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REVIEW ARTICLE

Training for Muscular Strength: Methods for Monitoring and Adjusting Training Intensity

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Abstract

Linear loading, the two-for-two rule, percent of one repetition maximum (1RM), RM zones, rate of perceived exertion (RPE), repetitions in reserve, set-repetition best, autoregulatory progressive resistance exercise (APRE), and velocity-based training (VBT) are all methods of adjusting resistance training intensity. Each method has advantages and disadvantages that strength and conditioning practitioners should be aware of when measuring and monitoring strength characteristics. The linear loading and 2-for-2 methods may be beneficial for novice athletes; however, they may be limited in their capacity to provide athletes with variation and detrimental if used exclusively for long periods of time. The percent of 1RM and RM zone methods may provide athletes with more variation and greater potential for strength–power adaptations; however, they fail to account for daily changes in athlete's performance capabilities. An athlete's daily readiness can be addressed to various extents by both subjective (e.g., RPE, repetitions in reserve, set-repetition best, and APRE) and objective (e.g., VBT) load adjustment methods. Future resistance training monitoring may aim to include a combination of measures that quantify outcome (e.g., velocity, load, time, etc.) with process (e.g., variability, coordination, efficiency, etc.) relevant to the stage of learning or the task being performed. Load adjustment and monitoring methods should be used to supplement and guide the practitioner, quantify what the practitioner 'sees', and provide longitudinal data to assist in reviewing athlete development and providing baselines for the rate of expected development in resistance training when an athlete returns to sport from injury or large training load reductions.

Key Points

Linear loading, the 2-for-2 method, percentage of one repetition maximum, and repetition maximum zone training may not serve as effective methods for monitoring resistance training intensity as they fail to account for daily changes in an athlete's performance capabilities.

The rating of perceived exertion, repetitions in reserve, set-repetition best, autoregulatory progressive resistance exercise, and velocity-based training monitoring methods may provide greater insight into an athlete's daily readiness due to their autoregulatory nature.

Future research may improve monitoring methods that assess the process of motor learning and skill acquisition to assist decisions in adjusting training intensity.

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1 Introduction

Muscular strength is a critical motor capacity or capability that underpins motor performances (e.g., vertical jump, sprinting, change of direction, anaerobic conditioning, etc.) [1]. Due to the number of factors that can influence an athlete's training program, it is essential to regularly assess and monitor an athlete's motor capacity (i.e., strength), motor capability, and motor performance so that strength and conditioning practitioners can determine how their athletes are responding to training. Athlete monitoring includes two important but overlapping purposes: fatigue management and program efficacy. To manage fatigue, sport scientists and practitioners seek to detect acute and accumulative fatigue that exceeds the magnitude expected and, therefore, negatively impacts the stimulus-recovery-adaptation process. Thus, fatigue management involves day-to-day manipulation of volume and intensity to ensure the stimulus remains effective over time and that any sustained decline in performance is avoided. Program efficacy includes the extent to which the training stimuli produces the expected results. Collectively, fatigue management and program efficacy serve as part of the athlete monitoring process where fitness characteristics and their underlying mechanisms are monitored throughout an athlete's training program. The monitoring of underpinning motor capacities (i.e., strength) and changes in coordination or more specifically, motor performance, associated with "*learning to use one's newfound strength*" [1] enables practitioners to determine the appropriate training methods and intensities (i.e., loads) for continued progress. This is particularly important since a variety of athlete constraints (e.g., underlying physiology, training age, competitive domain, etc.) can impact training prescription considerations (e.g., periodization, loading, set configurations, rest intervals, etc.) and subsequent training strategies [2]. Therefore, it is important to discuss the current methods used to monitor strength characteristics and how to use these methods to modify training stimuli to benefit an athlete's overall motor performance.

Historically, recording and tracking sets, repetitions, and intensity in the weight room has been a long-term monitoring strategy amongst strength and conditioning practitioners. The use of hand-written training diaries existed well before software-based tracking options. For strength development, absolute training volume and intensity are great examples of "large scale" monitoring in which these variables can be tracked across multiple macrocycles. Many authors have referred to the cyclical nature of periodization and the need to "circle back" to certain blocks of training [3, 4]. As athletes develop, their absolute training volumes and intensities should (to a point) rise for their various training phases. Monitoring volume and intensity allows the coach to take a step back and view the athlete's development in a quantified, "big picture" fashion. Therefore, the purpose of this review is to examine the methods currently used to monitor and adjust training intensity for strength development and provide practical recommendations on how to integrate monitoring into a training plan to enhance program efficacy.

2 Monitoring and Training Intensity Prescription Methods

2.1 Linear Loading

A fundamental concept in eliciting desired physiological and performance adaptations is the application of an appropriate overload stimulus. An overload can be defined as a training stimulus that produces an adaptation beyond an athlete's current abilities of physical performance [3]. Linear loading exploits this principle by gradually increasing training loads (i.e., weights prescribed for resistance training exercises) beyond those encountered in previous training sessions to facilitate improvements in maximal strength [5]. While linear loading may be beneficial for a brief period [6, 7], more variation of the training stimulus beyond continual increases in load is required to effectively manage fatigue and facilitate recovery-adaptation [3] while opening the potential to assist complex motor skill consolidation (i.e., observed improvement in lift performance between training sessions) [8, 9]. Simply put, a greater emphasis on load variation (i.e., planned increases/decreases in load) may allow practitioners to emphasize recovery and adaptation within each training phase and throughout the training program. In contrast, linear loading implemented over an extended period (e.g., months to years based on the athlete) will eventually impair an athlete's ability to recover and adapt from training stimuli, leading to performance stagnation, non-functional

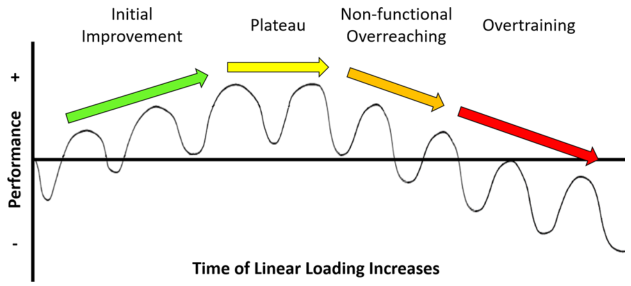


Fig. 1 The theoretical effects of extended linear loading and its effect on athlete adaptation, recovery, performance stagnation, non-functional overreaching, and overtraining. Modified from Cunanan et al. [10]

overreaching, and if continued, subsequent overtraining [5, 6, 10] (Fig. 1). Thus, because linear loading is driven by continual upward load adjustment, it is limited in its capacity to serve as an effective monitoring tool because it does not include enough load variation to account for an athlete's accumulated fatigue.

2.2 Two-for-Two Rule

The two-for-two rule refers to increasing the amount of weight for a given exercise if an individual can perform ≥ 2 repetitions over their assigned repetition goal in the last set in two consecutive training sessions [11]. Therefore, the monitoring and adjusting of training load in this method is principally based on completion of an assigned number or range of repetitions. For example, if an athlete is prescribed back squats at 100 kg for three sets of five repetitions but can perform seven repetitions on their final set during two consecutive sessions, the weight should be increased the next time the athlete squats. While this loading method may allow novice athletes to increase their muscular strength, it may promote training to failure (i.e., inability to perform additional repetitions at the same load) and ignores the athlete's technique, training goal(s), and relative intensity. First, although athletes may be able to complete a given number of repetitions, practitioners should seek some stability in technique prior to increasing the task demand through heavier loads. Second, if an athlete's training goal is improving general strength, it may be argued that the load is too light to maximize strength adaptations. If the athlete can perform ≥ 2 repetitions than prescribed during consecutive training sessions, it may be beneficial to modify the loads each set instead of prescribing the same load every set. Although traditionally viewed from a physiological adaptation perspective, changing loads every set also provides a potential benefit to skill acquisition (e.g., varied practice) with each set slightly altering the task demand [12]. Finally, if an athlete can perform extra repetitions after the final set, it may be by design. While repetitions in reserve will be discussed in Sect. 2.5, a progressive overload stimulus from week-to-week calls for an athlete to be able to theoretically perform repetitions beyond what was prescribed to avoid training to failure and manage fatigue.

2.3 Percentage of One Repetition Maximum

Expressing training intensity as a percentage of an athlete's one repetition maximum (1RM) is perhaps the most common method used to adjust intensity by strength and conditioning practitioners. A 1RM is traditionally established by identifying the heaviest weight that can be lifted with proper technique for one repetition [13]. This value can also be estimated using the heaviest mass lifted for multiple repetitions, as the number of repetitions performed is generally a function of the load lifted (e.g., 95% 1RM = 2RM) [14]. Once a 1RM is determined, resistance training intensities are prescribed as %1RM according to the number of repetitions performed in a set and the specific fitness characteristic being targeted [14]. However, it should be noted that 1RM prediction becomes less valid with higher repetition RMs [15].

Practitioners should be aware of the shortcomings of prescribing loads based on %1RM. Most notably, an athlete's 1RM is a dynamic value that fluctuates with changes in the athlete's physiological or psychological status [16, 17]. In fact, maximal strength can change substantially due to factors related to training, such as accumulated fatigue [16], or other life-related stressors (e.g., sleep deprivation, inadequate nutrition, stress, etc.) [17, 18]. Additionally, considerable variation in maximum repetitions performed at a given %1RM has been reported between athletes [19–22]. For example, Julio and colleagues [22] reported a wide range of maximum repetitions performed in the bench press at 70% (11–20 reps), 80% (5–15 reps), and 90% (2–7 reps) 1RM. Furthermore, an athlete's RM may also differ between exercises at the same %1RM, as the quantity of repetitions performed is also influenced by the amount of muscle mass involved [23]. For instance, Shimano and colleagues [23] reported significant differences in the number of back squat and bench press repetitions performed at 60% (29.9 v. 21.7), 80% (12.3 v. 9.2), and 90% 1RM (5.8 v. 4.0) in strength-trained participants. Lastly, other factors such as exercise type, gender/sex, and training status have also been reported to influence the maximum number of repetitions performed at a given %1RM [20]. Collectively, these limitations may lead to an inconsistent training stimulus, potentially resulting in divergent performance adaptations. This is not to say that %1RM should be eliminated as a form of prescribing resistance training intensity. Rather, it is recommended that this approach be combined with other load adjustment methods that help mitigate the aforementioned pitfalls and address the current physiological status of the athlete [24].

2.4 Repetition Maximum Zones

Rather than using %1RM to identify training loads, an athlete may select the heaviest load that can be lifted for a given repetition range (e.g., 3–5 repetitions) with the goal of reaching muscular failure on the final set of the exercise [25–27], termed RM zones. Proponents of the RM zone approach contend that it removes the limitations of %1RM, as the loads selected are adjusted according to the current physiological status of the athlete for each exercise [26]. This method may allow loads to be prescribed independent of 1RM testing, making it appealing for practitioners working with large groups of athletes.

While improvements in maximum strength have been reported using RM zones [6, 25, 28], practitioners should consider RM zone shortcomings. In particular, RM zones necessitate a constant relative maximum effort [27]. This is problematic when developing capacities, such as increasing power output and rate of force development (RFD), which are optimized by implementing a mixed methods approach utilizing both "heavy" and "light" days [29]. Consistent maximum exertion negates the use of "light" days, as each training session, regardless of the repetition range, becomes a "heavy" day when sets are performed to failure. Chronic training to failure also makes fatigue management very difficult, which may result in physiological consequences such as non-functional overreaching or overtraining [30, 31]. For instance, Carroll and colleagues [26] compared the training effects between groups implementing the RM zone and set-repetition best (SRB). Unlike RM zones, the SRB group utilized "heavy" and "light" days, as well as submaximal training loads. After the 10-week intervention, only the SRB group displayed significant improvements in absolute (Hedges' $g=1.05$, moderate) and allometrically scaled strength ($g=1.26$, large). In contrast, the RM zone group reported statistically greater training strain during the last seven weeks of training, as well as greater reductions in RFD at 50 ($g=1.25$, large) and 100 ms ($g=0.89$, moderate). Similar results were shown by Painter and colleagues [27], who compared the training effects between groups implementing daily undulating programming with RM zones and block programming with SRB over 10 weeks. Despite no statistical differences in maximal strength and RFD changes, the total number of repetitions ($g=3.89$, very large) and volume load ($g=1.69$, large) completed by the SRB group were significantly lower than in the daily undulating group.

Although RM zones alleviate some of the %1RM shortcomings, chronic training with maximal or near-maximal intensities may result in a plateau or maladaptation [32]. Consequently, other methods, particularly those allowing the use of submaximal loading as well as "heavy" and "light" days, may better facilitate long-term improvements in maximal strength, impulse, and RFD.

2.5 Rating of Perceived Exertion and Repetitions in Reserve

The rating of perceived exertion (RPE) developed by Gunnar Borg in the 1970s was intended as a perceptual (subjective) complement to other behavioral and physiological measures (i.e., objective) during performance of work. The original RPE scale features values ranging from 6 to 20 [33]; however, a simplified version of the scale includes values ranging from 0 to 10 [34]. Despite its aerobic training origins, this monitoring tool has also been used to assess the perception of resistance training intensity of each set [35, 36] as well as entire resistance training sessions (i.e., session RPE) [37–39]. While the current authors are not discounting the usefulness of the longitudinal monitoring of session RPE, the following discussion focuses on RPE following individual sets and its relationship to estimated repetitions in reserve [40–43]. For a specific discussion of set and session RPE for monitoring resistance training, readers are directed to a review by Scott and colleagues [24].

Researchers have indicated that RPE and estimated repetitions in reserve are highly correlated, but the strength of this relationship may be influenced by experience and training intensity. For example, Hackett and colleagues [43] showed strong positive correlations between estimated repetitions in reserve and actual repetitions in reserve in both the bench press ($r=0.95$) and squat ($r=0.93$) with trained bodybuilders. Further, estimated repetitions in reserve become more accurate when sets of exercise are being performed near failure [42]. However, in an effort to combine estimated repetitions in reserve and RPE in a single framework, Zourdos et al. [40] showed strong inverse relationships between mean barbell velocity and RPE/estimated repetitions in reserve in the experienced (> 1 year) ($r=-0.88$) and inexperienced (< 1 year) ($r=-0.77$) groups. Additional studies have reported similar relationships between mean barbell velocity and RPE/estimated repetitions in reserve in the deadlift [44], bench press [44, 45], chest press [41], and leg press [41]. Beyond correlational studies, other researchers have shown that RPE [44] and repetitions in reserve [46–48] may be valid and reliable methods for prescribing resistance training intensity.

In practice, RPE/estimated repetitions in reserve often entails providing resistance training intensities in the form of ranges. For example, an athlete may be assigned 3 sets of 5 repetitions with 1–2 estimated repetitions in reserve or the corresponding RPE value (i.e., 8–9), rather than %1RM. Studies comparing the use of RPE/estimated repetitions in reserve scales to %1RM have shown similar improvements in maximal strength between groups with small performance trends favoring the RPE/estimated repetitions in reserve groups [44, 46]. However, the efficacy of this approach across a variety of contexts (e.g., training status, gender/sex, athlete population, etc.) is unknown and it could be influenced by differences in training experience as described above. It is also important to note that different RPE/estimated repetitions in reserve scales were used in each intervention, suggesting that multiple methods of RPE/estimated repetitions in reserve may still provide appropriate training loads for improving maximal strength but not enough research is present to conclude which RPE/estimated repetitions in reserve scale is the most effective.

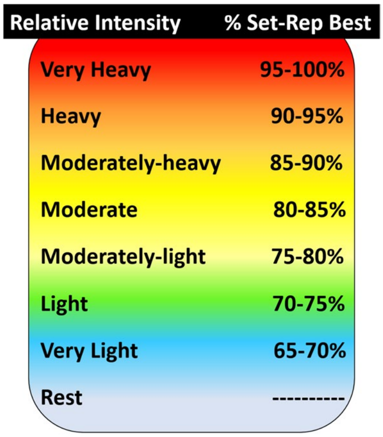
As the implementation of RPE/estimated repetitions in reserve is based more on subjective measures, it may be most effective when combined with other methods that include more objective measurements, such as %1RM or velocity-based training (VBT) to monitor and adjust training intensity effectively. Specifically, a practitioner may use %1RM to identify a desired training load for a session and RPE/estimated repetitions in reserve to adjust the load as a means of autoregulation. For example, if a maximum of six repetitions is estimated to be performed at 85% 1RM, a set of five repetitions performed with that load would be expected to yield approximately 1 estimated repetition in reserve (9 RPE) [40, 46]. If the athlete reports 2 estimated repetitions in reserve (8 RPE), the load can be increased to provide the intended training stimulus. When this approach is taken, RPE/estimated repetitions in reserve can be used to ensure that each athlete using this method is lifting a load within the same proximity to their relative maximal capacity.

The primary limitation of RPE/estimated repetitions in reserve is the potential for underreporting by athletes. For example, research indicated that despite reaching failure during an individual set (RPE = 10, maximal exertion), athletes still reported submaximal values (RPE < 10) [23, 43]. Additional researchers have shown that the ability to gauge exertion accurately may be influenced by athletic experience [49]. This may be due to inexperienced athletes displaying neuromuscular inefficiency or coordination. Consequently, practitioners should consider limiting autonomy when selecting training loads with untrained athletes until they display proficiency in reporting accurate RPE/estimated repetitions in reserve. It should be noted that this may not occur until athletes experience near-maximal loads during training. For example, Lovegrove et al. [47] suggested that prescribing resistance training intensities with a young population may be an effective method when using intensities that correspond to one repetition in reserve and following 1RM testing. Another limitation includes diminished estimated repetitions in reserve accuracy during higher repetition sets (e.g., > 12 repetitions) as well as lower relative intensities (e.g., > 4 repetitions in reserve) [50], similar to potential issues described previously with RM zones. This reduced ability to accurately monitor and critically adjust intensity with lighter training loads is concerning from the perspective of developing power output and RFD, which require high-velocity efforts using light-moderate loads that do not approach muscular failure. Thus, training in this manner may prevent the ability to use "heavy" and "light" days. As previously stated, these concerns might be effectively addressed by combining RPE/estimated repetitions in reserve with other methods like %1RM or VBT (Sect. 2.8).

