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Training monitoring for resistance exercise: Theory and applications

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REVIEW ARTICLE

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Key Points

- To quantify resistance exercise, it is important to understand the numerous factors contributing to the overall intensity of training, rather than simply the relative load being lifted.
- Methods to monitor the external volume load, perceptual training intensity, subjective wellness, and physical performance during resistance exercise all appear useful methods for monitoring resistance training.
- Strength coaches should identify which monitoring tools are applicable and viable for their athletes, and should take an integrative approach to resistance training monitoring to help inform their practice.

Abstract

Resistance exercise is difficult to quantify due to its inherent complexity with numerous training variables contributing to the training dose (type of exercise, load lifted, training volume, inter-set rest periods and repetition velocity). In addition, the intensity of resistance training is often inadequately determined as the relative load lifted (% 1-repetition maximum), which does not account for the effects of inter-set recovery periods, repetition velocity, or the number of repetitions performed in each set at a given load. Methods to calculate the volume load associated with resistance training, as well as the perceived intensity of individual sets and entire training sessions have been shown to provide useful information regarding the actual training stimulus. In addition, questionnaires to subjectively assess how athletes are coping with the stressors of training and portable technologies to quantify performance variables such as concentric velocity may also be valuable. However, while several methods have been proposed to quantify resistance training, there is not yet consensus regarding how these methods can be best implemented and integrated to complement each other. Therefore, the purpose of this review is to provide practical information for strength coaches to highlight effective methods to assess resistance training, and how they can be integrated into a comprehensive monitoring program.

1 Introduction

The ability to quantify stress imposed by exercise training allows a coach to determine whether the training stimulus experienced by an athlete is in accordance with their periodized plan. Monitoring the training loads associated with exercise is a vital step in ensuring that the actual training stimulus experienced by an athlete is in accordance with the aims of their current training phase. It is known that sudden increases in training load above the normal training limits can cause a decrease in performance and lead to injury or illness [1]. Monitoring the training process is therefore important to identify periods when an athlete may be more susceptible to such deleterious effects. Conversely, effective monitoring strategies may allow coaches to determine times at which an athlete may not be experiencing an optimal training stimulus, either because the intensity or volume of exercise is not sufficient. Researchers have proposed several methods to quantify training for steady state and endurance exercise, including measures of maximum aerobic power and oxygen consumption [2], blood lactate concentrations [3] and heart rate [4]. However, these methods are unsatisfactory for quantifying resistance exercise given intermittent nature of such training and its predominantly anaerobic energy profile. While most high-level athletes undertake resistance training at various stages of their annual training plan, there is currently no consensus regarding the best way to monitor this training modality. This is largely due to the numerous independent variables that elicit resistance training adaptations (e.g. type of exercise, relative load lifted, training volume, inter-set rest periods and repetition velocity) [5].

Despite the complexities associated with quantifying resistance training, several methods have been proposed. For the most part, these methods include measures of external workload [6, 7] and rating of perceived exertion (RPE) responses [8-10]. While these strategies do provide valuable information for the strength coach, there is no current consensus regarding the optimal way to monitor such variables and integrate the information they provide. In addition, there are several other methods that can also provide an index of the stresses associated with resistance training and how an individual is coping or adapting to this stress. These methods include indices of athlete wellness and neuromuscular function/fatigue, though these have not been included in a comprehensive assessment of training monitoring practices. Therefore, the purpose of this paper is to describe practical methods commonly used to monitor the training dose and fatigue responses resulting from resistance exercise. Furthermore, this paper will provide recommendations regarding how best to implement monitoring practices during resistance training programs for athletes.

2 Resistance Training Monitoring Theory

Training load can be considered as the product of exercise volume and intensity [11]. It is vital for strength coaches to have valid and reliable methods to quantify these variables, both for the prescription and monitoring of resistance training. The volume of exercise can be most easily considered as the number of repetitions performed and is simple to assess. However, while the intensity of resistance training is commonly referred to as the relative load lifted (e.g. % of 1-repetition maximum [1RM] or other known RM [repetition maximum]), this may be too simple of an assessment. Although this strategy does describe the intensity of the load used, the overall intensity associated with a resistance training session is a far more complex construct. Fisher et al. [12] argue that the truest definition of 'intensity' for resistance exercise sets relates the level of effort applied, irrespective of the weight lifted. Therefore, an individual lifting a load to failure will have worked at maximal intensity (for that particular set at least), whether the load is equal to 30% 1RM or 80% 1RM. Furthermore, the intensity of resistance training is strongly related to the repetition velocity, as well as the duration of inter-set recovery periods [5]. To this point, an individual will experience a vastly different training stimulus by lifting moderate-loads of 70% 1RM with maximal velocity (e.g. training for strength-speed) or with a controlled tempo (e.g. training for hypertrophy). Moreover, increasing the rate at which work is done in a training session via reductions in inter-set recovery duration will increase the global intensity of the training session. While the intensity of loads lifted have obvious implications for the overall training dose experienced by an individual, it is important to understand that other variables should also be considered to monitor resistance training sessions. It is therefore recommended that rather than using the terms low-, moderate- or high-intensity to describe the weight being lifted, terminology such as light/low-, moderate- and heavy/high-load be used.

For training monitoring to be meaningful, it must be able to inform decision-making. This means that if the outcomes of a specific test cannot be reported to a coach quickly enough to alter subsequent training, the test will not provide meaningful information and its use would be questionable [13]. An exception to this is if training data are archived to create a database of individual responses for future comparisons, at which time the test will become meaningful. In high-level athletes there is not often time for additional tests outside of normal training, and monitoring should ideally be integrated into the already existing training sessions. Practitioners working with athletes (particularly in large groups) therefore require monitoring processes that are simple to implement, non-invasive and easy to calculate and report on.

