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CURRENT OPINION

# Volume for Muscle Hypertrophy and Health Outcomes: The Most Effective Variable in Resistance Training

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**Abstract** Resistance training is the most effective method to increase muscle mass. It has also been shown to promote many health benefits. Although it is deemed safe and of clinical relevance for treating and preventing a vast number of diseases, a time-efficient and minimal dose of exercise has been the focus of a great number of research studies. Similarly, an inverted U-shaped relationship between training dose/volume and physiological response has been hypothesized to exist. However, the majority of available evidence supports a clear dose-response relationship between resistance training volume and physiological responses, such as muscle hypertrophy and health outcomes. Additionally, there is a paucity of data to support the inverted U-shaped response. Although it may indeed exist, it appears to be much more plastic than previously thought. The overarching principle argued herein is that volume is the most easily modifiable variable that has the most evidenced-based response with important repercussions, be these muscle hypertrophy or health-related outcomes.

**Key Points**

Low-volume resistance training has recently gained attention among many individuals, trainers, and researchers as a means of achieving or promoting time-efficient training.

The literature has convincingly shown that the volume of resistance training has a dose-response effect on muscle hypertrophy and health outcomes, and that the doses causing a ceiling effect or even detrimental effects are currently unknown.

Increasing training volume may be the most easily modifiable variable causing beneficial adaptations in an exercise program.

## 1 Introduction

Resistance training is commonly prescribed for skeletal muscle hypertrophy and strength development; it also promotes multiple health benefits, such as improving cardiovascular function, insulin sensitivity, inflammatory response, and muscle quality [1–4]. Resistance training has been consistently shown to be an important strategy for treatment and prevention of a wide range of diseases [5–8], and is thus recommended by several scientific societies and colleges as a complementary therapy for diabetes, dyslipidemia, cardiovascular diseases, and other conditions [7–10].

In addition to the health benefits described above, the skeletal muscle morphological adaptations induced by

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resistance exercise, such as hypertrophy, are strongly associated with the training variables applied within the training program. These include exercise intensity, rest intervals between sets, velocity, exercise order, type of exercise, weekly frequency, and volume. A well-design periodized program should manipulate these variables. However, very often, volume is neglected and, in many cases, trainers and researchers aim to reduce training volume in order to promote time-efficient training. This is partially because the least amount of work with the potential to promote health benefits appears to be attractive to the wider population, since time is cited as a deterrent for exercise adherence [11, 12], although "lack of time" can be exaggerated in many cases [13]. Regardless, time-efficient training has become an important factor influencing exercise prescription, which, for instance, could explain, at least partially, some of the attention paid to the reduced volume of the high-intensity interval training (HIIT) [14, 15]. Moreover, researchers and trainers believe that there is an inverted U-shaped relationship between total work/volume and physiological responses [16, 17]. In other words, resistance training may have a dose-dependent effect until a certain threshold is achieved, at which point the effect initially plateaus and then decreases if further work is conducted.

Resistance training volume is commonly described as the product of the number of repetitions × number of sets × intensity load, although other forms of representing volume or total work exist [18]. For the scope of this review, volume is considered as any factor that can increase the total work performed in a training program. In this article we review the effects of volume on hypertrophy and health, but not strength, because exercise intensity seems to be the predominant variable modulating muscle strength, in comparison to other variables [19]. However, it is important to highlight that when comparing different resistance training protocols using the same intensity, higher volume may result in higher strength gains [20–23].

## 2 Volume and Muscle Hypertrophy

The use of resistance training to promote muscle growth, either in healthy young sedentary individuals or in highly trained and competitive bodybuilders, has been widely researched and scrutinized. Different resistance training variables such as rest interval between sets, exercise choice and order, number of sets, load intensity, training frequency, and advanced techniques (also known as specialized strategies, such as drop-sets, supersets, forced repetitions, pyramids, prior exhaustive set, etc.) have been experimentally tested by many studies with the goal of maximizing muscle hypertrophy in response to training. However, many of those studies have found that the adaptations to various protocols of resistance training tend to be similar when equated for total volume, including manipulations of training frequencies [24, 25], rest intervals [26, 27], advanced techniques such as pyramids and drop-sets [28, 29], repetition-range [27, 30, 31], weekly splits [32], and training periodization [33].

Intensity is regarded as a very important variable in resistance training adaptations. Indeed, moderate and high intensity are usually recommended for hypertrophy or strength gains. However, training with lower external loads/low intensities but with higher volume (until muscle failure) can overcome the reduced intensity and promotes similar muscle gains as higher intensities [34, 35]. Another key variable that is important for determining hypertrophy is the rest interval between sets [36]. This is because increasing rest intervals allows the trainee to maintain high intensity for a high volume (repetitions) per set [36], which ultimately leads to a higher total training volume [37]. Additionally, a long-term study has demonstrated that longer intervals promote greater muscle hypertrophy and strength, which is partially explained by the increased volume that rest intervals allow [38]. Interestingly, studies that have not found an enhanced muscle adaptation with longer intervals have equated training volume, which appears to limit the benefits of greater rest intervals on muscle adaptations, even when longer rest intervals were associated with higher training intensities [26, 27, 38]. Mechanistically, the long rest intervals may increase muscle performance by restoring adenosine triphosphate secondary to allowing sufficient resynthesis via the creatine-phosphate pool. Interestingly, creatine supplementation is deemed one of the few dietary supplements associated with augmentation of muscle hypertrophy and performance in response to training [39]. One of the main mechanisms by which creatine improves resistance training adaptations is by allowing greater training volume and total work or maintenance of intense exercise for longer periods [40–44].

Although many advanced techniques, such as drop-sets, bisets, supersets, and pyramids, are usually described as strategies to increase exercise intensity—or more correctly put, perception of effort—most of these strategies are actually increasing exercise volume or density (greater volume, as repetitions or sets, over a given period of time). Still, those techniques do not seem to promote muscle growth per se. Drop-sets and pyramid sets have no greater effect on muscle hypertrophy than traditional sets when training volume is equated [28], but when drop-sets are utilized to increase training volume, this method seems to promote further muscle hypertrophy [45]. This has also been shown to be the case for a prior exhaustive set before traditional sets [46]. Thus, similar to the purpose of applying long rest intervals, the goal of applying advanced techniques during resistance training, in many cases, is to increase training volume. As a consequence, normalizing volume across different groups with or without those techniques will likely defeat the intended purpose.

It seems clear that adaptive response to resistance training is normally distributed in the population [47]. It is expected that, if a particular study has sufficient sample size, the hypertrophic response will have a unimodal distribution, meaning that it will have some high, mostly average, some low, and some potential non-responders on measurements specifically related to muscle hypertrophy. This is demonstrated by the high heterogeneity of muscle hypertrophy with resistance training [48, 49]. An interesting study of endurance training identified non-responders in terms of cardiorespiratory fitness following 6 weeks of the trial. These non-responders underwent another 6 weeks of additional training volume, during which they eventually responded to training [50]. It seems possible that a similar phenomenon might exist regarding the response to resistance exercise, such that increasing volume/dose may increase the likelihood of all subjects responding minimally or further increasing the response. Indeed, a dose-response between exercise volume as per number of sets and muscle hypertrophy has been clearly demonstrated in a small number of meta-analyses [17, 51, 52]. In particular, a recent meta-analysis of weekly number of sets and muscle hypertrophy demonstrated that volume has a dose-dependent effect on muscle growth [17]. Moreover, this meta-analysis found that ten weekly sets for each muscle group appeared to be required for maximal hypertrophy, and no plateau was found, which may lead to the hypothesis that higher volume could still promote greater muscle growth. The mechanism by which increasing training volume promotes muscle hypertrophy is not fully known. However, a few studies have demonstrated that muscle protein synthesis and the intracellular anabolic pathways are responsive to increasing training volume [53–55]. For instance, higher training volumes promote both the magnitude and duration of protein synthesis during recovery from exercise [53]. Whether this is reflective of muscle remodeling and/or muscle hypertrophy is yet to be determined; however, it is clear that training volume affects muscle anabolic intracellular processes.

Bodybuilders are known to perform a great volume of resistance training, with the use of various advanced techniques, regardless of variations in training intensities through periodization [56]. However, greater volume can be applied to any population. In sedentary overweight women, higher volume promoted greater muscle hypertrophy in knee extensors compared to lower volume resistance training [57]. Similarly, in the elderly, increasing volume may promote greater hypertrophy [52]. Thus, the aforementioned search for the minimal dose of resistance exercise to promote muscle hypertrophy may in fact lead to an under-dosed training program, especially for the older population [58].

It should be noted that different muscles may have different dose-response curves for training volume, and the purported plateau and decline in the response with further work may be at different ranges of total work. This seems to be the case for small versus large muscle. There is little evidence for different muscle groups, but it appears that elbow flexors and extensors show a shorter range of effective dose-response, within the same session at least, before plateauing, in comparison to the quadriceps muscles [59, 60], the threshold of which seems not so obviously defined. In addition, the load applied to muscle groups recruited and affected when targeting other muscle groups, such as the utilization of multi-joint exercises targeting the back or pectoral muscles and their respective effects on the biceps and triceps, may need to be taken into consideration for exercise prescription. For instance, the combination of seven weekly sets of compound and isolation exercises that affects the triceps muscle—directly or indirectly—may maximally promote hypertrophy, although fourfold greater volume does not seem to be detrimental [60]. Moreover, how the high training volume should be achieved may be a matter of debate. Whether it is beneficial to achieve greater volume by adding more sets to exercises in a program or by adding different exercises to the same muscle group is currently unknown. A recent study utilizing ten sets of the same exercises in a training program found no advantage in comparison to five sets in trained subjects [61]. If confirmed, this could indicate that high volume should be achieved by incorporation of different exercises rather than performing a high number of sets of the same exercises, although this effect may be different for highly trained individuals or athletes.

More studies are necessary to determine whether different muscles have different dose-responses and the effect of training status (untrained, trained, and athletes) on those responses. It is possible that highly trained individuals and athletes require greater training volumes for muscle growth than untrained and recreationally trained individuals, similar to what has been shown for muscle strength gains [20]. Combined, the available data demonstrate that, firstly, resistance training volume has the most profound effect on muscle hypertrophy independently of other variables, and secondly, that the volume at which muscle hypertrophy responses plateau or decline is not well understood.

## 3 Volume and Health

Resistance training has been shown to be safe for various patient populations in the treatment or prevention of cardiovascular diseases, osteopathy, diabetes, and sarcopenia [5–8]. In addition to resistance training being a welldocumented strategy for improving health, training volume appears to have a dose-dependent effect on health outcomes.

Volume has been studied in relation to the health responses on metabolism. Correa et al. [57] demonstrated that 11 weeks of three sets of eight different exercises compared to a single set of the same exercises three times a week significantly reduced resting fat oxidation and triglyceride concentrations relative to baseline in overweight women. These data support the use of a higher volume of resistance training for the prevention of cardiovascular disease. Indeed, resistance training is known to promote cardiovascular health. Specifically, resistance training promotes a reduction in resting systolic (SBP) and diastolic (DBP) blood pressure. Most importantly, the decreases in both SBP and DBP seem to be dependent on volume. In hypertensive patients, higher training volumes tend to further decrease both SBP and DBP compared to low training volumes [62].

The combination of endurance exercise with resistance training has also been demonstrated to be important for managing diseases. In this regard, when combining both modes of exercise, the number of sets performed per week has been negatively correlated with hemoglobin A1c changes in a meta-regression analysis [63]. Moreover, in a large prospective cohort study, with follow-up over 18 years, the time spent on resistance training sessions was associated with reduced risk of type 2 diabetes in a linear, dose-responsive fashion in men [64] and women [65]. In other words, the greater the time spent on resistance training, the lower the risk for type 2 diabetes. For every 60 min on resistance training per week there was a 13% reduction in risk for type 2 diabetes [64].

Regarding sarcopenia, elderly individuals also benefit from high-volume resistance training. A meta-analysis demonstrated that resistance training volume (7–39 weekly sets), but not any other training variable analyzed, predicted changes in lean body mass in old adults [52]. Indeed, high-volume resistance training has been proposed for preventing and managing sarcopenia in the elderly [58]. It is likely that in this population, training volume is the most easily modifiable variable that affects muscle mass maintenance and growth. Increasing intensity may not be an option in some cases, and trainers might be reluctant to increase external load, leading to a suboptimal dose of resistance exercise. Thus, increasing total volume seems the best option to guarantee optimal dosing. More studies are necessary to determine whether older people require more volume than younger subjects. However, based on the concept of anabolic resistance with aging and reduced response to a session of exercise in the elderly [66, 67], we propose that this could be the case.

A frequent criticism of high volume resistance training protocols is that they are prone to overtraining, and can be detrimental. The health benefits associated with increased volume of training in the healthy young, older individuals, and individuals with all types of diseases, vastly outnumber the purported potential for increased risk of injury. The majority of injuries in resistance training are related to inadequate supervision and improper technique [68]. As long as proper screening (and thus training individualization), progression, supervision, and techniques are applied, there should be no major concern regarding safety in increasing resistance training volume. Thus, in many cases when patients or older people are either unwilling or unable to perform intense resistance training, promoting high volume training can still cause significant and clinical relevant health benefits.

## 4 Conclusions

It has been hypothesized that a higher volume or dose of resistance training will cause a plateau in the response or event in the form of an inverted U-shaped response curve (i.e., after plateauing, the response will be detrimental) [16, 17]. However, the available data in the literature have not found such a threshold with resistance training for either hypertrophy [17] or health [64, 65]. It is likely that such a threshold exists; however, it appears to be much more malleable than previously thought, muscle group-dependent, and not as easily attained as generally assumed. More research is warranted to determine where such plateaus, upper limits, and thresholds occur.

Taken together, the findings presented here demonstrate that resistance training volume is a determinant variable affecting muscle hypertrophy and health outcomes. In resistance training programs intended to promote muscle hypertrophy and health, both intensity and volume can be manipulated. However, in some cases, increasing the volume can be better tolerated than increasing the intensity. Thus, volume is perhaps the most easily modifiable variable in a program with consistent positive effects on health and muscle hypertrophy. A minimum of ten weekly sets per muscle group seems to be necessary to maximize muscle hypertrophy response in untrained subjects, with the possibility of greater volume producing greater results. Moreover, increased volume in resistance training can be achieved in multiple ways. Within a session, it can be achieved via increased number of repetitions (repetitions per set), increased number of sets (sets per exercise), addition of exercises, increased frequency (sessions per week), or when all these have been kept constant, by increasing exercise intensity of load (assuming volume as total load lifted, i.e., repetition × sets × intensity load).

Other training variables can be manipulated to further facilitate the increase in training volume, such as appropriate rest intervals and the use of advanced techniques.

However, while finding a minimal dose of exercise that could maximize effect is important because time-efficient protocols are needed to treat the wider population, the volume should not be neglected. Whenever time is an issue for exercise adherence, or as a matter of personal choice, time-efficient protocols for resistance training can be beneficial and important for individual goals. However, trainees should be informed that optimal results may be achieved with high volumes. An alternative to promoting higher volume in a more time-efficient manner is to increase exercise density via use of advanced techniques, for instance. In conclusion, resistance training volume is a strong contributor to muscle adaptations, with dose-dependent effects. When equated, volume seems one of, if not the, most important factors affecting muscle hypertrophy, as long as training has sufficient intensity. Increasing resistance training volume seems to be the most easily modifiable variable when muscle hypertrophy and health outcomes are the main goals.

**Compliance with Ethical Standards**

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## References


1. You T, Arsenis NC, Disanzo BL, et al. Effects of exercise training on chronic inflammation in obesity: current evidence and potential mechanisms. Sports Med. 2013;43:243–56.
2. Ibañez J, Izquierdo M, Argüelles I, et al. Twice-weekly progressive resistance training decreases abdominal fat and improves insulin sensitivity in older men with type 2 diabetes. Diabetes Care. 2005;28:662–7.
3. Brooks N, Layne JE, Gordon PL, et al. Strength training improves muscle quality and insulin sensitivity in Hispanic older adults with type 2 diabetes. Int J Med Sci. 2006;4:19–27.
4. Hagerman FC, Walsh SJ, Staron RS, et al. Effects of high-intensity resistance training on untrained older men. I. Strength, cardiovascular, and metabolic responses. J Gerontol A Biol Sci Med Sci. 2000;55:B336–46.
5. Westcott WL. Resistance training is medicine: effects of strength training on health. Curr Sports Med Rep. 2012;11:209–16.
6. Aronow WS, Harrington RA, Fleg JL, et al. ACCF/AHA 2011 Expert consensus document on hypertension in the elderly. Circulation. 2011;123:2434–506.
7. Pescatello LS, Franklin BA, Fagard R, et al. American College of sports medicine position stand. Exercise and hypertension. Med Sci Sports Exerc. 2004;36:533–53.
8. American College of Sports Medicine. Progression models in resistance training for healthy adults. Med Sci Sport Exerc. 2009;41:687–708.
9. Williams MA, Haskell WL, Ades PA, et al. Resistance exercise in individuals with and without cardiovascular disease: 2007 update: a scientific statement from the American Heart Association Council on Clinical Cardiology and Council on Nutrition, Physical Activity, and Metabolism. Circulation. 2007;116:572–84.
10. Albright A, Franz M, Hornsby G, et al. American College of Sports Medicine position stand. Exercise and type 2 diabetes. Med Sci Sports Exerc. 2000;32:1345–60.
11. Gibala MJ. High-intensity interval training: a time-efficient strategy for health promotion? Curr Sports Med Rep. 2007;6:211–3.
12. Siddiqi Z, Tiro JA, Shuval K. Understanding impediments and enablers to physical activity among African American adults: a systematic review of qualitative studies. Health Educ Res. 2011;26:1010–24.
13. Heesch KC, Mâsse LC. Lack of time for physical activity: perception or reality for African American and Hispanic women? Women Health. 2004;39:45–62.
14. Thompson WR. Worldwide survey of fitness trends for 2017. ACSM's Heal Fit J. 2016;20:8–17.
15. Gibala MJ, Little JP. Just HIT it! A time-efficient exercise strategy to improve muscle insulin sensitivity. J Physiol. 2010;588:3341–2.
16. Philippe AG, Py G, Favier FB, et al. Modeling the responses to resistance training in an animal experiment study. Biomed Res Int. 2015;2015:914860.
17. Schoenfeld BJ, Ogborn D, Krieger JW. Dose-response relationship between weekly resistance training volume and increases in muscle mass: a systematic review and meta-analysis. J Sports Sci. 2017;35:1073–108.
18. McBride JM, McCaulley GO, Cormie P, et al. Comparison of methods to quantify volume during resistance exercise. J Strength Cond Res. 2009;23:106–10.
19. Borde R, Hortobágyi T, Granacher U. Dose-response relationships of resistance training in healthy old adults: a systematic review and meta-analysis. Sports Med. 2015;45:1693–720.
20. Peterson MD, Rhea MR, Alvar BA. Applications of the dose-response for muscular strength development: a review of meta-analytic efficacy and reliability for designing training prescription. J Strength Cond Res. 2005;19:950–8.
21. Peterson MD, Rhea MR, Alvar BA. Maximizing strength development in athletes: a meta-analysis to determine the dose-response relationship. J Strength Cond Res. 2004;18:377–82.
22. Rhea MR, Alvar BA, Burkett LN, et al. A meta-analysis to determine the dose response for strength development. Med Sci Sport Exerc. 2003;35:456–64.
23. Krieger JW. Single versus multiple sets of resistance exercise: a meta-regression. J Strength Cond Res. 2009;23:1890–901.
24. Candow DG, Burke DG. Effect of short-term equal-volume resistance training with different workout frequency on muscle mass and strength in untrained men and women. J Strength Cond Res. 2007;21:204–7.
25. Tavares LD, de Souza EO, Ugrinowitsch C, et al. Effects of different strength training frequencies during reduced training period on strength and muscle cross-sectional area. Eur J Sport Sci. 2017;17:665–72.
26. Ahtiainen JP, Pakarinen A, Alen M, et al. Short vs. long rest period between the sets in hypertrophic resistance training: influence on muscle strength, size, and hormonal adaptations in trained men. J Strength Cond Res. 2005;19:572–82.
27. Schoenfeld BJ, Ratamess NA, Peterson MD, et al. Effect of different volume-equated resistance training loading strategies on muscular adaption in well trained men. J Sports Sci. 2014;28:2909–18.

28. Angleri V, