Brief Review

The Journal of Strength and Conditioning Research™

OPEN

Maximizing Strength: The Stimuli and Mediators of Strength Gains and Their Application to Training and Rehabilitation

Barry A. Spiering,[1] Brian C. Clark,[2,3] Brad J. Schoenfeld,[4] Stephen A. Foulis,[1] and Stefan M. Pasiakos[1]

[1]Military Performance Division, U.S. Army Research Institute of Environmental Medicine, Natick, Massachusetts; [2]Ohio Musculoskeletal and Neurological Institute, Ohio University, Athens, Ohio; [3]Department of Biomedical Sciences, Ohio University, Athens, Ohio; and [4]Health Sciences Department, CUNY Lehman College, Bronx, New York

Abstract

Spiering, BA, Clark, BC, Schoenfeld, BJ, Foulis, SA, and Pasiakos, SM. Maximizing strength: the stimuli and mediators of strength gains and their application to training and rehabilitation. *J Strength Cond Res* 37(4): 919–929, 2023—Traditional heavy resistance exercise (RE) training increases maximal strength, a valuable adaptation in many situations. That stated, some populations seek new opportunities for pushing the upper limits of strength gains (e.g., athletes and military personnel). Alternatively, other populations strive to increase or maintain strength but cannot perform heavy RE (e.g., during at-home exercise, during deployment, or after injury or illness). Therefore, the purpose of this narrative review is to (a) identify the known stimuli that trigger gains in strength; (b) identify the known factors that mediate the long-term effectiveness of these stimuli; (c) discuss (and in some cases, speculate on) potential opportunities for maximizing strength gains beyond current limits; and (d) discuss practical applications for increasing or maintaining strength when traditional heavy RE cannot be performed. First, by conceptually deconstructing traditional heavy RE, we identify that strength gains are stimulated through a sequence of events, namely: giving maximal mental effort, leading to maximal neural activation of muscle to produce forceful contractions, involving lifting and lowering movements, training through a full range of motion, and (potentially) inducing muscular metabolic stress. Second, we identify factors that mediate the long-term effectiveness of these RE stimuli, namely: optimizing the dose of RE within a session, beginning each set of RE in a minimally fatigued state, optimizing recovery between training sessions, and (potentially) periodizing the training stimulus over time. Equipped with these insights, we identify potential opportunities for further maximizing strength gains. Finally, we identify opportunities for increasing or maintaining strength when traditional heavy RE cannot be performed.

Key Words: force, sarcopenia, spaceflight, sports, supercompensation

Introduction

The U.S. Army has a renewed interest in improving the physical performance of soldiers beyond current upper limits while using ethical interventions. Of the many candidate interventions available to support this goal, few interventions improve soldier physical performance as impressively as traditional heavy resistance exercise (RE) training (52,53). In addition to improving soldier performance, traditional heavy RE training has important benefits for civilian populations as well. Specifically, traditional heavy RE improves performance on various daily, occupational, athletic, and recreational tasks (7,11,69). Therefore, exploring opportunities for maximizing strength gains beyond current upper limits has important implications for soldiers and civilians alike.

Soldiers and civilians also face scenarios in which traditional heavy RE cannot be performed; for example, when insufficient RE equipment is available (e.g., during at-home exercise or deployment to austere environments), after musculoskeletal injury (i.e., when musculoskeletal tissues cannot tolerate heavy loads), or because of joint degeneration as a result of aging or arthritis. In these scenarios, increasing or maintaining physical performance remains an important objective. Therefore, developing effective interventions for increasing or maintaining physical performance when traditional heavy RE cannot be performed represents a worthy endeavor.

The benefits of RE on physical performance are, in part, the result of the associated improvements in maximal strength (60,89). As such, the specific purpose of this narrative review is to (a) identify the known stimuli that trigger RE-induced gains in strength; (b) identify the known factors that mediate the long-term effectiveness of these RE stimuli; then leverage these insights to (c) discuss potential future directions for further maximizing strength gains beyond current upper limits; and finally (d) discuss practical applications for increasing or maintaining strength in special scenarios in which traditional heavy RE cannot be performed.

Definitions

In the context of this review, we define "traditional heavy RE" as the activity commonly seen in fitness facilities and rehabilitation clinics; that is, lifting and lowering an external load (through either free weights or commonplace exercise machines) through a

Address correspondence to Barry A. Spiering, barryspiering@gmail.com.

Journal of Strength and Conditioning Research 37(4)/919–929

full range of motion. We further define "heavy" as using an external load that allows between 1 and 5 repetitions per set when using maximal effort, as previous research shows that these loads maximize strength gains (78).

We define "strength" as the maximal level of volitional force or torque generated during a single attempt of both simple tasks (e.g., knee extension) and during complex tasks that require selective engagement of muscles in a coordinated, context-sensitive manner (e.g., squatting, gripping, etc). Most studies cited in this review use an individual's one repetition maximum (1RM; i.e., the most amount of weight that can be safely lifted through a full range of motion using correct technique) as the method to quantify strength because this test most closely represents traditional RE training activities. Some of the cited studies used alternative methods of strength assessment, such as isometric strength (maximal force generated at a fixed position against an immovable object) or isokinetic strength (maximal force generated at a fixed velocity using specially designed equipment). We refer the interested reader to other articles describing the large variability and associated specificity in strength gains after RE when using different testing methods to assess strength (e.g., traditional free-weight RE training increases maximal strength during free-weight tests more than it increases maximal strength during isometric or isokinetic tests) (12,16). Finally, we emphasize that this review focuses on strength, not on muscular power (the product of force and velocity), endurance (the ability to perform prolonged or repetitive muscle contractions), or muscle size (also known as hypertrophy).

Scope, Style, and Limitations

As a foundation for discussing opportunities for maximizing strength gains, we first identify the stimuli that trigger gains in strength. Existing review articles already give insight into the *external* stimuli for increasing strength (e.g., training load, number of sets, etc) (54,78). Such information is critical for providing practitioners with evidence-based guidance for enhancing strength. This article instead focuses on the *internal* stimuli. In other words, the goal is to identify factors that link the external action (resistance exercise) to the desired end state (strength gains). By first identifying the internal stimuli that trigger gains in strength, we intend to uncover insights that allow others to creatively research, monitor, and manipulate these stimuli in the hopes of maximizing strength gains beyond our current upper limits.

Finally, this review strives to integrate current knowledge about RE and share existing insights for (and, in some cases, openly speculate on) future opportunities for maximizing strength. To facilitate the assimilation of broad ideas into a coherent paradigm, preference is given to referring to recent systematic reviews (when available) with limited discussion about the associated nuance and underlying mechanisms. To emphasize, our primary goal is to *identify* potential opportunities for future exploration and not to deeply analyze and contextualize each opportunity. Another limitation is that by using a narrative format (as opposed to a systematic format), there is risk of study selection bias that can unduly influence conclusions (34). Therefore, the reader is forewarned about the limitations of this review and encouraged to explore the cited references. A potential strength of this review, though, is that focusing on broader themes might help to clearly convey potential theories, as well as future opportunities for maximizing strength gains.

Stimuli of Strength Gains

After conceptually deconstructing traditional heavy RE, our proposed paradigm suggests that strength gains are stimulated through a sequence of events, namely: giving maximal mental effort, leading to maximal neural activation of muscle to produce forceful contractions, involving lifting as well as lowering movements (concentric-eccentric muscle actions), training through a full range of motion, and (potentially) inducing muscular metabolic stress.

Maximal Mental Effort

The signal to perform RE, or any volitional action, originates in the brain—the motor cortices specifically. Long-term RE training produces measurable adaptations in the central nervous system that importantly contribute to the observed gains in strength (including increased neural drive, decreased antagonist coactivation, etc.) (31,82). Therefore, perhaps not surprisingly, the mental effort associated with performing RE is itself a stimulus for strength gains. As evidence, imagined forceful muscle contractions performed in the absence of actual or physical muscle contractions (also known as, motor imagery training) effectively increase strength over time (70). Moreover, these improvements are accompanied by physiological changes (central neural adaptations that ultimately result in increased descending command), indicating that the strength gains are not simply the result of psychological or motivational factors (70). This same analysis found that greater intensity of mental effort during motor imagery training produced greater subsequent gains in strength (70). In the context of relatively low-force muscle contractions, greater mental effort during training produces greater strength gains over time compared with lower mental effort training, despite the same external force output and duration of muscle contraction (49). These findings indicate that mental effort independently and progressively stimulates strength gains.