3 External Volume and Load Measures

The volume and associated load imposed by resistance exercise is recognized as a potent stimulus for muscular adaptations [14]. When seeking to comprehensively understand the physical demands of resistance exercise, it is possible to mathematically calculate the amount of mechanical work accomplished by multiplying the force exerted by the displacement of the centre of mass or the bar [7, 15]. McBride et al. [15] previously demonstrated that calculating the total work achieved during a resistance training session is the most appropriate method for determining resistance exercise volume for back squat exercise targeting hypertrophy (4 sets of 10 repetitions at 75% 1RM) and strength (11 sets of 3 repetitions at 90% 1RM), and during jump squats for power development (8 sets of 6 repetitions at body weight). However, this method is impractical for the strength coach in a real-world setting, as it is difficult to measure the force and displacement variables without specialized equipment (force platforms and/or linear position transducers), and analysing each repetition performed for all exercises would be extremely labour intensive and time consuming. More simple methods to quantify resistance exercise must therefore be explored.

3.1 Repetition Method

The most basic method to quantify resistance exercise is the repetition method to determine training volume [7]. The repetition method simply is the summated number of repetitions performed in a specific exercise, a training session, or within a training week or cycle (equation 1). While this approach may be attractive due to its simplicity, it is inadequate to describe the actual stress associated with resistance training. To illustrate, consider Athlete A in Figure 1, who has a bench press 1RM of 120 kg. If Athlete A was to perform maximal strength-based training (10 sets of 3 repetitions at 90% 1RM) or hypertrophy-based training (3 sets of 10 repetitions at 70% of 1RM), a different training response would be expected. However if monitored using the repetition method, Athlete A would be measured to perform the same training volume during both these training sessions (30 repetitions), and therefore these differences would not be expressed (Table 1). Therefore, while the repetition method is very simple to calculate, even for very large squads of athletes, it offers a poor estimate of the actual training stimulus. A more applicable approach is to consider the weight lifted during each repetition in conjunction with the repletion volume, often termed the volume load.

INSERT FIGURE 1 NEAR HERE

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$$\text{Repetition volume} = \text{number of sets} \times \text{number of repetitions} \qquad \text{(Eq. 1)}$$

3.2 Volume Load

The volume load is an extension of the repetition method. This simply involves multiplying the number of repetitions performed of a given exercise by the absolute load lifted for these repetitions (equation 2). The absolute volume load for each different exercise performed in a training session can then be summated to calculate the total weight lifted during training. This is typically expressed as the volume load (kg), or tonnage (metric tonne; 1000 kg). The volume load method is attractive for strength and conditioning coaches in that it is easy to implement and calculate, and provides a single number to represent the load of a training session. Importantly, recent research has also shown that volume load is largely related to measures of internal load and physiological stress during resistance exercise at various intensities [6].

$$\text{Absolute volume load} = \text{number of sets} \times \text{number of repetitions} \times \text{weight lifted (kg)} \qquad \text{(Eq. 2)}$$

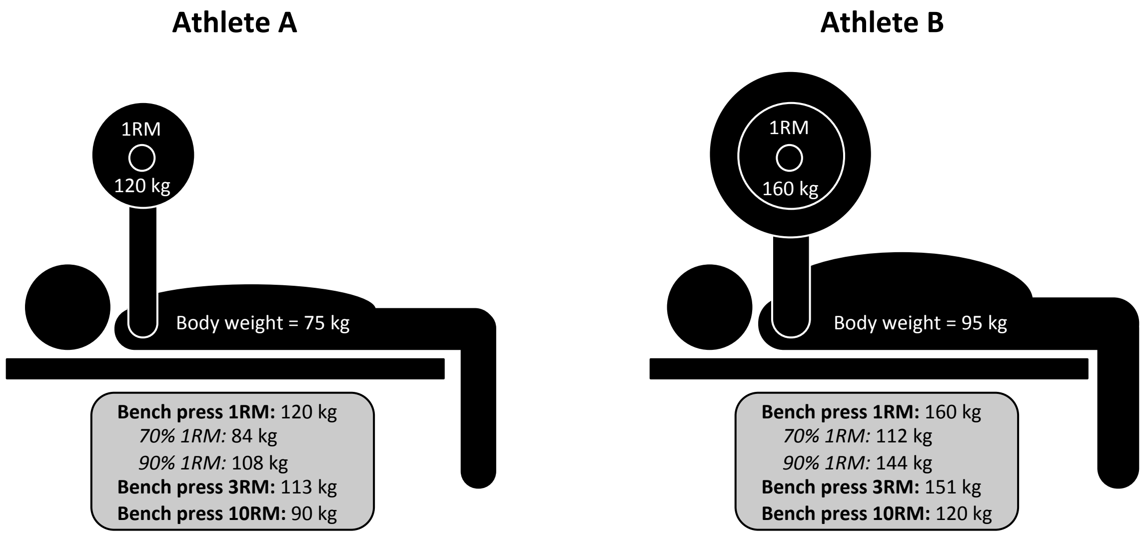

Athlete A
1RM
120 kg
Body weight = 75 kg
Bench press 1RM: 120 kg
70% 1RM: 84 kg
90% 1RM: 108 kg
Bench press 3RM: 113 kg
Bench press 10RM: 90 kg
Athlete B
1RM
160 kg
Body weight = 95 kg
Bench press 1RM: 160 kg
70% 1RM: 112 kg
90% 1RM: 144 kg
Bench press 3RM: 151 kg
Bench press 10RM: 120 kg

Table 1. Example calculations for resistance training volume and volume loads.