2.6 Set-Repetition Best

To the authors' knowledge, percentage of SRB was first introduced by Stone and O'Bryant [51] and later described in further detail by DeWeese et al. [52]. Simply, percentage of SRB is used to prescribe relative intensities (percent ranges) in which an athlete's maximum weight is estimated based on their performance of a given set-repetition scheme. Figure 2 displays percent ranges and the corresponding relative intensity "days" (e.g., very heavy, heavy, moderately heavy, etc.). The 5% range allows coaches to assess each athlete (observation, athlete feedback, etc.) and thus, provide a degree of autoregulation and confirmation. Two studies by Carroll et al. [26, 53] showed that training with SRB may elicit greater adaptations in both skeletal muscle fiber (e.g., type I and II cross-sectional area, myosin heavy chain, and muscle thickness) and strength–power characteristics (e.g., vertical jump height, RFD, and isometric peak force) compared to RM zone training. The authors suggested that their results may be explained by the variation in workload distribution via heavy and light training sessions [53] and the greater training strain that occurred with RM zone training [26]. Based on the extant literature [26, 27, 53–57] and its autoregulatory nature in prescribing relative training loads, SRB may be an effective monitoring and adjustment method to use during resistance training.

While the %1RM strategy may allow practitioners to take the load for a given RM (e.g., 3RM, 5RM, etc.) and estimate an athlete's 1RM and RM for various repetitions [14], it is worth noting that %1RM estimates are based on a single set and one repetition. Thus, it is important to consider the accumulated fatigue from multiple sets. SRB may be used to adjust an athlete's maximal loads on a weekly basis depending on the loads completed during previous training sessions [52, 58]. Moreover, loads may be estimated when switching from one set-repetition scheme to another (Table 1) [51]. It is worth mentioning that the maximum load estimate is based on "ideal conditions" meaning that the athlete has been developing strength qualities specific to the



Relative Intensity	% Set-Rep Best
Very Heavy	95-100%
Heavy	90-95%
Moderately-heavy	85-90%
Moderate	80-85%
Moderately-light	75-80%
Light	70-75%
Very Light	65-70%
Rest	----------

Fig. 2 Relative intensity "days" and corresponding percent ranges. Modified from DeWeese et al. [52] and reprinted with permission from Elsevier

Table 1 Approximate percent changes for squat and pull exercises for various set-repetition schemes

Set-repetition scheme	Load % change from 3×2
3×2	–
3×3	↓ 5%
3×5	↓ 15%
5×5	↓ 17.5%
3×10	↓ 25%
5×10	↓ 27.5%

Modified from Stone and O'Bryant [51]. Practitioners may consider using ~ 10% lower alterations in percent changes for upper body exercises. There may be a decrease of ~ 10% from an individual's assessed one repetition maximum to their 3×2 load

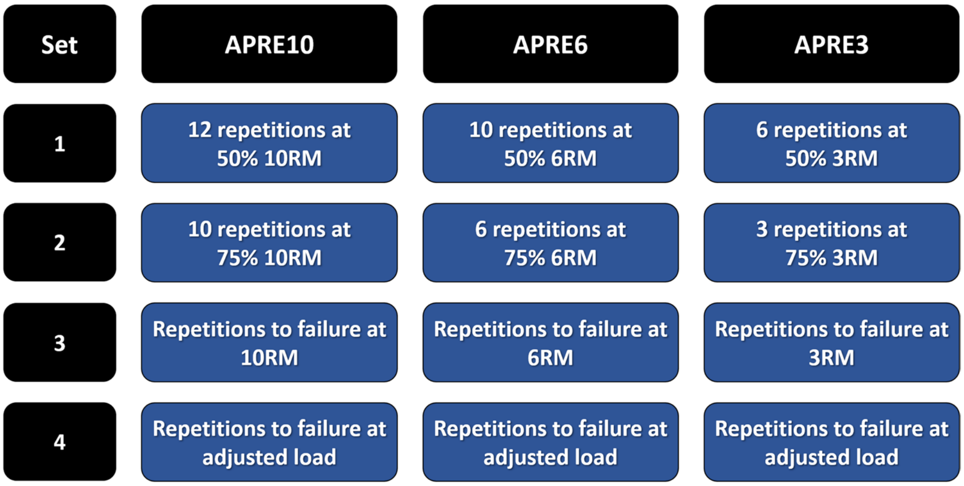
given set-repetition ranges for some time. From a practical perspective, SRB loads are based on percentages of the RM of the prescribed repetitions. For example, a prescription of 90% of 3 sets of 5 repetitions is based on 90% of an athlete's 3 × 5RM weight.

For practitioners less familiar with SRB, it may be difficult to understand where to start with novice athletes. A general recommendation of SRB is to load conservatively in the early stages before progressing in subsequent weeks. Practitioners often use a 3:1 weekly loading paradigm (i.e., summated microcycles) for strength-focused training blocks early in a macrocycle. Using this approach, the first three weeks may allow for "jumps" to be made as more observation takes place and input from the athlete is received. However, if a basic strength block (e.g., 3 × 5) follows a strength-endurance block (e.g., 3 × 10), starting certain exercises (e.g., back squat) with the heaviest weights performed in the previous block may be a good starting point before progressing in the subsequent weeks. A practical aspect of percentage of SRB is that it has a built-in goal setting component in which the athlete becomes aware of their "bests" for various set-repetition schemes and can plan on surpassing them in the future. In this regard, percentage of SRB may serve as a monitoring tool to determine if an athlete is responding to the training stimulus as expected or if training needs to be adjusted to prevent maladaptation. In the authors' experience, athletes can become accustomed to percentage of SRB within one or two summated microcycles (3–8 weeks).

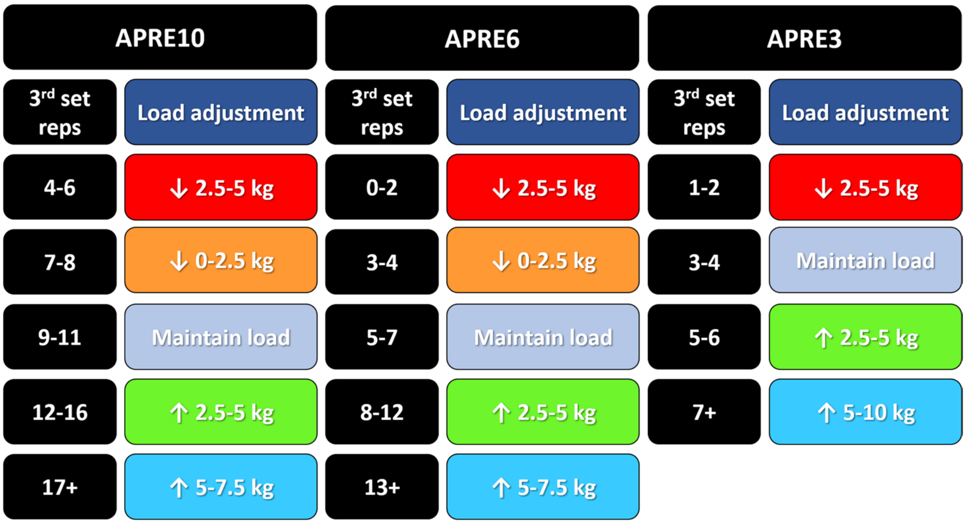
2.7 Autoregulatory Progressive Resistance Exercise

Autoregulatory progressive resistance exercise (APRE) may be defined as resistance training exercise that is adjusted to an individual's day-to-day training readiness [59]. The first model of APRE was termed progressive resistance exercise (PRE) and was used to treat orthopedic injuries from World War II [60]. This system used three progressively heavier sets of 10 repetitions, with the first two sets being at 50 and 75% of the primary 10 repetition set. Participants performed as many repetitions as possible on the final set, with a goal of 10 repetitions [61, 62]. Based on the performance of the third set, the load was adjusted for the following workout. The PRE model was renamed as daily adjustable progressive resistance exercise (DAPRE) in the 1970s and included a fourth set and adjustment chart [63] as well as a heavier six-repetition protocol [64]. The most recent modification added a three-repetition protocol and terminology change to what is known as APRE [65]. Thus, APRE is based on the use of three loading methods: APRE10, APRE6, and APRE3 (Fig. 3), which use different percentages of an athlete's 10RM, 6RM, and 3RM, respectively, and emphasize the development of specific physical characteristics (e.g., APRE10 = hypertrophy, APRE6 = hypertrophy and strength,

Fig. 3 Autoregulatory progressive resistance exercise (APRE) 10 repetition maximum (10RM), 6RM, and 3RM protocols. Modified and reprinted with permission from Mann [73]



Set	APRE10	APRE6	APRE3
1	12 repetitions at 50% 10RM	10 repetitions at 50% 6RM	6 repetitions at 50% 3RM
2	10 repetitions at 75% 10RM	6 repetitions at 75% 6RM	3 repetitions at 75% 3RM
3	Repetitions to failure at 10RM	Repetitions to failure at 6RM	Repetitions to failure at 3RM
4	Repetitions to failure at adjusted load	Repetitions to failure at adjusted load	Repetitions to failure at adjusted load



APRE10		APRE6		APRE3	
3rd set reps	Load adjustment	3rd set reps	Load adjustment	3rd set reps	Load adjustment
4-6	↓ 2.5-5 kg	0-2	↓ 2.5-5 kg	1-2	↓ 2.5-5 kg
7-8	↓ 0-2.5 kg	3-4	↓ 0-2.5 kg	3-4	Maintain load
9-11	Maintain load	5-7	Maintain load	5-6	↑ 2.5-5 kg
12-16	↑ 2.5-5 kg	8-12	↑ 2.5-5 kg	7+	↑ 5-10 kg
17+	↑ 5-7.5 kg	13+	↑ 5-7.5 kg		

Fig. 4 Autoregulatory progressive resistance exercise (APRE) 10 repetition maximum (10RM), 6RM, and 3RM load adjustment protocols. Modified and reprinted with permission from Mann [73]

and APRE3 = strength and power). As displayed in Fig. 4, the APRE adjustment charts require the athlete to either decrease, maintain, or increase the load based on the repetitions performed during the third set.

Previous studies indicated that autoregulatory strategies may stimulate greater strength adaptations compared to other loading strategies [59, 66–68]. However, it is important to distinguish APRE as a distinct training method compared to those that require the collection of additional data (e.g., RPE/estimated repetitions in reserve and VBT). Researchers indicated that APRE may lead to greater back squat, bench press, and hang clean strength adaptations compared to linear loading [69]. Similarly, Mann et al. [59] indicated that a six-week APRE program produced greater bench press and squat strength, as well as bench press strength endurance, compared to linear loading. Finally, Weber [70] showed that collegiate wrestlers produced greater increases in bench press maximum strength after an eight-week APRE program compared to linear loading, and may have been more efficient at producing increases in strength. It should be noted that all of the previous studies compared APRE to a linear loading program, of which the latter may eventually result in a plateau effect as noted above (Sect. 2.1) and in previous research [71]. In addition to healthy participants, Horshig et al. [72] showed that APRE may serve as an effective method to help athletes gain strength following an ACL reconstruction. Collectively, the extant literature suggests APRE may serve as an effective monitoring and load adjustment method for healthy and rehabilitating athletes due to the performance of 10RM, 6RM, or 3RM lifts and the individualized load adjustments within each training session. However, further research should compare APRE with other loading methods.