Maximal Neural Activation of Muscle to Produce Forceful Contractions

During traditional RE, maximal mental effort leads to maximal neural activation of muscle, which inevitably produces forceful muscle contractions. This neuromuscular interaction, regularly produced over time, causes adaptations in both the corticospinal and reticulospinal tracts and in the muscle (83). The motor neuron, the final common pathway to force generation, has been the most extensively studied; at its level, gains in strength have been attributable to a higher instantaneous discharge rate of motor units (e.g., higher firing rates) and a higher incidence of doublet discharges (i.e., a unit that discharges twice in very rapid succession) (26). The muscle also adapts to repeated contractions performed during training, including, but not limited to, increases in the contractility of the muscle (16,63) and increases in the number of force-generating contractile proteins, which further contribute to increases in muscle size (41,98). At least 3 lines of evidence support the theory that forceful muscle contractions independently stimulate strength gains. First, while imagined muscle contractions improve strength, strength gains are greater after traditional physical contractions (i.e., maximal mental effort plus corresponding forceful muscle contractions) (70). Second, electrically evoked contractions (i.e., forceful muscle contractions without any mental effort) increase strength over time (5). Third, training with increasingly heavier loads (which requires increasingly greater muscular forces) produces progressively greater strength gains over time, even when all training progresses to the point of maximal mental effort despite differences in external load (78). Collectively, this evidence indicates that forceful muscle contractions independently and progressively promote strength gains.

Involving Lifting and Lowering Movements (Concentric-Eccentric Muscle Actions)

Traditional RE involves lifting and lowering an external load, which requires concentric (shortening) and eccentric (lengthening) muscle actions, respectively. Traditional concentric-eccentric training seems to produce greater improvements in strength than concentric-only training (27). This indicates that including lowering (eccentric) and lifting (concentric) muscle actions maximizes strength gains after traditional RE training. That stated, combined concentric-eccentric actions are likely not an independent stimulus for strength gains (e.g., common low-intensity activities like walking, which also involve concentric-eccentric actions, do not potently stimulate strength gains in healthy subjects). Rather, the effectiveness of concentric-eccentric actions for increasing strength likely only occurs in the context of forceful muscle contractions (or substantial metabolic stress, as discussed below).

Training through a Full Range of Motion

Heavy RE with combined concentric and eccentric muscle actions leads to forceful muscle actions through a given range of motion (ROM). Although strength gains tend to be specific to the ROM used during training (68), training with a full ROM generally maximizes strength gains across most contexts (68). Clearly, ROM itself is not an independent stimulus for strength gains (i.e., passive motion through a particular ROM will likely not increase strength in healthy individuals). Rather, we view ROM as an interrelated stimulus (i.e., ROM is inextricably linked to performing concentric-eccentric actions; strength gains are related to the corresponding ROM used during training; and strength gains related to ROM only occur in the context of forceful muscle contractions).

Inducing Muscular Metabolic Stress

Muscular contractions increase metabolic reactions and, when performed repeatedly, lead to metabolic stress (reflected by the depletion of intramuscular energy substrates and accumulation of metabolic by-products) (98). At least 196 metabolites significantly change in concentration after an acute bout of exercise (79). Conflicting evidence exists whether metabolic stress stimulates muscle growth and, consequently, strength gains (21,98). Furthermore, it is difficult to determine whether metabolic stress is an independent stimulus (stimulates strength gains without muscle contraction) (14) or whether metabolic stress instead exerts a synergistic effect (stimulates strength gains only when accompanied by muscle contraction) (66). What is seemingly incontrovertible, though, is that blood flow restriction (BFR, which typically involves using commercially available pneumatic cuffs or bands) in combination with low-load RE training increases intramuscular metabolic stress (92) and enhances long-term strength gains compared with low-load RE without BFR (84); impressively, low-load BFR training might even cause comparable improvements in muscle strength as traditional heavy-load RE (although conflicting evidence exists (38,58)).

Mediators of Strength Gains

To optimize strength gains in response to RE training, we identify several factors that mediate the long-term effectiveness of these RE stimuli, namely, optimizing the dose of RE within a session, beginning each set of RE in a minimally fatigued state, optimizing recovery between training sessions, and (potentially) periodizing the training stimulus over time.

Optimizing the Dose of Resistance Exercise Within a Session

The optimal dose of RE within a training session can be quantified in terms of the intensity (external load) and the volume (number of repetitions per set and number of sets). With respect to intensity, there seems to be a dose-response relationship such that higher training loads produce greater subsequent gains in strength (78). With respect to the number of repetitions per set, during traditional RE, the relationship between load and the number of repetitions is inversely linked (i.e., lighter loads allow higher repetitions per set and heavier loads allow fewer repetitions per set). Generally, heavier loads that allow approximately 1–5 repetitions per set maximize strength gains over time (78). With respect to the number of sets, as little as one set per exercise can increase strength over time, even in subjects with previous RE training experience (4). That said, greater volumes of RE produce greater improvements in strength, up to a given point. More specifically, although 2–3 sets per exercise stimulates greater strength gains than 1 set per exercise, further increase in the dose to 4–6 sets per exercise might have little additional benefit (although, this is potentially because of the limited number of studies using doses of >3 sets) (54). Overall, this research (54,78) generally supports using relatively heavy loads (i.e., loads that allow $\sim$1–5 repetitions per set) and approximately 2–3 sets per exercise as the optimal dose of RE within a session to maximize strength gains over time. That stated, more research is needed to determine whether >3 sets per exercise per session might further enhance strength gains. Relatedly, identifying a maximally effective dose (beyond which increasing the number of sets does not produce greater strength gains) would be very practically relevant.

Beginning Each Set of Resistance Exercise in a Minimally Fatigued State

Acute RE can lead to transient fatigue (reflected in temporarily reduced maximal strength capabilities) (33,51). At least 3 lines of evidence indicate that beginning each set of RE in a fatigued state can, over time, diminish gains in strength. First, performing RE using short interset rest intervals ($\leq$2 minutes) diminishes strength gains compared with using long rest intervals ($>$2 minutes), at least in well-trained individuals (although, the use of short rest intervals seems less detrimental in novice individuals) (37). Second, placing an exercise last in the exercise session (as opposed to first) diminishes strength gains after long-term training (64). Third, performing endurance exercise immediately before RE diminishes long-term strength gains when compared with inserting a recovery interval between endurance exercise and RE

(50) or when compared with performing RE before endurance exercise (30,62). Collectively, these lines of evidence indicate that initiating each set of RE in a relatively "fresh" (minimally fatigued) state helps maximize long-term strength gains.

Optimizing Recovery Between Training Sessions

Resistance exercise does not enhance strength; rather, *recovery from and subsequent adaptation to RE* enhances strength. In other words, RE causes fatigue and muscle damage, which actually can impair strength in the short term (33,51). However, if sufficient recovery is provided, then "supercompensation" (incremental improvements in performance beyond previous capabilities) occurs as an adaptive response (97). Over time, these small, repeated, incremental improvements lead to measurable, practically meaningful increases in strength (see Figure 1 for conceptualization).

Periodizing the Training Stimulus Over Time

Although performing monotonous or uncomplicated RE increases strength over time, advanced practitioners typically include "periodization"; that is, planning and organizing the training stimulus over time according to strategic goals in an attempt to maximize strength gains, minimize signs of overtraining, and reduce the risk of overuse injuries. There is a sound logical basis for the systematic planning of training as a means to balance stimulus and recovery, which (conceivably) helps to maximize results. A recent meta-analysis concluded that periodized RE training enhances strength gains compared with nonperiodized training (100), although critiques of existing periodization research exist (2,13,65). Therefore, additional research would help objectively determine whether periodized training indeed maximizes strength gains. In the meantime, most experts generally believe that periodization remains the best practice, and there is no reason to believe that periodization detrimentally affects strength development (100).