External volume/load measure (unit)	Hypertrophy training *(3 sets x 10 reps using 70% 1RM)*		Strength training *(10 sets x 3 reps using 90% 1RM)*	
	Athlete A	Athlete B	Athlete A	Athlete B
Repetition volume (reps)	30	30	30	30
Absolute volume load (kg)	2520	3360	3240	4320
Relative volume load (AU)	2100	2100	2700	2700
RM-based volume load (AU)	2790	2790	2850	2850

RM repetition maximum, *reps* number of repetitions, *AU* arbitrary units.

However, it must be acknowledged that this approach has several limitations. It is not possible to compare absolute volume load measures between individuals, given that this measure does not reflect the relative intensity of the loads lifted by each individual. To illustrate, if Athlete A and Athlete B (Figure 1) both perform the bench press for 3 sets of 10 repetitions using 70% of their individualized 1RM scores, they have essentially undergone the same relative training stimulus. However, given the difference in the absolute loads lifted due to differing strength levels (84 and 112 kg, respectively), their absolute volume loads will be vastly different (Table 1), making it impossible to compare the training dose between individuals. A possible solution for this is to multiply the number of repetitions performed by the relative rather than the absolute load used, making the volume load measure relative to each participant's capabilities (equation 3). This then corrects for inter-individual variations in strength while still providing an index of the actual exercise stimulus in arbitrary units.

$$\text{Volume load relative to 1RM} = \text{number of sets} \times \text{number of repetitions} \times \%1\text{RM} \qquad \text{(Eq. 3)}$$

While relative volume load may be good reflection of the training stimulus, a limitation with assessing both relative and absolute volume loads is that the difficulty associated with performing the prescribed number of repetitions in a set at a given load is not accounted for. It is obvious that resistance exercise will be much more demanding if more repetitions are performed in each set at a given weight. For example, Athlete A will have much more difficulty performing 3 sets of 10 repetitions using 70% 1RM (84 kg) than 10 sets of 3 repetitions at this weight, despite the same absolute and relative volume loads (2520 kg and 2100 arbitrary units [AU], respectively). Previous attempts to correct for this have required participants to complete sets of resistance exercise until they perceived that they were 1-2 repetitions from voluntary exhaustion [6]. This is a practical and likely an effective strategy, but it is possible that some inexperienced participants with could stop prior to this point or extend the set too far. Furthermore, stopping 1-2 repetitions short of failure will result in disproportionate volume changes between heavy and light loads. For example, stopping 2 repetitions short of failure in a set using 4RM will decrease the set volume by 50%, whereas set volume would only be decreased by 20% following the same instructions using a 10RM load.

A strategy to counteract this is to calculate the intensity and volume loads for each set relative to the predicted RM weight for the prescribed number of repetitions. An individual's RM for a given number of repetitions can be calculated using various predictive equations if their maximal strength is known [16]. Taking this approach using the example above and the equation developed by Brzycki [17], it can be calculated that Athlete A will have a 10RM of 90 kg and a 3RM of 113 kg. Therefore, lifting 84 kg for sets of 10 repetitions would mean that Athlete A is working at 93% of 10RM, whereas when lifting 84 kg for only 3 repetitions Athlete A is working at 74% of 3RM. Extending this strategy further to calculate relative volume loads (equation 4), performing 3 x 10 repetitions using 93% 10RM yields a higher volume load (2790 AU) compared to 10 x 3 repetitions using 74% 3RM (2220 AU). Therefore, the difficulty of each set is accounted for in the RM-based volume load, rather than solely the total volume load.

$$\text{Volume load relative to specific RM} = \text{number of sets} \times \text{number of repetitons} \times \\ \text{\%RM for repetition range used} \quad \text{(Eq. 4)}$$

While the previous examples demonstrate that it is possible to calculate volume loads based on the intensity of the resistance lifted, there are several limitations to these measures of external volume and load. The durations of inter-set rest periods are not accounted for in these equations. The inter-set recovery duration is known to be a primary determinant of the overall intensity of a resistance training session [5], and has a marked effect on physiological responses such as blood lactate concentration [18]. Additionally, measures of volume load do not take into account repetition velocity, which also contributes to the overall intensity of resistance exercise. This was highlighted by McBride et al. [15], who reported that measures of volume load underestimated the demands imposed by body weight power training, likely due to the increased repetition velocity, even when volume load was corrected for body mass minus shank mass. Therefore, the overall demands imposed on an athlete during resistance training may be misrepresented by the volume load measures, irrespective of how it is calculated. Other methods to monitor resistance training that take into account inter-set rest durations and repetition velocity should therefore be explored. Additionally, to calculate volume loads relative to an athlete's individual level of strength, their specific 1RM (or another RM) must be known. This is not feasible for real-world resistance training programs comprised of several different exercises, as maximum testing for many exercises is both time consuming and demanding on the athlete. While external measures of load provide important information, they may not accurately reflect internal load, making the prediction and assessment of physiological training outcomes very difficult [6].

4 Internal Load Measures

Given the limitations associated with measures of external load and intensity, it may be useful for strength coaches to calculate the internal loads associated with resistance training. Perceptual ratings of exercise stress are easy to collect, and are becoming commonplace in high-performance sport. The RPE approach has been previously used to quantify the intensity of resistance exercise in a number of studies [10, 19, 20], and is proposed as a simple strategy to determine the perceived stress associated with bouts of resistance exercise. A benefit of this technique is that RPE scores can be taken from a range of different exercise modalities, meaning that the perceived exertion associated with resistance exercise can be compared to other types of training. This has important implications in simplifying the monitoring approach for athletes.