Several other factors should be considered when using APRE in training including technical failure, psychological momentum, and alterations to the load adjustment chart [73]. First, when performing repetitions to failure, it is important that proper technique is maintained during repetitions. If an individual sacrifices proper technique to complete additional repetitions, practitioners should stop the set [73]. Second, APRE adjustment protocols may be used as a motivational tool for athletes in the weight room. For example, if an athlete becomes familiar with the adjustment protocols, he or she may be motivated to perform an additional repetition so that they can increase the weight on the barbell during the next training session. Finally, practitioners who are using APRE protocols should understand that despite the recommended increases and decreases in weight, the load on the barbell should be put into context. For example, adding 5–7.5 kg may account for a greater increase in relative load (e.g., 100 kg 6RM = 5–7.5% increase v. 250 kg 6RM = 2–3% increase). Therefore, practitioners should be wary of an athlete's maximal strength and modify the adjustment protocols accordingly.

While APRE may serve as an effective method to increase muscular strength [59, 69, 70], at least initially, objective measurements (e.g., mean barbell velocity) may provide a better indicator of an athlete's performance rather subjective measurements (e.g., RPE) [74]. Therefore, practitioners may consider supplementing APRE loading with VBT measurements to ensure proper load prescription to allow for both adequate monitoring and adjustment of intensity. As noted in Sect. 2.4, practitioners should be cautious when using APRE protocols due to the potential for greater fatigue given the emphasis of training to failure.

2.8 Velocity-Based Training

Another method that has become popular over the last decade is the measurement of movement velocity of resistance training exercises, termed velocity-based training (VBT). VBT requires the use of equipment (e.g., linear position transducer, inertial measurement unit, etc.) that measures and/or calculates metrics such as barbell displacement and velocity. There are several purported benefits of VBT that include instantaneous feedback, the potential to predict the 1RM of specific exercises, and the use of velocity thresholds to monitor and adjust training intensity [75]. An overview of VBT applications is displayed in Table 2.

Using VBT as a method of feedback may supplement other prescription and adjustment methods such as %1RM [75]. Researchers have shown that using VBT as feedback to athletes led to increases in velocity and power outputs up to as much as 10% [77–79], which may have been due to intrinsic or extrinsic motivating factors (i.e., within- or between-athlete competition) [79]. For example, Weakley et al. [78] showed that there was an increase in motivation and competitiveness within adolescent rugby players with the addition of visual feedback during resistance training as measured by Dundee Stress State Questionnaire [88] and an adapted version of a 4-item competitiveness scale [89], respectively. Additional research showed that VBT feedback increased CMJ height up to ~ 8% [74], which may have been due to the increases in back squat strength (7.5%). However, it should be noted that no mechanistic changes in CMJ force–time characteristics were discussed in this study [74]. While performance may improve with additional feedback, competition between athletes may also increase [79]. For example, athletes can continue to motivate each other to achieve faster velocities during each repetition. While motivational benefits are present and VBT provides an external focus of attention, a lack of self-control on choosing when the athlete receives feedback from VBT devices may result in reducing autonomy which is contrary to recommendations for improving skill acquisition [90] and does not allow for a decreased dependency [91] when performing exercises where motor learning is important. Further, questions can arise if a focus on velocity is appropriate when a goal is also improving the motor skill which would likely be a focus of many complex exercises. While VBT may be an effective tool for feedback with more traditional resistance training movements (e.g., squat, bench press, etc.), further research still should evaluate if a short-term focus on velocity as the measure of performance has an effect on skill acquisition and coordination changes, particularly during more complex lifts (e.g., weightlifting movements) that have been shown to improve velocity through technical, not velocity-focused, instruction [92] and have fundamentally more complex coordination strategies [93].

Practitioners may be able to predict a daily 1RM of certain exercises since lifting velocity has been shown to decrease as external load increases [94–98] and continues until the terminal velocity is achieved during a 1RM [94].

Table 2 Benefits, limitations, and additional considerations for velocity-based training (VBT) uses

VBT Uses	Benefits	Limitations	Additional considerations
Real-time feedback	May increase athlete motivation May increase competitiveness in the weight room	Potential loss of focus on exercise technique to achieve higher velocities	Feedback should be provided consistently during exercise sets [75] Best implemented with heavy load, multi-joint movements (e.g., squat, bench press, etc.) or velocity-focused exercises (e.g., jump variations) [75–79]
Daily 1RM prediction	Daily training percentages are based on the current training state of the athlete	An athlete may not give maximal effort during their warm-up repetitions resulting in an underestimation of the daily 1RM Load–velocity profiles may overestimate a 1RM [80–83] Additional time may be needed to determine exercise load–velocity profiles, especially with group training sessions and multiple exercises performed throughout each week	General equations that use the velocity at 1RM from all athletes may help simplify load–velocity assessments [75] The two-point method may be useful for upper body exercises [84–86], but not lower body exercises [80]
Velocity loss thresholds	Increased ability to monitor fatigue during exercise sets Potential use of "flexible" repetition schemes that may compensate for athlete fatigue	Additional time may be needed with more frequent load adjustment throughout training sessions, especially with group training sessions Individual testing variability and time needed to establish velocity baselines	Accumulation phases may warrant the maintenance of the greatest velocity despite dropping below a threshold "Flexible" repetition schemes may modify the training stimulus and effectively alter the focus of the training day/phase [87]

This is further supported by researchers who have shown near perfect relationships between velocity and %1RM [99, 100]. VBT may be used to estimate the 1RM of an exercise using general [101] or individualized load–velocity relationship equations [80, 82]. Briefly, general, and individualized load–velocity prediction equations may be generated using the mean barbell velocity during single repetitions of an exercise or the mean barbell velocity produced with several submaximal loads, respectively. While each method allows practitioners to estimate a 1RM, it should be noted that both general and individualized equations have limitations. Regarding general prediction equations, previous literature has noted that the relationship between mean barbell velocity during single repetitions and 1RM percentage may be influenced by exercise type [99, 102–104], technique [105, 106], gender/sex [107, 108], and the device used to measure velocity [104, 109–111], but may also be specific to the individual [112]. Regarding prediction equations that use an individual's mean barbell velocity against several loads, it should be noted that individual mean barbell velocities at 1RM may not be reliable in 1RM prediction equations [80, 82, 113]. While this has led to the recommendation that general equations that use the mean barbell velocity of all athletes be used to simplify load–velocity assessments [75], other researchers have shown that using minimal velocity threshold reference values to predict 1RM may result in moderate-high absolute error when predicting the 1RM of an individual [114]. Further research on this topic is needed; however, it is recommended that strength and conditioning practitioners exercise caution when predicting 1RMs using load–velocity relationships using either general or individualized prediction equations.

A third way VBT has been used is velocity thresholds when monitoring resistance training. Traditional exercise sets require athletes to perform consecutive repetitions at a given load until the prescribed number of repetitions is met. However, large reductions in velocity may occur while using this method [115, 116]. Researchers have shown decreases in muscle fiber shortening velocity are linked to exercise-induced fatigue and further reductions in voluntary exercise velocity [117, 118]. Thus, velocity loss may be used as an indicator of volume and relative intensity prescription [75]. Weakley et al. [119] showed that velocity loss thresholds of 10, 20, and 30% displayed linear reductions in neuromuscular function as well as increases in perceived effort and metabolic responses. Additional research showed that these same thresholds may be used to maintain velocity and power outputs during resistance training [120]. Practically speaking, velocity thresholds may be used to monitor fatigue during single or multiple exercise sets [119, 120]. This may also allow for the use of "flexible" repetition schemes that use barbell velocity as an objective measure of exercise intensity rather than a standard set-repetition scheme.

While the addition of technology in the weight room may be appealing, there are potential disadvantages that can be present without knowledge and use of skill acquisition and motor learning principles. As mentioned above, the understanding of frequency of feedback, appropriate type of feedback relative to athlete need, and the subsequent effect of velocity as a focus on subsequent skill acquisition and coordination must be considered. In other words, the cost–benefit of an athlete focusing on trying to achieve a higher velocity at the expense of their technique should be addressed. Such a consideration explains why it has been recommended that athletes solidify their technique before implementing VBT [121], but this has been largely ignored in current VBT literature since much of the research has used a Smith machine with a fixed axis rather than free weights. Additionally, most literature examined exercises using a concentric-only movement following a pause rather than a traditional eccentric–concentric movement. Therefore, it is recommended that practitioners should interpret and apply the literature with caution to broader or less-constrained exercises. In summary, it is likely that VBT has its greatest application as a specific monitoring complement as alluded to in the previously described methods and has disadvantages for adjusting training intensity broadly across all exercises or athletes. While a brief overview of VBT was included above, readers are directed to Weakley et al. [75] for a more thorough discussion.

3 Monitoring Motor Learning and Skill Acquisition

The monitoring and adjusting of intensity for strength development as the purpose of this article should not be presented in isolation to understanding and assessing the quality of movements performed during resistance training or the enhancement of motor skills (e.g., sprinting, throwing, etc.) that may ultimately be the intended result. Measures of strength as described in the current paper would fall on the spectrum of measures of motor capacity or motor capability when classified according to previous research definitions [122]. However, one must also determine changes to subsequent motor performances that are relevant to athletes and their sporting performance (Fig. 5). It is acknowledged that coaches may use their experiential knowledge to qualitatively assess movement skill in combination with quantitative analysis [123], particularly where exercises have a higher technical or coordination complexity. To further this assessment, research using principles and measures from the motor behavior literature is being integrated into strength and conditioning literature in contrast to a commonly strict physiological perspective [124–126] to describe the learning of skill over time versus the typical cross-sectional

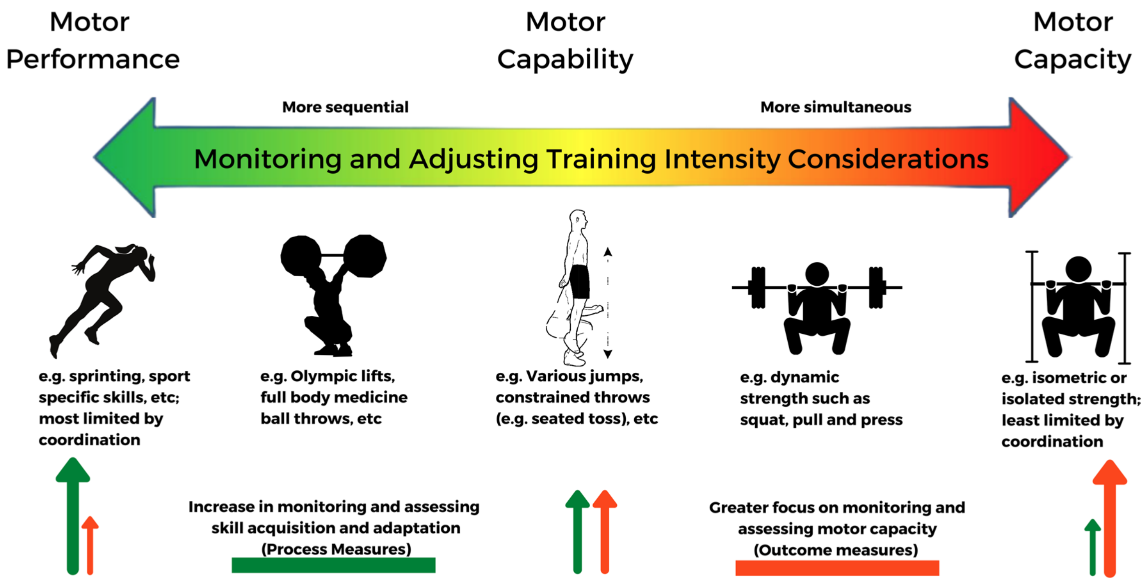


Fig. 5 Lag-time in transfer of training from enhancing motor capacity to enhancing motor skill may alter decisions in adjusting training intensity. For example, stagnation in motor learning may support when to make changes to intensity or apply a task variation to improve future skill acquisition. Such decisions are dependent upon multiple factors (e.g., training age, phase of training, training intent). Motor skills (e.g., sprinting) may require greater assessment of motor learning or skill acquisition versus motor capacity tasks (e.g., isometric) that may be more dependent on monitoring of outcome (e.g., force)

assessment described in biomechanics research. As a result, there is future potential to quantify and monitor when stagnation in skill acquisition or adaptation to motor performance or motor capabilities occurs during resistance training phases seeking improvements in motor capacities (i.e., strength). Therefore, monitoring the *process* of motor learning and adaptation or skill acquisition could be combined with monitoring methods previously described that focus on *outcome* (e.g., VBT). Such an approach would allow for more holistic monitoring of resistance training. While the recommendation to monitor motor learning and skill acquisition is fine in principle, the current caveat is data processing, additional technology, and a greater understanding of which variable or feature of learning (e.g., adaptation, coordination, transfer, etc.) is most appropriate to monitor during resistance training monitoring. An abundance of variables and measures used to assess motor learning could be applicable if adapted from neurorehabilitation research [127] or sporting skill monitoring [128]. However, specific research related to the exercises or movements most relevant to resistance training monitoring is warranted but beyond the scope of the current paper to review and outline.

The applicability of including measures that monitor the process of motor learning and skill acquisition is clear when considering the implications of athletes at various stages of learning (i.e., coordination, control, skill [12]). Future monitoring may be guided by a combination of outcome-focused resistance training monitoring methods already determined to be affected by athlete experience/skill (e.g., VBT or RPE/repetitions in reserve) and process-focused resistance training methods. For example, if a novice athlete required technique stabilization, measures of bi-variate coordination variability [91] or execution variability [129] could be the process measures driving intensity adjustments instead of outcome measures. Further, measures of coordination or variability magnitude or structure might help to determine when to implement or change resistance training techniques or determine when to change the exercise task [125]. Unfortunately, there is a paucity of research within the context of strength and conditioning, but the existing qualitative practice of coaches highlights the need for and importance of including measures of skill acquisition and motor learning for comprehensive monitoring practice. Future resistance training monitoring should aim to include a combination of measures that quantify outcome (e.g., velocity, load, time, etc.) with process (e.g., variability magnitude or structure, coordination, efficiency, etc.) relevant to the stage of learning as previously explained or to the task being performed as displayed in Fig. 5. Such an approach will align with recommendations of needing to understand the interaction of the individuals' motor capability and motor control [130].

4 Conclusions

Strength and conditioning practitioners have access to a wide variety of methods that can be used to monitor and adjust training intensity during resistance training. However, it is important that practitioners understand the advantages and disadvantages of each method to choose the method(s) that works for them from both a practical and financial standpoint. The linear loading and 2-for-2 methods may be beneficial for novice athletes given that their exercise technique and relative strength may change on a daily basis; however, these methods are limited in their capacity to provide athletes with variation and may be detrimental if used exclusively for long periods of time. %1RM and RM zone training may provide athletes with more variation and greater potential for strength–power adaptations; however, they fail to account for daily changes in athlete's performance capabilities (e.g., fatigue, life stressors, sleep quality, etc.). However, an athlete's daily readiness can be addressed to various extents by both subjective (e.g., RPE/estimated repetitions in reserve, SRB, and APRE) and objective (e.g., VBT) load adjustment methods. Many of the previously discussed methods can be used together to provide greater insight into an athlete's training state. In addition, future monitoring strategies may add to these output-focused measures, process measures of skill acquisition, and motor learning within the athlete. Thus, practitioners could consider using a combination of methods to ensure they adequately measure and account for daily changes in an athlete's fitness and fatigue. Finally, it is important to note that the addition of devices or monitoring tools should not substitute for the actual coaching of lifts. Instead, monitoring tools should be used to supplement and guide the practitioner, quantify what the practitioner 'sees', and provide longitudinal data to assist in reviewing athlete development and providing baselines for the rate of expected development in resistance training when an athlete returns to sport from injury or large training load reductions.

4.1 Additional Considerations and Recommendations

While this review has primarily focused on monitoring and adjusting intensity within the weight room using traditional resistance training exercises (e.g., squats, presses, and pulls), it should be noted that other forms of resistance training such as weightlifting movements [131–137], eccentric training methods [138–144], isometric training [145–147], plyometric training [148–152], and loaded jumps [153–155] may require different monitoring methods due to unique loading methods (e.g., eccentric, isometric, etc.) or coordinative complexity (e.g., weightlifting movements and jump variations). In addition, practitioners should consider the fact that novice athletes may lack consistency in the weight room due to modifications of their strength, technique, and effort. Thus, more simplistic methods of monitoring and adjusting training intensity, such as RPE/repetitions in reserve or APRE, might be advantageous. In contrast, more experienced athletes who are seeking very small improvements in their performance may require more frequent adjustments to their training loads, as well as information about how they are moving different loads in the weight room or even the coordinative strategies (behavioral flexibility) they are able to demonstrate. These athletes may benefit from using methods such as SRB and/or VBT in combination with methods that can also provide process measures of monitoring as they are developed.

Despite the benefits of monitoring "inside" the weight room, integrating measures "outside" of the weight room (e.g., vertical jump, isometric mid-thigh pull, speed, etc.) may provide a more holistic view of how an athlete is responding to the accumulated stress of weight training, practice, games, and psychological stressors, in addition to giving practitioners the opportunity to observe the non-linear or lagged response of improved abilities and ultimately motor skill relative to capacity development (Fig. 5). This in turn may allow practitioners to program and adjust training accordingly to promote strength–power adaptations, manage fatigue, help mitigate injuries, and enhance the recalibration of the motor system as one "*learns how to use newfound strength*" within sporting skills. Regardless of the method(s) used to adjust the intensity in the weight room, an athlete's prescribed loads must be put into context. Specifically, practitioners should consider athlete feedback, laboratory/field test results, and the goals of past, current, and future blocks within the athlete's long-term training plan. By doing so, practitioners can use a comprehensive, evidence-based approach when prescribing loads for their athletes and avoid being overly reactive to minimal monitoring information.

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