Continuous CMJ	Single session	4	12 repetitions	30% 1RM	2 minutes	0	PPS rotary encoder	↔MaxMP Set 1: 1160±121, Set 2: 1154±127, Set 3: 1139±131, Set 4: 1111±132 W ↓AvgMP Set 1: 1095±125, Set 2: 1076±131, Set 3: 1049±128 Set 4: 1037±119 W ↑La 1.2±0.4 to 9.6±3.3 mmol·L^{-1} FI%- 5.29%
Hester et al. (2014) (71)	19 resistance trained men	Speed squat	Single session	5	16 repetitions	40% 1RM	2 minutes	0	Tendo rotary encoder	↔ maxPP 1985-2045 W Within set FI% = 17.9-22.3% Between set FI% = 31.3%
Mackey et al. (2018) (72)	14 resistance trained men and 16 resistance trained women	Speed squat	Single session	5	16 repetitions	40% 1RM	2 minutes	0	Biodex isokinetic dynamometer	↓Vmax Post0-Post30 (M: 491±9 to 481±16, 478±24, 477±22, 480±17; F: 485±8 to 476±15, 480±12, 479±11, 479±11 deg·s^{-1})
Mosey (2011) (59)	4 elite M rowers	Continuous CMJs	2 sessions per week/ 6 weeks	3	15 repetitions	Progressed from 30-40 kg	3 minutes	Progressed from 10 s, 5 s and 0 s	Gym Aware rotary encoder	Mixed responses in individuals- no statistical analysis provided
Nunes et al. (2011) (73)	14 elite F basketball players	Speed Bench Press, Speed Squat and Speed Biceps Curl	Single session	9 (total sets)	10 repetitions	50% 1RM	3 minutes	0	Salimetrics-Salivary Testosterone Immunoassay kit	Data not reported No difference between pre and post-training C Post session C trending lower than strength/hypertrophy scheme ($p \le 0.08$) No differences in T or IgA between lifting schemes
Romero-Arenas et al. (2018) (63)	29 healthy M	Circuit- Speed bench, Repeat CMJs, Clean Pull, Cycle Sprint	3 sessions per week/ 6 weeks	Week 1-3 = 3 Week 4-6 = 5	10 seconds = 5-10 repetitions	Bench Press = 30% 1RM Clean Pull = 60% 1RM	Circuit = 15 s or traditional = 90 s	0		
Tufano et al. (2016) (74)	12 strength trained M	Speed squat	Single session	3	12 repetitions	60% 1RM	2 minutes	0	AMTI force plate and Celesco tranducers	↓AvgMP Set 1: 1181±83, Set 2: 1154±77, Set 3:1096±107 Within set FI%: 8% 1st-36th repetition FI%: 23%
Volek et al. (1997) (65)	14 recreationally active men	Continuous CMJs	Single session	5	10 repetitions	30% 1RM	2 minutes	0	PPS rotary encoder	↔maxMP (not analysed) Set 1: 1160, Set 2:1140, Set 3: 1145, Set 4: 1120, Set 5: 1090 W ↑La 1.09±0.7 to 16.1±3.9 mmol·L^{-1}

M male*, F* female*, 1RM* 1 repetition maximum*, PT* peak torque, *RTD* rate of torque development, *La* lactate, *MaxMP* maximum mean power, *MaxPP* maximum peak power, *AvgMP* average mean power, *FI%* fatigue index %, *ACC*240 angular acceleration at 240 *deg·s*$^{-2}$, ACC500 angular acceleration at 500 *deg·s*$^{-2}$, Vmax maximal unloaded velocity, *C* cortisol, *T* testosterone, *IGA* immunoglobulin A, *CMJs* Counter Movement Jumps).

Table 4 The chronic effect of HVPT on RPA and other performance variables

Authors	Participants	RPA	Power	Strength	COD	Speed	Repeated Speed	Repeated COD	Anaerobic Capacity	Aerobic Power
Apanukul et al. (2015) (60)	30 competitive male tennis players	Speed Squat avg.rel.PP (W/kg)- 51.3±2.5 to 65.3±1.8 and 53±5.4 to 60.9±4.3	Speed Squat relPP (W/kg):64.8±3.9 to 81.3±5.4 and 64.6±5 to 75.0±4.1		17.39±0.6 to 16.11±0.68 and 17.81±0.75 to 16.45±0.37 s					
Balsalobre-Fernandez et al. (2013) (61)	7 high level M hurdlers		SJ flight time (ms): 580.2±48 to 594.1±54 MaxP %1RM: 56±4.4 to 63±6.5	Half Squat 1RM (kg): 172.5±23.9 to186.2±26.5		30-m sprint 4.19±0.19 to 4.13±0.16				
Bosco et al. (1994) (58)	12 international Alpine Skiers		Jump height BW (cm) - 34.6±3.8 to 42.7±5.0 cm Jump height +20 kg (cm)- 25.1±3.2 to 32.0±5.1 cm Jump height +1xBW (cm) 10.1±2.6 to 15.7±2.4						15BJT avg.rel.PP (W/kg)- 27.1±2.2 to 30.5±3.2 30BJT avg.rel.PP (W/kg)- 24.6±3.3 to 28.9±3.1	
Gonzalo-Skok et al. (2016) (50)	22 male elite young basketball players		UHop (cm)- 169.1±16.8 and 170.4±16.6 to 180.9±14.4 and 182.7±12.8				RSAm (s)- 7.52±0.23 to 7.4±0.23	RCODm (s)- 6.86±0.25 to 6.72±0.23		
Romero-Arenas et al. (2017) (63)	29 healthy males		Jump height BW (cm)- 32.3±5.8 to 34.3±4.4 Clean pull (W)- 1522.8 ± 208.4 to 1710.4±273.9 Win. MaxP (W)- 811.4±121 to 883.7±134.4	Clean Pull (kg)- 58.5±11.2 to 63.4±9.3 Bench Press (kg): 72.4±13.8 to 74.5±12.2					Win. avgP (W)- 662.9±85.9 to 706.9±96.4	MAS ($km \cdot h^{-1}$)- 17.5±0.8 to 18.2±0.9

avg.rel.PP average relative peak power, *avg.rel.MP* average relative mean power, *relPP* relative peak power, *MaxP* maximal power, *1RM* 1 repetition maximum, *BW* body weight, *UHop* unilateral hop, *RSAm* repeated sprint ability mean sprint time, *RCODm* repeated change of direction mean time, *15BJT* 15 second repeated Bosco jump test, *30BJT* 30 second repeated Bosco jump test, *MAS* maximal aerobic speed, *Win.* 30 s Wingate.

Table 5 The different assessments proposed for assessing RPA, including reliability and validity results where reported

Authors	Participants	Type	Equipment	Load	Set x repetitions/ duration	Depth	Maximal Power reference value	Pacing strategy	Assessment tool/s	Data analysis procedure	Reliability	Validity	Results (%)
Alemany et al. (2005) (64)	10 healthy male soldiers	Continuous CMJ	Smith Machine	30 % 1RM parallel squat	1 x 30	Self-selected			Ballistic Measurement System	avgMP avgPP avgMvel avgPvel work	CV's = 3.2-5.7% ICC's = 0.73-0.97		~↓47.8 avgMP
Apanukul et al. (2015) (60)	30 competitive male tennis players	Continuous CMJ (Alemany et al., 2005 protocol)	Smith Machine	30 % 1RM parallel squat	1 x 30	Self-selected			Fitech Force plate	avg.rel.MP			
Baker and Newton (2007) (16)	15 professional rugby league players	Continuous CMJ	Smith Machine	60 kg (= group avg. of 35% 1RM)	1 x 10	Self-selected			PPS velocity transducer	relMP FI%			↓6.88 relMP
Fry et al. (2014) (68)	14 resistance trained men	Concentric Speed Squats	Smith Machine	70% 1RM System mass	1 x 15	Posterior thigh parallel to ground		Squat every 6 seconds	Fitrodyne velocity transducer	relMP avgMP FI%	ICC's = 0.754-0.937	WAnT r = 0.752-0.775 (FI% r = 0.174)	↓20.4 ± 13.9 FI%
Garcia-Ramos et al. (2016) (69)	16 active-duty soldiers	Concentric Speed Squats	Smith Machine	~52% 1RM and ~67% 1RM	1 x ~19-20 1 x ~14-18	90˚ knee angle		Squat every 3 seconds	T-Force System velocity transducer	MP%loss			↓8%: 6 and 4 repetitions, ↓15%: 12 and 8 repetitions respectively
Patterson et al. (2014) (29)	13 well trained men	Discontinuous CMJ	Barbell	40% of body weight	1 x 2.5 minutes	90˚ knee angle	Assessed and Utilised	Jump every 2.5 seconds	SPSport Force plate	avg.rel.MP%avg.rel.MP	ICC's = 0.881-0.987		~↓20.9 avg.rel.MP
Patterson et al. (2019) (62)	10 elite female Alpine ski racers	Discontinuous CMJ	Barbell	20% of body weight	1 x 2 minutes	90˚ knee angle	Assessed and Utilised	Jump every 2.5 seconds	SPSport Force plate	relMP Avg.rel.MPFI%			14.8-17.3 FI%

CMJ countermovement jump, *1RM* 1 repetition maximum, *avgMP* average mean power, *avgPP* average peak power, *avgMvel* average mean velocity, *avgPvel* average peak velocity, *avg.rel.MP* average relative mean power, *CV* coefficient of variation, *ICC* inter-class correlation, *relMP* relative mean power, *FI%* fatigue index %, *WAnT* wingate anaerobic threshold, *MP%loss* mean power % loss, *%avg.rel.MP* % average relative mean power.