4.1 Set RPE

Research has assessed the intensity of resistance exercise using both Borg's 15-category scale [20, 21] and Category Ratio-10 scale [22]. More recently, research has employed the OMNI-resistance exercise scale to measure perceived exertion [10, 23], which is designed specifically for use with resistance exercise and includes both verbal and mode-specific pictorial descriptors along a 0-10 scale. Some studies have demonstrated that RPE scales are sensitive to the intensity of the load being lifted, with higher values being reported during sets of high-load resistance exercise (5 repetitions at 90% 1RM) compared to higher repetitions sets using low-loads (15 repetitions at 30% 1RM) [21]. However, these results are not surprising when considering that 90% 1RM is equivalent to ~101% 5RM, whereas 30% 1RM is only equivalent to ~49% 15RM (Brzychi's equation [17]). This is important, as although the high- and low-load trials were matched for relative volume load, it is likely that the low-load trial was in fact much less difficult. However, to our knowledge research has not yet examined the RPE responses to resistance exercise of differing loads, but relative intensity (i.e. % of RM) following individual sets.

An interesting application of RPE scores may be the use of differential ratings to describe specific body segments [20, 21]. Lagally et al. [20] observed that differentiated RPE scores for active muscles were consistently higher than for the whole body (i.e. overall RPE) across a range of exercise loads (30-90% 1RM). This may indicate more intense feelings of exertion within the contracting muscles, and that localized exertion is decreased when considered in the context of whole body exertion. However, while it is relatively simple to collect RPE scores after or during each set of resistance exercise in theory, the practical application of this approach for real-world settings is limited. Especially for strength coaches working with large groups of athletes, it is simply not feasible to record RPE scores for every set performed by each individual. A more practical method to obtain perceptual ratings of exercise intensity may involve taking a session RPE (sRPE) score to reflect the global intensity of a whole training session.

4.2 sRPE Method

The sRPE method has gained popularity in recent years as a simple metric by which internal training intensity can be assessed. The sRPE method allows the subject to provide a single global rating for how difficult an entire training session was using an RPE scale [8], and has been reported as a valid [22] and reliable [19, 24] indicator of resistance training intensity. A benefit of this strategy is that this rating will consider the actual loads being lifted in concert with the number of repetitions, inter-set rest periods and velocity of repetitions during the session. Furthermore, this value will provide an indicator for how strenuous an athlete perceived training to be in the context of their current physical and psychological state [25]. This has obvious benefits in simplifying the monitoring process, as the individual is only required to provide one rating following the conclusion of training, rather than numerous responses during the session after each set.

While sRPE scores have been traditionally obtained ~30 minutes after the conclusion of training to limit the final phase of training impacting on the value [8], recording sRPE at 15 minutes following a session also yields reliable estimates of resistance training intensity [26]. Singh et al. [27] have shown that sRPE recordings taken prior to this (i.e. 5 or 10 minutes post-exercise) are higher, possibly due to influences from the final set of exercise, and therefore they should not be used to quantify resistance exercise. It has been suggested that sRPE scores can reflect the intensity of the load being lifted [19, 22, 24]. However, similarly to the points raised previously for research assessing set RPE values, these studies did not account for how the number of repetitions performed at each given load would impact on the actual intensity of training. This has also been highlighted in a recent paper from Genner and Weston [6]. In this investigation, participants trained using 3 sets of 5 different exercises, with each set ceasing once the participant perceived that they were 1-2 repetitions from volitional exhaustion. This method resulted in likely substantial differences in sRPE scores between trials using 55%, 70% and 85% of 1RM (8.0 ± 1.6 AU, 6.9 ± 1.4 AU and 6.2 ± 2.2 AU, respectively). Interestingly, a similar trend was observed in absolute volume load (12,396 ± 944 kg, 10,560 ± 1753 kg and 8319 ± 1412 kg for 55%, 70% and 85% 1RM, respectively), suggesting that sRPE values may be more related to the volume load rather than the heaviness of the loads lifted when relative effort in each set is controlled. These findings corroborate other research from Pritchett et al. [28], who recorded higher sRPE scores and volume load during moderate-load (60% 1RM) resistance exercise to failure compared to high-load (90% 1RM) training. However, Singh et al. [27] reported similar sRPE values between resistance exercise targeting strength (3 sets of 5 repetitions using 90% 1RM) and hypertrophy (3 sets of 10 repetitions using 70% 1RM), despite higher relative volume loads in the hypertrophy-focused exercise. Further research is therefore required to understand the impact of altering acute resistance training variables on subsequent sRPE responses.

A useful application of sRPE is to calculate internal training load. This is achieved by multiplying the sRPE score by the duration of training in minutes (equation 5) [11]. The sRPE load has become a popular method for strength and conditioning coaches to monitor a different types of training sessions, as it is both time efficient and simple to implement. For example, this approach is widely adopted in team sports, where many players are training at once using a range of technical, tactical and conditioning drills [29]. Importantly, if the sRPE load is also calculated for resistance training sessions in this environment, the internal loads associated with this training can be added to the loads calculated for all other training sessions in a given week or microcycle, meaning that the total internal load across all training sessions can be determined. This is obviously an advantage of using of the sRPE load to quantify resistance training rather than measures of external load in isolation. Having a single metric to determine the load associated with all training sessions also lends itself to graphs and tables of load values, which are easily interpreted by other coaches.

$$\text{sRPE load} = \text{sRPE} \times \text{training duration (min)} \qquad \text{(Eq. 5)}$$

Monitoring the sRPE load associated with resistance training also allows the strength coach to calculate other variables such as training monotony and strain. Training monotony refers to the variation in training load across a week, and is calculated as the mean daily sRPE load divided by the standard deviation of sRPE load over the previous 1-week period [1]. Training strain is the product of sRPE load and monotony [1], and reflects the overall stress imposed on the athlete. These values are easy to calculate once sRPE loads are determined, and research has shown that minimizing training monotony and strain can be an effective strategy for avoiding overtraining in athletes [1].

5 Perceived Wellness Measures

Wellness questionnaires to determine how athletes are coping with the stresses of training are now commonplace in high-level sport. These psychological assessments may be able to identify players who are at increased risk of overtraining, as such individuals often present with global mood disturbances [30]. While appropriate exercise has been shown to enhance the mood state of well-trained individuals [31], excessive exercise can have a negative effect on subjecting measures of wellness [32], suggesting a possible relationship between training load and mood state. Accordingly, there is a growing trend for strength and conditioning coaches to monitor the subjective wellbeing of athletes during training cycles. While these assessments do not quantify the effects of resistance exercise on wellness directly, they do provide an index of how the overall stress of training (including resistance and other training modes) is impacting on an individual. Wellness questionnaires should therefore be implemented in the monitoring battery of any athlete who performs resistance training.

Recent evidence suggests that coaches believe many of the questionnaires established in the scientific literature are too extensive and time demanding, and that they are not sports specific [33]. This has obvious implications for athlete compliance and increases the complexity of data analysis and reporting. Survey results published in 2012 have shown that while self-report questionnaires were the most common method to assess athlete fatigue in Australian and New Zealand high-performance sport (84% of respondents), the implementation of assessments from the scientific literature is limited [33]. Established questionnaires such as the Recovery-Stress Questionnaire for Athletes, Profile of Mood States and Daily Analysis of Life Demands for Athletes were only in minor use (13%, 2% and 2% of questionnaire users, respectively). Interestingly, most coaches administered customized questionnaires (80% of questionnaire users), generally with 4-12 items assessed on Likert point scales ranging from

1-5 or 1-10. These customized questionnaires primarily focused on assessing perceived muscle soreness, sleep duration and quality, and perceived fatigue and wellness [33].

In line with these survey responses, a simple yet comprehensive questionnaire has been developed by McLean et al. [34] to assess overall wellbeing in team sport athletes. This questionnaire assesses the perceived fatigue, sleep quality, general muscle soreness, stress levels and mood of athletes using a 5-point scale (1-5 with 0.5 point increments). Using this tool, it is possible to monitor these five characteristics of wellness individually, and also to examine overall wellbeing by summing the five scores [34]. Research using this questionnaire in team sport athletes has shown it to be sensitive to subtle daily changes in training load [35], and to corroborate neuromuscular and muscle damage responses during intensified periods of competition [36]. As previously discussed regarding sRPE load assessment, using this (or similar) questionnaires to monitor how athletes are responding to resistance training sessions allows direct comparisons with other types of training, making data analysis and reporting more simple. However, to our best knowledge this questionnaire has not yet been validated specifically for use in resistance training. Therefore, while it is likely to be an effective method to indicate overall wellbeing in athletes, further research is required.

Given the importance placed upon indicators of muscle soreness in high-performance sport [33], it may be of interest to extend on the general assessment used by McLean et al. [34] and examine soreness in specific body segments following resistance training. This is particularly pertinent for resistance training when considering the muscle damage responses associated with this form of training, and the subsequent impact on contractile function [37]. Previous team sport research has used a scale from 1 (no soreness) to 10 (extremely sore) to assess soreness in the hamstrings, calves, gluteals, groin, quadriceps and lower back following a match [38]. This same approach could be applied to assess soreness following resistance exercise.

A benefit to quantifying subjective ratings of wellness is that results can be very quickly assessed, and used to inform training. To illustrate, if a team sport athlete reports very sore hamstrings at three days following high-load deadlift training, the strength and conditioning coach should discuss this issue further with the athlete to determine whether subsequent training should be manipulated or more closely monitored. If the athlete then discloses that they cannot move freely and exhibit limited range of motion about the hip and knee joints, it would be unwise to perform maximal sprint and/or acceleration training until their soreness ratings have returned closer to baseline levels. However, as this example highlights, it is still vital to discuss the findings of monitoring strategies with athletes prior to altering their planned training (this is discussed further in Section 7). Furthermore, it is important to acknowledge that measures of wellness are affected by additional training and competition outside of resistance exercise, and as such cannot typically be used to quantify the responses to resistance training in isolation.

6 Monitoring Repetition Velocity

With the recent advent of portable technologies to quantify movement velocity such as linear position transducers, new methods to monitor resistance exercise have become available. These devices can be attached to a barbell, weight stack or other resistive object by a retractable tether, to record the displacement of the moving object during exercise. From this it is possible to calculate variables related to repetition performance including concentric velocity and acceleration [39]. This has important applications for quantifying resistance exercise, as well as for examining the adaptive responses to a training plan.

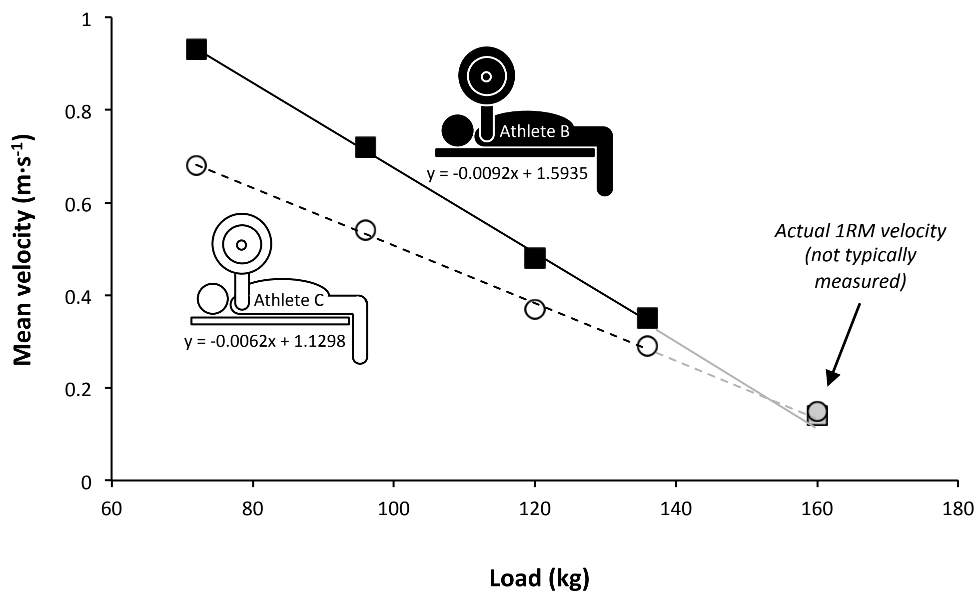
Athletes requiring high levels of muscular power such as throwing athletes, sprinters and some team sport athletes, will often perform explosive resistance exercise at various stages of their yearly plan. The goal with such exercises (e.g. bench throws, power cleans, loaded squat jumps) is to move the load with the highest possible effort. The intention to lift a load explosively is hypothesized to drive adaptations to power training, irrespective of the contraction type, load used or actual movement velocity [40]. Nevertheless, research has collectively demonstrated that improvements in maximal power are largely related to the actual movement velocity utilized during training [41]. Linear position transducers can therefore be used to objectively monitor whether the actual velocity of repetitions during training are appropriate to achieve the desired training outcome. A benefit of linear position transducers is that they provide immediate feedback, which can be displayed to the athlete even between repetitions. In a high-performance sport setting, strength and conditioning coaches can use this to their advantage. It can promote a competitive environment during training, and encourage athletes to express maximal effort during explosive lifts which will likely benefit adaptive responses to such training [42].

6.1 Load-Velocity Relationships

Aside from monitoring the velocity during resistance exercise for motivation purposes, there are other useful, yet more complex applications of linear position transducers. For example, they can be used to develop a load-velocity profile to describe the relationship between the load lifted and the maximal velocity with which the lift can be made [43]. Research has shown that a linear relationship exists between the relative load lifted and mean concentric velocity during resistance exercise at submaximal loads (ranging from 35-90% 1RM) [44, 45]. Developing a load-velocity relationship for an athlete can therefore indicate how that individual performs across varying submaximal loads. This has implications for prescribing loads to elicit a desired movement velocity, and also for tracking the adaptive responses to velocity-specific training programs. In addition, the load-velocity relationship allows coaches to compare different athletes' velocity performance across sub-maximal loads, who may otherwise appear to possess similar strength qualities [43]. For example, if two athletes demonstrate analogous 1RM scores and velocities at 1RM for the bench press exercise, then maximal strength testing may not be sufficient to differentiate between these individuals. However, if each athlete undergoes a load-velocity profile, differences in concentric velocity across submaximal loads may become apparent (Figure 2). In this example, Athlete B can lift submaximal loads at a higher velocity than Athlete C, which could benefit power output during athletic activities and thus result in improved sporting performance.

INSERT FIGURE 2 NEAR HERE

Interestingly, research has shown that the final repetition during sets of bench press and squats performed to failure is associated with a specific velocity, which is the same across various intensities (60%, 65%, 70% and 75% of 1RM) for a specific exercise [46]. In addition, this velocity (i.e. the minimal velocity threshold) has been shown to be very stable across time, even when maximum strength is improved and in individuals with varying levels of absolute strength [46]. If an individual athlete's minimum velocity threshold is known, it may also be used to assess the degree of residual neuromuscular fatigue and estimate the athlete's readiness to train. For example, a strength coach could implement 3-4 specific warm-up sets at the beginning of a training session, where the participant lifts light loads with maximum effort. This can be used to develop a load-velocity relationship for that specific day, which can be extrapolated to calculate a daily 1RM [43]. Theoretically, this would



Mean velocity (m·s-1)
1
0.8
0.6
0.4
0.2
0
60
80
100
120
140
160
180
Load (kg)
Athlete B
y = -0.0092x + 1.5935
Athlete C
y = -0.0062x + 1.1298
Actual 1RM velocity (not typically measured)

account for daily variations in strength due to residual fatigue, muscle damage, or a lack of psychological focus, and training loads for that session can be made more specific for the athlete's current state.

In addition, monitoring velocity during resistance training may be used to estimate the metabolic stress and neuromuscular fatigue during exercise [47]. Sánchez-Medina and González-Badillo [47] observed that decreases in velocity across sets of different load and repetition schemes was very strongly related to blood lactate concentration for both the bench press (r = 0.95-0.97) and squat (r = 0.93-0.97) exercises. In addition, velocity has been found to gradually decrease with each repetition across a set of resistance exercise [47, 48]. Given that fatigue is thought to occur as a continuous phenomenon, rather than at an abrupt failure-point [49], the gradual decrease in repetition velocity that occurs during a set of resistance exercise could be interpreted as evidence of impaired neuromuscular function [47]. Monitoring the velocity of repetitions during resistance training therefore offers strength coaches a novel means of controlling the extent to which an athlete will fatigue during resistance exercise [43]. While further work in this area is needed, it may be possible to implement velocity-based end points to sets, whereby an athlete is instructed to complete repetitions with maximum effort until the point when concentric velocity has decreased by a set magnitude. This may be an effective strategy to ensure that concentric effort is emphasised during each repetition, and that fatigue is limited.