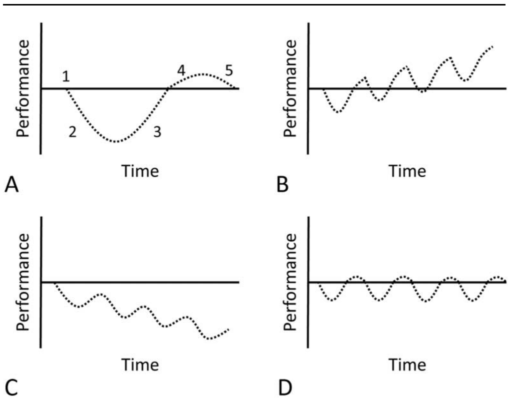

Figure 1. Conceptualization of "supercompensation theory," which is originally credited to NN Vakovlev (Viru (97)). (A) General concept within the context of one bout of resistance exercise (RE). Specifically, (1) the onset of RE causes fatigue and tissue damage, leading to (2) a temporary decline in performance. Subsequently, over time, (3) performance recovers and, if enough time is given between RE training bouts, then (4) performance supercompensates. If too much time is given between RE training bouts, then (5) performance decays back to baseline. (B) Upward trend in performance that might occur when optimal recovery is given between multiple RE training sessions. (C) Downward trend in performance that might occur if too little recovery is given between multiple RE training sessions (also known as "overtraining"); although, this concept of overtraining has been critically evaluated by others (Kataoka et al. (51)). (D) Maintenance in performance that might occur when extensive recovery is given between multiple RE training sessions. Importantly, much work remains to determine the scientific realities of supercompensation theory for influencing long-term gains in strength.

Future Directions for Maximizing Strength Gains

Considering these above-noted insights on the stimuli and mediators of strength gains, we herein identify (and, in some cases, speculate on) future opportunities for further maximizing strength gains beyond the current upper limits. The future directions are organized into 4 primary themes: (a) supramaximal training intensity (in terms of external load and mental effort); (b) supplemental activities; (c) optimizing and potentially individualizing recovery strategies to foster subsequent strength gains (also known as supercompensation); and (d) technological applications.

Supramaximal Training Intensity

Because of the dose-response relationship between forceful muscle contractions and subsequent strength gains, using "supramaximal" muscle contractions (forceful contractions beyond that normally encountered during traditional heavy RE) might further enhance strength gains (see Figure 2 for conceptualization). For example, because of the molecular mechanics of muscle contraction, muscles can produce greater force during eccentric actions than during concentric actions (25). Therefore, during traditional heavy RE (when the load remains constant during the concentric and eccentric phases), muscles are near-maximally loaded during the concentric (lifting) phase and submaximally loaded during the eccentric (lowering) phase. With this insight in mind, research indicates that incorporating supramaximal (beyond concentric 1RM) eccentric-only training or incorporating "accentuated eccentric loading" (when the load during the eccentric phase is greater than the load during the corresponding concentric phase) seems to further enhance strength gains (24), as well as provide other neural, muscle, tendon, and performance advantages (24,25). That stated, eccentric-based overload training might require longer recovery between sessions because of potentially greater exercise-induced muscle damage (17,25); therefore, the optimal implementation of eccentric-based overload training into a traditional RE training program remains to be determined. Practically, several options exist to help incorporate eccentric-based overload training into training and rehabilitation. Commercially available exercise hardware that allows eccentric overload already exists (e.g., devices that allow users to manually or digitally manipulate the eccentric load (90,91)). Alternatively, low-tech options include external weight releasers, as well as lifting an object bilaterally and then lowering the object unilaterally.

Other practical interventions involving "supramaximal" contractions exist. For example, during some exercises (e.g., squat and bench press), individuals can generate more force when closer to full extension. Therefore, some researchers have investigated the effectiveness of "variable-load" RE (i.e., traditional free weights plus added elastic bands or heavy chains that result in progressively greater loads nearer to full extension). Existing evidence indicates that variable-load RE might have merits for further enhancing strength gains (88). Additional research to substantiate these findings is warranted (88).

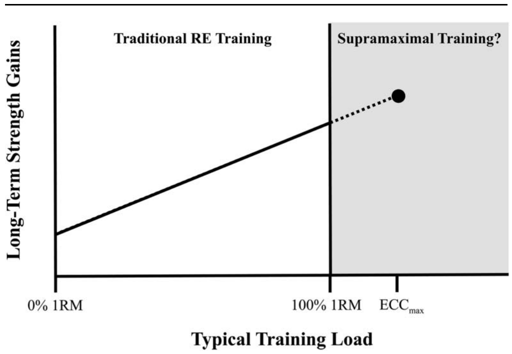

Figure 2. Conceptualization of the dose-response relationship between traditional resistance exercise (RE) training load (as a percent of one repetition maximum [1RM] strength) and subsequent long-term gains in maximal strength. Notable points include the following: (a) the dose-response relationship assumes that training occurs at a traditional or voluntary speed and, regardless of training load, each set of RE proceeds to the point of maximal mental effort; (b) even no-load conditions like motor imagery (Paravlic et al. (70)) and maximal muscle actions without an external load (Counts et al. (18)) can increase strength over time as long as mental effort is maximal, which explains why the dose-response line does not cross the horizontal axis; (c) the slope and the intercept are roughly based on data by Lasevicius et al. (55); (d) the dose-response relationship assumes that the training volume-load is equated (as an example, based on the data of Lasevicius et al. (55), training using 3 repetitions at 90% 1RM would produce greater strength gains over time than 9 repetitions at 30% 1RM, despite equal volume-load); and (e) maximal eccentric loads (ECC$_{max}$) are at least 25% greater than concentric 1RM (Hollander et al. (45)). Supramaximal loads (e.g., eccentric-based overload training) might further enhance strength gains beyond what is capable with traditional RE (Douglas et al. (24)). That said, an upper threshold likely exists, probably near ECC$_{max}$. Other strategies such as biofeedback (Lepley et al. (57)), variable-load RE (Suchomel et al. (88)), certain forms of external stimulation (Tallent et al. (93) and Alghadir et al. (3)), and cognitive strategies (Tod et al. (94)) also seem to increase acute training loads, which might enhance subsequent strength gains beyond traditional upper limits; however, further research must substantiate these effects.

Research has also investigated whether supplementing RE with various forms of external stimulation might directly enhance forceful contractions during training and, consequently, maximize long-term gains in strength. Examples of centrally or peripherally stimulating forceful contractions (as a supplement to volitional effort) include using neuromuscular electrical stimulation (NMES) (40), whole-body electromyostimulation (WB-EMS) (101), repetitive transcranial magnetic stimulation (TMS) (93), or transcranial direct current stimulation (tDCS) (44,56,67,99). Each of these techniques stimulate the nervous system to facilitate forceful muscle contractions, albeit at different locations within the nervous system (central vs. peripheral) and through different mechanisms (e.g., direct stimulation vs. enhanced excitability to voluntary drive). Ostensibly, enhancing the forcefulness of muscle contraction could in turn enhance long-term strength gains (see above discussion). Alternatively, manipulation of sensory input (e.g., via brief, local vibration or sensory nerve electrical stimulation) represents another neural-based strategy that may have potential to maximize strength gains. These approaches augment sensory feedback to modulate (or prime) neural excitability and can, in some instances, immediately improve performance on clinical tests of motor function in selected populations (3,46,76,81,87). However, clinical populations and those with neurological disorders are more likely to positively respond to approaches that manipulate sensory input than healthy, high-performing individuals (because of a ceiling effect in the latter population). Overall, given the diversity in tools, protocols, and associated mechanisms used in these lines of research, more research is necessary before making educated recommendations for the use of external stimulation in general populations. That stated, some of these techniques might hold promise for further enhancing strength gains (e.g., tDCS), whereas other techniques seem to minimally affect strength gains beyond traditional heavy RE in healthy subjects (e.g., WB-EMS). Also noteworthy, although some of these tools might be available in clinical or research settings, the practical relevance of these tools for general populations deserves scrutiny; however, some devices are certainly more practically applicable than others (e.g., local vibration and tDCS are likely more practically applicable than TMS).

Because of the dose-response relationship between mental effort and subsequent strength gains (49,70), we also hypothesize that "supramaximal" mental effort during training might further enhance strength gains. Indeed, certain cognitive strategies (e.g., methods to enhance arousal) acutely enhance force output in some contexts (94). Whether repeated implementation of cognitive strategies to accentuate mental effort or arousal (during RE or during motor imagery) could subsequently enhance long-term gains in strength requires additional research. In support of this notion, the dendrites of spinal motor neurons generate a strong persistent inward current that facilitates descending commands from the brain (42,43). The persistent inward current is highly dependent on the degree of physiological arousal, which is largely regulated by the degree of monoaminergic drive from the brain stem (42,43). At high monoaminergic drive levels, the persistent inward current dominates synaptic integration and can amplify the current as much as 5-fold (42,43). Ultimately, these insights build to the conclusion that physiological arousal is likely linked to enhancements in mental effort as well as in human motor neuronal firing patterns, which could conceivably lead to more robust training–induced gains in strength. The importance of arousal is something that many practitioners inherently know, but it deserves greater scientific attention.

Another logical question is whether RE training needs to proceed to the point of momentary muscular failure (i.e., when the subject attempts but is unable to conduct another repetition) to ensure effort is truly maximal. In fact, current evidence indicates that lifting loads to failure versus short of failure (when training volume is equated) does not provide any long-term strength benefits (36). Precisely how close to failure each set of RE needs to be performed (e.g., 1 repetition short of failure vs. 2 repetitions short of failure, etc.) to maximize strength gains requires additional research (36). Tentatively, this indicates that as long as the training volume is equated, the act of achieving failure is not essential for maximizing strength gains. Alternatively, it is reasonable to hypothesize that any potential advantage of going to failure (from a mental effort perspective) is offset by the observation that going to failure significantly increases fatigue and delays the subsequent recovery timeline both between the sets (96) and between the sessions (61). Therefore, unless and until evidence indicates otherwise, proceeding to the point of momentary failure does not seem to be necessary for maximizing strength gains.

Supplemental Activities

Supplemental activities (used in conjunction with traditional RE) might also maximize strength gains. For example, the use of BFR has received considerable attention in this regard. As stated above, BFR typically involves using commercially available pneumatic cuffs or bands in combination with RE. Although BFR increases the long-term gains in strength due to low-load RE, the mechanism of this effect remains unclear. Possible mechanisms include BFR-induced enhancements in metabolic stress, which in turn stimulate muscle growth (98) or BFR-induced changes in muscle activation, which in turn stimulates muscle growth through increased mechanical stress (21). Most commonly, BFR is used in conjunction with low-load RE (e.g., normally ≤50% 1RM). With respect to using BFR in conjunction with relatively heavier RE (≥65% 1RM), the limited existing research provides conflicting findings regarding whether the application of BFR further enhances strength gains (80). This supports the need for additional highly rigorous research to determine whether combining BFR with heavy RE further enhances strength gains beyond traditional heavy RE. Similarly, limited evidence indicates that supplementing traditional heavy RE training with occasional low-load BFR training might further enhance strength gains (80). Additional research seems warranted to substantiate and contextualize these effects (e.g., identifying the optimal volume and frequency of supplemental low-load BFR training). Finally, considering that passive BFR (without any associated muscle contractions) might help to maintain strength during immobilization (14), exploring whether passive BFR increases strength in normal (nonimmobilized) conditions warrants investigation. To support this notion, evidence indicates that just 3 weeks of BFR during walking enhances strength in healthy young adult (although not resistance-trained) men (1). If passive BFR does increase strength, then it seems worthy to investigate whether passive BFR might be a useful supplement to traditional heavy RE for further enhancing strength. Collectively, many avenues of exploration exist regarding the supplemental use of BFR to augment strength gains in response to heavy RE.

Another potential supplementary activity is motor imagery. Traditional RE causes fatigue and muscle damage (33), which potentially limits the dose of training that can be tolerated (because of the need to recover and avoid overtraining). Thus, traditional RE could conceivably be supplemented with kinesthetic motor imagery training to further enhance strength gains without exacerbating fatigue and muscle damage. The limited number of studies in this area indicates potential room for more research and innovation (70). Importantly, existing research indicates that supplementing traditional RE with motor imagery provides no added benefit beyond RE alone (70). That stated, supplementing motor imagery with technology-enabled biofeedback might feasibly enhance the efficacy of supplemental motor imagery training (discussed below); however, this hypothesis remains untested.

Optimizing and Potentially Individualizing Recovery Strategies

Given the critical importance of recovery and adaptation for realizing gains in strength, the scientific realities of supercompensation theory deserves more attention. For example, do subjects need to wait for supercompensation or full recovery to occur before commencing the next training bout to maximize long-term strength gains, or can effective training occur despite residual fatigue from the prior training bout? If the former, then what is the best metric for determining readiness for next bout? For example, recovery of peak torque and recovery of total work capacity occur at different rates after RE (33), and each might be an important stimulus for strength gains. Moreover, is optimal recovery duration dictated by the dose (20) and choice of exercises (86) in the preceding bout of RE, as well as by the age (32) and training status (71) of the individual? These are difficult questions to address; however, determining optimal recovery timelines between bouts of RE seems essential for maximizing strength gains. For the time being, current evidence-based guidance for RE training frequency is provided in a systematic review and meta-analysis (35), which indicates that, when weekly training volume is equated, training frequency might not have an independent effect on strength gains (stated differently, increasing training frequency might simply be a means with which to increase weekly training volume, and greater weekly training volume subsequently produces greater strength gains (75)). Given the uncertainties around the realities of supercompensation theory (mentioned above), and the potential need to individualize training frequency according to the attributes of preceding RE as well as the attributes of the individual, more research is needed to determine the optimal training frequency for maximizing strength gains. Finally, a large body of research attempts to identify methods to expedite the rate of recovery or maximize the magnitude of supercompensation (e.g., sleep, energy and nutrient intake, dietary supplements, active recovery, heating, cooling, massage, compression garments, etc). It is beyond the scope of this article to discuss each recovery interventional strategy. Suffice it to state that more research and innovation related to recovery interventions might help maximize strength gains.

Technological Applications

The insights regarding the stimuli and mediators of strength gains indicate many opportunities for technological applications. One example is biofeedback (i.e., using technology to provide real-time physiological insight intended to maximize the effectiveness of training); and there are many contexts in which biofeedback could prove effective. First, biofeedback could be used to enhance forceful muscle contractions or to direct and maximize mental effort to promote "supramaximal" training intensities. For example, although limited research exists in healthy populations, real-time biofeedback through electromyography (EMG, which gives insight into the electrical activity inside the muscle and somewhat approximates force output) enhances forceful muscle contractions during RE and, over time, produces greater strength gains compared with traditional RE without biofeedback (57). Interestingly, "gamification" of the EMG biofeedback (in other words, turning the feedback process into a game-like activity) might further facilitate forceful muscle contractions during RE (95). Noteworthy, the gamified biofeedback was provided through wireless EMG devices connected to a smartphone or tablet, potentially reflecting the future applicability of such an approach for broader populations, especially as the price of wireless EMG devices continues to decrease. Regarding motor imagery, some subjects struggle to effectively perform motor imagery tasks (70), potentially limiting the effectiveness of motor imagery training for increasing strength. Perhaps, providing biofeedback (e.g., using electroencephalography [EEG]) or using virtual reality could enhance the effectiveness of motor imagery for increasing strength (see Jeunet et al. (48) for an opinion of how EEG and virtual reality might be used in other contexts). Electroencephalography assesses the electrical activity of given brain regions. Because some regions of the brain increase activity during muscle contractions (either real contractions or imagined), in theory, subjects therefore can view EEG amplitude during motor imagery or even during traditional RE to better direct their mental effort by learning how to observe and control the electrical activity in their brain. Collectively, these forms of biofeedback might maximize forceful muscle contractions or mental effort to augment gains in strength, although this remains speculative.

Biofeedback has other applications beyond maximizing forceful contractions and mental effort. For example, if future research determines that muscular metabolic stress during RE is indeed associated with strength gains—and if optimal muscular metabolic stress values can be established—then perhaps existing wireless sensors (like near-infrared spectroscopy [NIRS], which detects the deoxygenation of muscle tissue during RE, as well as the reoxygenation of muscle tissue during recovery from RE (6,59)), can be used to provide real-time biofeedback to ensure that each set of RE achieves a desired magnitude and duration of metabolic stress. Alternatively, given the importance of beginning each set of RE in a minimally fatigued state, technology (e.g., wireless NIRS devices) could possibly be used to help monitor and minimize fatigue between the sets of RE. Technology can be also used to reinforce and record the ROM during RE (e.g., via the sensors in smart-devices, linear position transducers, or electrogoniometers) to facilitate an optimal ROM and, thus, potentially maximize strength gains. Collectively, biofeedback represents an intriguing opportunity for maximizing strength gains. That stated, in addition to evaluating the efficacy of these speculative forms of biofeedback, consideration must also be given to the many barriers of implementation (e.g., cost, training, time, etc).

Technology could also serve in tracking the dose of RE and making future recommendations regarding training and recovery. For example, commonplace smart devices have impressively sensitive integrated physical sensors (e.g., accelerometers, gyroscopes, etc.) (73). Commercially available solutions already exist that use smart devices, along with associated applications, to help individuals monitor the RE dose over time. Similarly, some commercially available exercise devices include embedded physical sensors to track various attributes of RE (e.g., velocity, power, fatigue). Whether such technologies enhance long-term gains in strength remains to be determined. Similarly, if future research indicates that periodization is indeed more effective for long-term gains in strength, then perhaps existing technology (e.g., smartphone applications) can be leveraged to make these insights easily and readily available for broader populations, not just those who train under direct supervision of qualified practitioners. Perhaps, existing technology can also be used to help identify when individuals are physiologically ready for the next training session (for example, using heart rate variability [HRV] as a biomarker to assess readiness for individual training bouts seems to enhance gains in endurance (29); however, the worthiness of HRV for enhancing gains in strength requires additional research (22)). For those looking to truly push the limits of human performance, some combination of wearable sensors, smartphone applications, and even rapid point-of-care tests using minimally invasive techniques (e.g., measuring training stress or recovery biomarkers in the blood via fingerstick) might holistically capture training stress and recovery to maximize long-term strength gains (28). Perhaps, more importantly, by using relatively simple devices to track the dose of RE and assist in guiding training and recovery, technological applications could help maximize strength gains in broad populations. Intriguingly, technology might also enhance the appeal of or adherence to long-term RE training interventions, although this notion remains speculative.

Finally, and importantly, individuals demonstrate marked variability in strength gains after long-term RE, with one large-scale study indicating a range in 1RM strength gains of 0–250% in general populations after 12 weeks of RE training (47). Much additional work is needed to evaluate the relative contributions of modifiable (e.g., the RE stimulus, the recovery intervention) and nonmodifiable (e.g., genetic) factors that determine the diversity of strength responses to RE training. Subsequently, developing individually tailored RE and recovery strategies might help ensure maximally effective strengthening interventions for all individuals.

Practical Applications for Special Scenarios

The insights gained from discussing the RE stimuli and mediators yield 3 key applications for increasing or maintaining strength in special scenarios in which traditional heavy RE cannot be performed (e.g., during at-home exercise, deployment, or rehabilitation): (a) no-load interventions; (b) low-load interventions; and (c) supplemental activities (in addition to RE).

No-Load Interventions

No-load interventions are appealing because they do not require equipment and because, during rehabilitation, they do not expose the injured limb to undue mechanical stress. Herein, we discuss 3 examples of no-load interventions: motor imagery, contralateral limb training, and passive BFR. First, motor imagery provides an impressively powerful effect on muscle strength. For example, in the context of at-home exercise, initial evidence indicates that motor imagery training completely preserves (and in fact slightly improves) strength for up to 6 weeks in professional athletes unable to access training facilities because of the recent coronavirus outbreak (23). Perhaps motor imagery can also help maintain strength during deployment to austere environments (e.g., military, spaceflight (39)). During 4 weeks of immobilization (as would be seen after injury), motor imagery attenuates the loss of strength by approximately half, likely because of increased voluntary neural activation of muscle or reduced corticospinal inhibition (15); therefore, clinicians might consider using motor imagery to preserve strength without exposing the injured limb to undue mechanical stress (15,19). Similarly, other alternative techniques take advantage of central adaptations to preserve strength of an injured limb, such as contralateral limb training; that is, unilateral training of the uninjured limb also preserves strength in the injured limb through the "cross-education" effect (19). Finally, passive BFR (without any associated muscle contractions) might help to maintain strength during immobilization (14). A review by Patterson et al. (72) provides practical recommendations and safety considerations for the use of BFR in various contexts, including recommendations for passive BFR therapy. Collectively, these insights might help maximize strength when no exercise equipment is available or add to a clinician's arsenal of techniques for maintaining strength of injured limbs.

Low-Load Interventions

When limited RE equipment exists, individuals can partially compensate for the lack of adequate external load by exercising with maximal mental effort (i.e., low-load but high-effort exercise). This strategy has 3 distinctly different applications. First, low-load high-repetition exercise can increase strength, which might also be helpful in clinical contexts when trying to limit the mechanical stress on injured tissues. Even very light loads (e.g., ~20% of the individual's 1RM strength) can increase strength as long as repetitive lifting proceeds to the point of a high level of effort (55) (noteworthy, however, lifting light loads to a high level of effort produces smaller strength gains than lifting heavier loads to a high level of effort) (78). Second, low-load high-velocity exercise can increase strength, which might also be helpful for developing muscular power, an important adaptation for functional performance. Limited evidence indicates that performing low-load (~30–50% of 1RM) but high-velocity (and presumably high-effort) RE training produces similar strength gains as traditional heavy-load RE in athletic populations (9) as well as in community-dwelling older individuals with physical limitations (77). More research is needed to better elucidate the effects of light-load high-velocity RE (along with studying any potential safety concerns) across populations. Third, forceful muscle contractions through a full ROM without an external load (e.g., voluntary co-contraction of agonists and antagonists during a movement) can increase strength over time (noteworthy, we consider this a low-load intervention because, although it does not involve an external load, it does involve forceful muscle contractions). A single study found that performing forceful muscle contractions in the absence of an external load produces small yet significant changes in strength, at least in untrained subjects (18). Whether this approach can maintain strength in individuals with RE experience or be used to facilitate rehabilitation remains to be determined. Importantly, these various low-load interventions are likely more effective for increasing or maintaining strength than no-load interventions.

Supplemental Activities

Supplemental activities (used in conjunction with RE) might help to rehabilitate strength. For example, in addition to potentially maximizing strength in healthy populations, biofeedback (57) and external stimulation (8,74,87,93) might also help to rehabilitate strength capabilities in some clinical contexts. That stated, the associated nuance and necessary clinical judgement prevents detailed recommendations. Adding BFR to low-load RE also has applications for special scenarios in which traditional heavy RE cannot be performed (e.g., during rehabilitation) (72). Overall, no-load, low-load, and supplemental activities provide individuals, coaches, and clinicians with several options for increasing or maintaining strength when traditional heavy RE is not possible.

Conclusions

Traditional, multiple-set, heavy RE is well-established for improving strength because it requires maximal mental effort leading to forceful, concentric-eccentric muscle actions through a full range of motion, as well as induces muscular metabolic stress. To optimize strength gains in response to RE training, consideration should also be given to the factors that mediate the long-term effectiveness of these RE stimuli, namely: optimizing the dose of RE within a session, beginning each set of RE in a minimally fatigued state, optimizing recovery between training sessions, and (potentially) periodizing the training stimulus over time. Future efforts might consider creatively researching, monitoring, and manipulating these "stimuli" and "mediators" to advance strength gains beyond our current upper limits.

To further enhance strength beyond what is capable with traditional heavy RE, 4 key themes seem to emerge. First, *supramaximal training intensity* (in terms of external load and mental effort) might be one key to pushing the upper limits of strength gains; with this insight in mind, areas for future exploration include eccentric-based overload training, variable-load RE, certain forms of external stimulation, and cognitive strategies. Second, the use of *supplemental activities* (in addition to heavy RE) like BFR (with or without exercise) and motor imagery might further enhance strength gains. Third, the scientific realities of the *supercompensation theory* deserves closer examination. Given the critical importance of recovery for realizing strength gains, identifying simple yet valid metrics of supercompensation, along with optimized and individualized recovery timelines and interventions, remains a fruitful area of inquiry. Fourth, *technology* might be an agent for pushing the upper limits of strength gains; opportunities include biofeedback (in some cases, with gamification), virtual reality (during motor imagery training), smartphone applications to track and recommend the dose of RE, or technology-sensed biomarkers used to determine readiness for the next set of RE (like NIRS) or the next training bout (like HRV). Whether technology might also enhance the appeal of or adherence to long-term RE training interventions remains speculative. Collectively, these areas of exploration represent intriguing opportunities for further enhancing the limits of human performance.

To increase or maintain strength when heavy RE is not possible, 3 key themes seem to emerge. First, *no-load interventions* exist to preserve strength when either no equipment is available or when clinicians strive to maintain strength without exposing the injured limb to undue mechanical stress; no-load examples include motor imagery, contralateral limb training, and passive BFR. Second, *low-load yet high-effort interventions* are likely more effective than no-load interventions for increasing or maintaining strength; examples include low-load high-repetition training, low-load high-velocity training, and using forceful contractions in the absence of an external load. Third, *supplemental activities* (in conjunction with RE) like biofeedback, certain forms of external stimulation, and BFR can help to recover strength after injury. Collectively, these strategies represent real-world opportunities to increase or maintain strength during at-home exercise, deployment to austere environments, or recovery from injury.

Finally, after conceptually deconstructing RE, our paradigm suggests that strength gains are a function of mental effort, forceful muscle contractions, type of muscle action (typically concentric-eccentric), and ROM, as well as potentially muscular metabolic stress. To assess the accuracy of this model, future research could systematically reconstruct these RE stimuli to determine the independent and interrelated roles of each stimulus. As an example, given that all of these RE stimuli can be triggered without physically performing RE, researchers could use an experimental approach in which a group of volunteers performs "training" sessions consisting of motor imagery plus electrically evoked contractions under isometric conditions (to control for contraction-type and ROM) while simultaneously receiving passive blood flow restriction for a period of several weeks. The change in maximal strength associated with this artificial training could be compared with another group of volunteers who perform isometric RE training over the same period. In other words, when keeping the RE stimuli relatively similar, does artificial RE enhance strength to a similar degree as more traditional RE? Noteworthy, the idea of combining multiple nonexercise interventions has been explored by other researchers with sometimes synergistic (85) and sometimes antagonistic (10) effects, suggesting that a systematic approach might be necessary. To our knowledge, no experimental evidence exists that combines all of the aforementioned stimuli and compares that condition with a more traditional RE training protocol. Such experiments could challenge the accuracy of the current paradigm. Regardless of the outcome, however, the results could have meaningful implications, particularly for special or clinical scenarios.

Practical Applications

To maximize strength gains, practitioners should implement traditional heavy RE when possible. Practitioners can further enhance the effectiveness of heavy RE by optimizing the dose of RE within a session (~2-3 sets per exercise), beginning each set of RE in a minimally fatigued state, optimizing recovery between training sessions, and (potentially) periodizing the training stimulus over time. Exciting opportunities exist for those wishing to push the upper limits of strength gains (e.g., athletes or military personnel). However, future research must fully evaluate these opportunities before their wide-spread use. These opportunities include eccentric-based overload training, variable-load RE, certain forms of external stimulation, cognitive strategies (like arousal), RE plus blood flow restriction, biofeedback, incorporating technology into training, and using simple yet valid metrics of recovery to determine the individual's readiness for the next bout of training. When heavy RE is not possible (e.g., during at-home exercise, recovery from injury, or deployment to austere environments), practitioners can choose from a variety of potential interventions to increase or maintain strength. For example, when musculoskeletal tissues cannot tolerate mechanical stress or when no exercise equipment is available, then no-load interventions like motor imagery, contralateral limb training, and passive BFR can be used. Alternatively, low-load yet high-effort interventions are likely more effective than no-load interventions for increasing or maintaining strength; examples include low-load high-repetition training, low-load high-velocity training, and using forceful contractions in the absence of an external load. Finally, supplemental activities (used in conjunction with RE) like biofeedback, certain forms of external stimulation, and BFR can increase strength. Collectively, these interventions represent effective opportunities to increase or maintain strength when individuals cannot perform heavy RE.

Acknowledgments

The opinions or assertions contained herein are the private views of the authors and are not to be construed as official or as reflecting the views of the U.S. Army, the Department of Defense, or the U.S. Government. Any citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement or approval of the products or services thereof. This research was supported, in part, by an appointment (to B. A. Spiering) to the Research Participation Program at the U.S. Army Research Institute of Environmental Medicine administered by the Oak Ridge Institute for Science and Education through an interagency agreement between the U.S. Department of Energy and the U.S. Army Medical Research and Development Command. This development of the manuscript was also supported, in part, by grants from the National Institutes of Health's National Institute on Aging to B. C. Clark (R01AG044424 and R01AG067758). B. J. Schoenfeld serves on the scientific advisory board of Tonal Corporation, a manufacturer of fitness equipment. B. A. Spiering, B. C. Clark, S. A. Foulis, and S. M. Pasiakos declare that they have no conflicts of interest relevant to this article.

References

1. Abe T, Kearns CF, Sato Y. Muscle size and strength are increased following walk training with restricted venous blood flow from the leg muscle, Kaatsu-walk training. *J Appl Physiol (1985)* 100: 1460–1466, 2006.
2. Afonso J, Rocha T, Nikolaidis PT, et al. A systematic review of meta-analyses comparing periodized and non-periodized exercise programs: Why we should go back to original research. *Front Physiol* 10: 1023, 2019.
3. Alghadir AH, Anwer S, Zafar H, Iqbal ZA. Effect of localised vibration on muscle strength in healthy adults: A systematic review. *Physiotherapy* 104: 18–24, 2018.
4. Androulakis-Korakakis P, Fisher JP, Steele J. The minimum effective training dose required to increase 1RM strength in resistance-trained men: A systematic review and meta-analysis. *Sports Med* 50: 751–765, 2020.
5. Bax L, Staes F, Verhagen A. Does neuromuscular electrical stimulation strengthen the quadriceps femoris? A systematic review of randomised controlled trials. *Sports Med* 35: 191–212, 2005.
6. Biazon TMPC, Ugrinowitsch C, Soligon SD, et al. The association between muscle deoxygenation and muscle hypertrophy to blood flow restricted training performed at high and low loads. *Front Physiol* 10: 446, 2019.
7. Blagrove RC, Howatson G, Hayes PR. Effects of strength training on the physiological determinants of middle- and long-distance running performance: A systematic review. *Sports Med* 48: 1117–1149, 2018.
8. Blazevich AJ, Collins DF, Millet GY, Vaz MA, Maffiuletti NA. Enhancing adaptations to neuromuscular electrical stimulation training interventions. *Exerc Sport Sci Rev* 49: 244–252, 2021.
9. Blazevich AJ, Jenkins DG. Effect of the movement speed of resistance training exercises on sprint and strength performance in concurrently training elite junior sprinters. *J Sports Sci* 20: 981–990, 2002.
10. Bouguetoch A, Martin A, Grospretre S. Insights into the combination of neuromuscular electrical stimulation and motor imagery in a training-based approach. *Eur J Appl Physiol* 121: 941–955, 2021.
11. Buckner SL, Jessee MB, Dankel SJ, et al. Resistance exercise and sports performance: The minority report. *Med Hypotheses* 113: 1–5, 2018.
12. Buckner SL, Jessee MB, Mattocks KT, et al. Determining strength: A case for multiple methods of measurement. *Sports Med* 47: 193–195, 2017.
13. Buckner SL, Jessee MB, Mouser JG, et al. The basics of training for muscle size and strength: A brief review on the theory. *Med Sci Sports Exerc* 52: 645–653, 2020.
14. Cerqueira MS, Do Nascimento JDS, Maciel DG, Barboza JAM, De Brito Vieira WH. Effects of blood flow restriction without additional exercise on strength reductions and muscular atrophy following immobilization: A systematic review. *J Sport Health Sci* 9: 152–159, 2020.
15. Clark BC, Mahato NK, Nakazawa M, Law TD, Thomas JS. The power of the mind: The cortex as a critical determinant of muscle strength/weakness. *J Neurophysiol* 112: 3219–3226, 2014.
16. Clark LA, Russ DW, Tavoian D, et al. Heterogeneity of the strength response to progressive resistance exercise training in older adults: Contributions of muscle contractility. *Exp Gerontol* 152: 111437, 2021.
17. Clarkson PM, Hubal MJ. Exercise-induced muscle damage in humans. *Am J Phys Med Rehabil* 81: S52–S69, 2002.
18. Counts BR, Buckner SL, Dankel SJ, et al. The acute and chronic effects of "NO LOAD" resistance training. *Physiol Behav* 164: 345–352, 2016.
19. Cuenca-Martinez F, Angulo-Diaz-Parreno S, Feijoo-Rubio X, et al. Motor effects of movement representation techniques and cross-education: A systematic review and meta-analysis. *Eur J Phys Rehabil Med* 58: 94–107, 2022.
20. Dankel SJ, Mattocks KT, Jessee MB, et al. Frequency: The overlooked resistance training variable for inducing muscle hypertrophy? *Sports Med* 47: 799–805, 2017.
21. Dankel SJ, Mattocks KT, Jessee MB, et al. Do metabolites that are produced during resistance exercise enhance muscle hypertrophy? *Eur J Appl Physiol* 117: 2125–2135, 2017.
22. De Oliveira RM, Ugrinowitsch C, Kingsley JD, et al. Effect of individualized resistance training prescription with heart rate variability on individual muscle hypertrophy and strength responses. *Eur J Sport Sci* 19: 1092–1100, 2019.

23. Dello Iacono A, Ashcroft K, Zubac D. Ain't just imagination! Effects of motor imagery training on strength and power performance of athletes during detraining. *Med Sci Sports Exerc* 53: 2324–2332, 2021.
24. Douglas J, Pearson S, Ross A, McGuigan M. Chronic adaptations to eccentric training: A systematic review. *Sports Med* 47: 917–941, 2017.
25. Douglas J, Pearson S, Ross A, McGuigan M. Eccentric exercise: Physiological characteristics and acute responses. *Sports Med* 47: 663–675, 2017.
26. Duchateau J, Semmler JG, Enoka RM. Training adaptations in the behavior of human motor units. *J Appl Physiol (1985)* 101: 1766–1775, 2006.
27. Dudley GA, Tesch PA, Miller BJ, Buchanan P. Importance of eccentric actions in performance adaptations to resistance training. *Aviat Space Environ Med* 62: 543–550, 1991.
28. Duking P, Achtzehn S, Holmberg HC, Sperlich B. Integrated framework of load monitoring by a combination of smartphone applications, wearables and point-of-care testing provides feedback that allows individual responsive adjustments to activities of daily living. *Sensors (Basel)* 18: E1632, 2018.
29. Duking P, Zinner C, Trabelsi K, et al. Monitoring and adapting endurance training on the basis of heart rate variability monitored by wearable technologies: A systematic review with meta-analysis. *J Sci Med Sport* 24: 1180–1192, 2021.
30. Eddens L, van Someren K, Howatson G. The role of intra-session exercise sequence in the interference effect: A systematic review with meta-analysis. *Sports Med* 48: 177–188, 2018.
31. Enoka RM. Muscle strength and its development. New perspectives. *Sports Med* 6: 146–168, 1988.
32. Fernandes JFT, Lamb KL, Norris JP, et al. Aging and recovery after resistance-exercise-induced muscle damage: Current evidence and implications for future research. *J Aging Phys Act* 29: 544–551, 2021.
33. Ferreira DV, Gentil P, Ferreira-Junior JB, et al. Dissociated time course between peak torque and total work recovery following bench press training in resistance trained men. *Physiol Behav* 179: 143–147, 2017.
34. Garg AX, Hackam D, Tonelli M. Systematic review and meta-analysis: When one study is just not enough. *Clin J Am Soc Nephrol* 3: 253–260, 2008.
35. Grgic J, Schoenfeld BJ, Davies TB, et al. Effect of resistance training frequency on gains in muscular strength: A systematic review and meta-analysis. *Sports Med* 48: 1207–1220, 2018.
36. Grgic J, Schoenfeld BJ, Orazem J, Sabol F. Effects of resistance training performed to repetition failure or non-failure on muscular strength and hypertrophy: A systematic review and meta-analysis. *J Sport Health Sci* 11: 202–211, 2022.
37. Grgic J, Schoenfeld BJ, Skrepnik M, Davies TB, Mikulic P. Effects of rest interval duration in resistance training on measures of muscular strength: A systematic review. *Sports Med* 48: 137–151, 2018.
38. Gronfeldt BM, Lindberg Nielsen J, Mieritz RM, Lund H, Aagaard P. Effect of blood-flow restricted vs heavy-load strength training on muscle strength: Systematic review and meta-analysis. *Scand J Med Sci Sports* 30: 837–848, 2020.
39. Guillot A, Debarnot U. Benefits of motor imagery for human space flight: A brief review of current knowledge and future applications. *Front Physiol* 10: 396, 2019.
40. Happ KA, Behringer M. Neuromuscular electrical stimulation training vs. conventional strength training: A systematic review and meta-analysis of the effect on strength development. *J Strength Cond Res* 36: 3527–3540, 2022.
41. Haun CT, Vann CG, Roberts BM, et al. A critical evaluation of the biological construct skeletal muscle hypertrophy: Size matters but so does the measurement. *Front Physiol* 10: 247, 2019.
42. Heckman CJ, Hyngstrom AS, Johnson MD. Active properties of motoneurone dendrites: Diffuse descending neuromodulation, focused local inhibition. *J Physiol* 586: 1225–1231, 2008.
43. Heckman CJ, Johnson M, Mottram C, Schuster J. Persistent inward currents in spinal motoneurons and their influence on human motoneuron firing patterns. *Neuroscientist* 14: 264–275, 2008.
44. Hendy AM, Kidgell DJ. Anodal tDCS applied during strength training enhances motor cortical plasticity. *Med Sci Sports Exerc* 45: 1721–1729, 2013.
45. Hollander DB, Kraemer RR, Kilpatrick MW, et al. Maximal eccentric and concentric strength discrepancies between young men and women for dynamic resistance exercise. *J Strength Cond Res* 21: 34–40, 2007.
46. Hortobagyi T, Lesinski M, Fernandez-Del-Olmo M, Granacher U. Small and inconsistent effects of whole body vibration on athletic performance: A systematic review and meta-analysis. *Eur J Appl Physiol* 115: 1605–1625, 2015.
47. Hubal MJ, Gordish-Dressman H, Thompson PD, et al. Variability in muscle size and strength gain after unilateral resistance training. *Med Sci Sports Exerc* 37: 964–972, 2005.
48. Jeunet C, Hauw D, Millan JDR. Sport psychology: Technologies ahead. *Front Sports Act Living* 2: 10, 2020.
49. Jiang CH, Ranganathan VK, Siemionow V, Yue GH. The level of effort, rather than muscle exercise intensity determines strength gain following a six-week training. *Life Sci* 178: 30–34, 2017.
50. Jones TW, Petersen N, Howatson G. Optimization of exercise countermeasures for human space flight: Operational considerations for concurrent strength and aerobic training. *Front Physiol* 10: 584, 2019.
51. Kataoka R, Vasenina E, Hammert WB, et al. Is there evidence for the suggestion that fatigue accumulates following resistance exercise? *Sports Med* 52: 25–36, 2022.
52. Knapik JJ, Harman EA, Steelman RA, Graham BS. A systematic review of the effects of physical training on load carriage performance. *J Strength Cond Res* 26: 585–597, 2012.
53. Kraemer WJ, Mazzetti SA, Nindl BC, et al. Effect of resistance training on women's strength/power and occupational performances. *Med Sci Sports Exerc* 33: 1011–1025, 2001.
54. Krieger JW. Single versus multiple sets of resistance exercise: A meta-regression. *J Strength Cond Res* 23: 1890–1901, 2009.
55. Lasevicius T, Ugrinowitsch C, Schoenfeld BJ, et al. Effects of different intensities of resistance training with equated volume load on muscle strength and hypertrophy. *Eur J Sport Sci* 18: 772–780, 2018.
56. Lattari E, Oliveira BRR, Monteiro Junior RS, et al. Acute effects of single dose transcranial direct current stimulation on muscle strength: A systematic review and meta-analysis. *PLoS One* 13: e0209513, 2018.
57. Lepley AS, Gribble PA, Pietrosimone BG. Effects of electromyographic biofeedback on quadriceps strength: A systematic review. *J Strength Cond Res* 26: 873–882, 2012.
58. Lixandrao ME, Ugrinowitsch C, Berton R, et al. Magnitude of muscle strength and mass adaptations between high-load resistance training versus low-load resistance training associated with blood-flow restriction: A systematic review and meta-analysis. *Sports Med* 48: 361–378, 2018.
59. Miranda-Fuentes C, Chirosa-Rios LJ, Guisado-Requena IM, Delgado-Floody P, Jerez-Mayorga D. Changes in muscle oxygen saturation measured using wireless near-infrared spectroscopy in resistance training: A systematic review. *Int J Environ Res Public Health* 18: 4293, 2021.
60. Mitchell WK, Williams J, Atherton P, et al. Sarcopenia, dynapenia, and the impact of advancing age on human skeletal muscle size and strength; a quantitative review. *Front Physiol* 3: 260, 2012.
61. Moran-Navarro R, Perez CE, Mora-Rodriguez R, et al. Time course of recovery following resistance training leading or not to failure. *Eur J Appl Physiol* 117: 2387–2399, 2017.
62. Murlasits Z, Kneffel Z, Thalib L. The physiological effects of concurrent strength and endurance training sequence: A systematic review and meta-analysis. *J Sports Sci* 36: 1212–1219, 2018.
63. Naimo MA, Varanoske AN, Hughes JM, Pasiakos SM. Skeletal muscle quality: A biomarker for assessing physical performance capabilities in young populations. *Front Physiol* 12: 706699, 2021.
64. Nunes JP, Grgic J, Cunha PM, et al. What influence does resistance exercise order have on muscular strength gains and muscle hypertrophy? A systematic review and meta-analysis. *Eur J Sport Sci* 21: 149–157, 2021.
65. Nunes JP, Ribeiro AS, Schoenfeld BJ, Cyrino ES. Comment on: "Comparison of periodized and non-periodized resistance training on maximal strength: A meta-analysis". *Sports Med* 48: 491–494, 2018.
66. Nyakayiru J, Fuchs CJ, Trommelen J, et al. Blood flow restriction only increases myofibrillar protein synthesis with exercise. *Med Sci Sports Exerc* 51: 1137–1145, 2019.
67. Oki K, Mahato NK, Nakazawa M, et al. Preliminary evidence that excitatory transcranial direct current stimulation extends time to task failure of a sustained, submaximal muscular contraction in older adults. *J Gerontol A Biol Sci Med Sci* 71: 1109–1112, 2016.
68. Pallares JG, Hernandez-Belmonte A, Martinez-Cava A, et al. Effects of range of motion on resistance training adaptations: A systematic review and meta-analysis. *Scand J Med Sci Sports* 31: 1866–1881, 2021.
69. Papa EV, Dong X, Hassan M. Resistance training for activity limitations in older adults with skeletal muscle function deficits: A systematic review. *Clin Interv Aging* 12: 955–961, 2017.

70. Paravlic AH, Slimani M, Tod D, et al. Effects and dose-response relationships of motor imagery practice on strength development in healthy adult populations: A systematic review and meta-analysis. *Sports Med* 48: 1165–1187, 2018.
71. Pareja-Blanco F, Rodriguez-Rosell D, Gonzalez-Badillo JJ. Time course of recovery from resistance exercise before and after a training program. *J Sports Med Phys Fitness* 59: 1458–1465, 2019.
72. Patterson SD, Hughes L, Warmington S, et al. Blood flow restriction exercise: Considerations of methodology, application, and safety. *Front Physiol* 10: 533, 2019.
73. Proessl F, Swanson CW, Rudroff T, Fling BW, Tracy BL. Good agreement between smart device and inertial sensor-based gait parameters during a 6-min walk. *Gait Posture* 64: 63–67, 2018.
74. Qiu J, Ong MT, Leong HT, et al. Effects of whole-body vibration therapy on quadriceps function in patients with anterior cruciate ligament reconstruction: A systematic review. *Sports Health* 14: 216–226, 2021.
75. Ralston GW, Kilgore L, Wyatt FB, Baker JS. The effect of weekly set volume on strength gain: A meta-analysis. *Sports Med* 47: 2585–2601, 2017.
76. Rosenberger A, Beijer A, Johannes B, et al. Changes in muscle cross-sectional area, muscle force, and jump performance during 6 weeks of progressive whole-body vibration combined with progressive, high intensity resistance training. *J Musculoskelet Neuronal Interact* 17: 38–49, 2017.
77. Sayers SP, Gibson K. A comparison of high-speed power training and traditional slow-speed resistance training in older men and women. *J Strength Cond Res* 24: 3369–3380, 2010.
78. Schoenfeld BJ, Grgic J, Van Every DW, Plotkin DL. Loading recommendations for muscle strength, hypertrophy, and local endurance: A Re-examination of the repetition continuum. *Sports (Basel)* 9: 32, 2021.
79. Schranner D, Kastenmuller G, Schonfelder M, Romisch-Margl W, Wackerhage H. Metabolite concentration changes in humans after a bout of exercise: A systematic review of exercise metabolomics studies. *Sports Med Open* 6: 11, 2020.
80. Scott BR, Loenneke JP, Slattery KM, Dascombe BJ. Blood flow restricted exercise for athletes: A review of available evidence. *J Sci Med Sport* 19: 360–367, 2016.
81. Shinohara M. Effects of prolonged vibration on motor unit activity and motor performance. *Med Sci Sports Exerc* 37: 2120–2125, 2005.
82. Siddique U, Rahman S, Frazer AK, et al. Determining the sites of neural adaptations to resistance training: A systematic review and meta-analysis. *Sports Med* 50: 1107–1128, 2020.
83. Skarabot J, Brownstein CG, Casolo A, Del Vecchio A, Ansdell P. The knowns and unknowns of neural adaptations to resistance training. *Eur J Appl Physiol* 121: 675–685, 2021.
84. Slysz J, Stultz J, Burr JF. The efficacy of blood flow restricted exercise: A systematic review & meta-analysis. *J Sci Med Sport* 19: 669–675, 2016.
85. Slysz JT, Burr JF. The effects of blood flow restricted electrostimulation on strength and hypertrophy. *J Sport Rehabil* 27: 257–262, 2018.
86. Soares S, Ferreira-Junior JB, Pereira MC, et al. Dissociated time course of muscle damage recovery between single- and multi-joint exercises in highly resistance-trained men. *J Strength Cond Res* 29: 2594–2599, 2015.
87. Stockley RC, Hanna K, Connell L. To stimulate or not to stimulate? A rapid systematic review of repetitive sensory stimulation for the upper-limb following stroke. *Arch Physiother* 10: 20, 2020.
88. Suchomel TJ, Nimphius S, Bellon CR, Stone MH. The importance of muscular strength: Training considerations. *Sports Med* 48: 765–785, 2018.
89. Suchomel TJ, Nimphius S, Stone MH. The importance of muscular strength in athletic performance. *Sports Med* 46: 1419–1449, 2016.
90. Suchomel TJ, Wagle JP, Douglas J, et al. Implementing eccentric resistance training-Part 1: A brief review of existing methods. *J Funct Morphol Kinesiol* 4: E38, 2019.
91. Suchomel TJ, Wagle JP, Douglas J, et al. Implementing eccentric resistance training-Part 2: Practical recommendations. *J Funct Morphol Kinesiol* 4: E55, 2019.
92. Suga T, Okita K, Morita N, et al. Intramuscular metabolism during low-intensity resistance exercise with blood flow restriction. *J Appl Physiol (1985)* 106: 1119–1124, 2009.
93. Tallent J, Woodhead A, Frazer AK, et al. Corticospinal and spinal adaptations to motor skill and resistance training: Potential mechanisms and implications for motor rehabilitation and athletic development. *Eur J Appl Physiol* 121: 707–719, 2021.
94. Tod D, Edwards C, McGuigan M, Lovell G. A systematic review of the effect of cognitive strategies on strength performance. *Sports Med* 45: 1589–1602, 2015.
95. Vaidya M, Armshaw B. Surface electromyography and gamification: Translational research to advance physical rehabilitation. *J Appl Behav Anal* 54: 1608–1624, 2021.
96. Vieira JG, Sardeli AV, Dias MR, et al. Effects of resistance training to muscle failure on acute fatigue: A systematic review and meta-analysis. *Sports Med* 52: 1103–1125, 2022.
97. Viru A. Early contributions of Russian stress and exercise physiologists. *J Appl Physiol (1985)* 92: 1378–1382, 2002.
98. Wackerhage H, Schoenfeld BJ, Hamilton DL, Lehti M, Hulmi JJ. Stimuli and sensors that initiate skeletal muscle hypertrophy following resistance exercise. *J Appl Physiol (1985)* 126: 30–43, 2019.
99. Williams PS, Hoffman RL, Clark BC. Preliminary evidence that anodal transcranial direct current stimulation enhances time to task failure of a sustained submaximal contraction. *PLoS One* 8: e81418, 2013.
100. Williams TD, Tolusso DV, Fedewa MV, Esco MR. Comparison of periodized and non-periodized resistance training on maximal strength: A meta-analysis. *Sports Med* 47: 2083–2100, 2017.
101. Wirtz N, Dormann U, Micke F, et al. Effects of whole-body electromyostimulation on strength-sprint-and jump performance in moderately trained young adults: A mini-meta-analysis of five homogenous RCTs of our work group. *Front Physiol* 10: 1336, 2019.