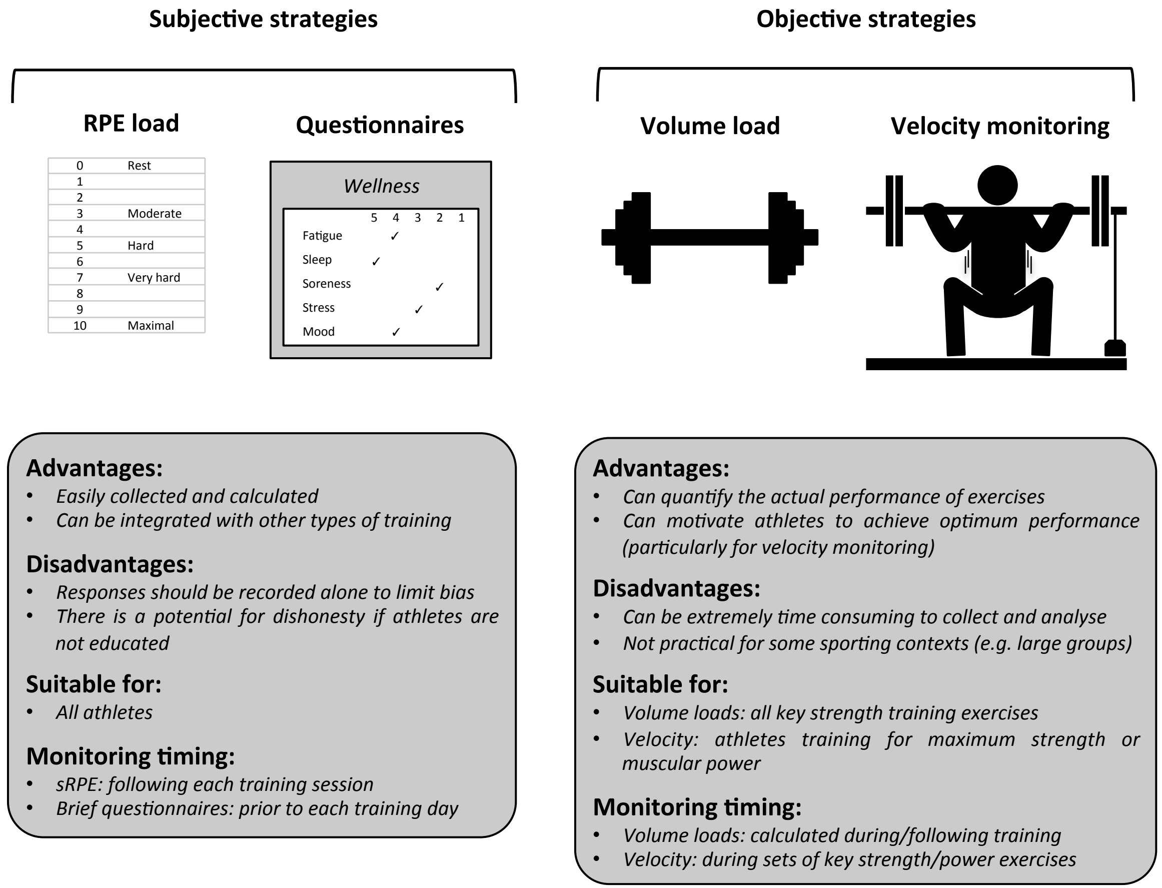
However, it must be acknowledged that while the use of linear position transducers to quantify resistance training via the various methods highlighted in this paper appear promising, very little research has been completed in this area. As such, the efficacy of these strategies to monitor and prescribe resistance training is not fully understood. Another important consideration for strength coaches is whether monitoring exercise velocity is relevant for their specific athlete, and for the current training aims. To illustrate, an athlete training for hypertrophy should focus on lifting moderate loads (~8-15RM) with relatively brief inter-set recovery periods (60-120 s) and a controlled, rather than explosive, tempo [5]. Hypertrophic training will result in a high magnitude of metabolic stress [50], which is likely important for the targeted morphological responses [51], and decreases in repetition velocity across sets would therefore be expected. As such, monitoring the velocity of hypertrophy training would not be beneficial. It is important that strength coaches take an integrative approach to monitoring resistance training, using the monitoring methods most applicable for the context of training.

7 An Integrative Approach to Monitoring Resistance Training

Unfortunately, there is no 'silver bullet' monitoring process capable of assessing the stress of training with perfect accuracy [13]. For strength coaches in particular, an integrative approach to training monitoring is most appropriate, by quantifying the most relevant and meaningful data from several sources [13] and assimilating these results to inform decision making. In order to determine which training monitoring data is relevant for particular athletes, it is first important to consider the current aims of their resistance training. In addition, logistical issues such as time constraints, the number of athletes to be monitored, the equipment available and the staff or analyses required for monitoring strategies should be considered (Figure 3).

INSERT FIGURE 3 NEAR HERE

Due to their ease of collection and analysis, subjective resistance training monitoring strategies can be collected for athletes in all sports. We propose that simple wellness


Subjective strategies
Objective strategies
RPE load
Questionnaires
Volume load
Velocity monitoring
0 Rest
1
2
3 Moderate
4
5 Hard
6
7 Very hard
8
9
10 Maximal
Wellness
5 4 3 2 1
Fatigue ✓
Sleep ✓
Soreness ✓
Stress ✓
Mood ✓
Advantages:
• Easily collected and calculated
• Can be integrated with other types of training
Disadvantages:
• Responses should be recorded alone to limit bias
• There is a potential for dishonesty if athletes are not educated
Suitable for:
• All athletes
Monitoring timing:
• sRPE: following each training session
• Brief questionnaires: prior to each training day
Advantages:
• Can quantify the actual performance of exercises
• Can motivate athletes to achieve optimum performance (particularly for velocity monitoring)
Disadvantages:
• Can be extremely time consuming to collect and analyse
• Not practical for some sporting contexts (e.g. large groups)
Suitable for:
• Volume loads: all key strength training exercises
• Velocity: athletes training for maximum strength or muscular power
Monitoring timing:
• Volume loads: calculated during/following training
• Velocity: during sets of key strength/power exercises

questionnaires be completed by athletes at the beginning of each training day to assess not only how they are coping with resistance exercise, but how they are coping with all training. In addition, sRPE scores should be collected 15 minutes following each resistance training session, and sRPE training loads subsequently calculated. To quantify resistance exercise using objective measures, relative volume loads should calculated rather than absolute values. However, this may only be possible in key lifts for which 1RM or another RM value is known. Similarly, measuring concentric velocity is only likely to provide meaningful information if assessed during repetitions which are performed with maximal effort. From a practical standpoint, it is therefore likely that objective strategies will provide most beneficial information during maximal strength or power training phases and for the key exercise in an athlete’s program.

In order to automate the analysis process, monitoring data could be collected using computers, tablet devices or smart phones. This allows data to be immediately submitted to a central data-base and analysed, without the strength coach having to manually assess raw data. The use of computer programs such as Microsoft Excel® in this process allows for calculations to be made using each athlete’s raw data, to identify individuals who may not be responding to training as expected. A common method employed by strength and conditioning coaches involves the use of “red flags” to identify meaningful changes in responses based on arbitrary cut-off values that are considered important by coaching staff [33]. This is often achieved by calculating the Z-score, which indicate how many standard deviations (SD) above or below the mean a data point is. Typically, a Z-score of ± 1 or 2 SD is noted as a red flag that warrants further investigation. An extension of using red flags is the “traffic lights” system, whereby Z-scores are visually represented as a green score (<1 SD), amber score (1-2 SD) or red score (>2 SD). A green score indicates a normal or expected variation, whereas an amber score represents a possible deviation from expected monitoring values (i.e. the athlete should be carefully monitored in subsequent training), and a red score indicates a meaningful change that should be investigated further to limit the chance of injury or maladaptation. This system has practical benefits in that it can be easily quantified, interpreted and understood by coaches.

However, scientific understanding regarding the magnitude of change that is actually meaningful when monitoring training is limited. In order to make informed decisions based on the monitoring strategies discussed in this review, it is important to consider at what point a change in a specific monitoring variable begins to represent excessive fatigue. This can be termed the smallest worthwhile change, and this value will vary between different monitoring strategies and populations [33]. In addition, recent work has developed a framework for the interpretation of meaningful change in physical performance for team sport athletes using progressive statistical approaches (including mixed linear modelling and magnitude-based inferences) [52, 53]. While a comprehensive review of the statistical processes related to quantifying changes in performance is beyond the scope of this paper, it is important that appropriate methods are employed to manage monitoring data and to determine when alterations in these data could indicate maladaptation.

While the strategies presented in this paper are becoming popular to monitor resistance training in high-performance sport, our understanding regarding the optimal ways to interpret the data they provide is in its infancy and further research is necessary. There are also some additional strategies not discussed in this paper, such as biochemical analyses of body fluids/tissues, which may provide useful information regarding training stress, muscle damage and inflammation. However, these methods are not widely used in high-performance sport due to their more invasive nature, associated expenses and logistical difficulties when dealing with large groups of athletes. It is important to acknowledge that monitoring tools provide data to indicate the individual training response. In high-performance sport, it is unlikely that an athlete will have their training altered based only on the results of monitoring methods. Essentially, these tools aid the strength coach by highlighting athletes who may be at risk of non-functional overreaching. This should prompt conversation with the athlete to further investigate how they are coping before their training plan is altered, which is often termed the "art of coaching".

8 Conclusions

To quantify resistance exercise, it is important that the contributing factors to the overall intensity of training are considered. Methods to monitor the external volume load, perceptual training intensity, subjective wellness, and physical performance during resistance exercise all appear useful methods for monitoring resistance training. Strength coaches should identify which monitoring tools are applicable and viable for their athletes, and should attempt to integrate the results from several monitoring strategies to provide comprehensive data regarding the training dose experienced by athletes.

Compliance with Ethical Standards

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Conflicts of Interest

Brendan Scott, Grant Duthie, Heidi Thornton and Ben Dascombe declare that they have no conflicts of interest relevant to the content of this review.

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Figure Captions

Figure 1. Example athlete characteristics for the quantification of external resistance training volume and load measures.

RM repetition maximum.

Figure 2. Example of how load-velocity relationships may differ between two athletes with very similar maximum strength characteristics for the bench press (1RM of 160kg). Adapted from Jovanović M, Flanagan EP. Researched applications of velocity based strength training. J Aust Strength Cond. 2014;22(2):58-69 [43], with permission from the Australian Strength and Conditioning Association. *Note:* the actual velocity of a 1RM attempt is not necessary to determine a load-velocity relationship, but is included here to highlight how maximal testing alone may not differentiate between athletes.

RM repetition maximum.

Figure 3. Recommendations for an integrative approach to resistance training monitoring using the strategies discussed in this paper.

RPE rating of perceived exertion, *sRPE* session rating of perceived exertion.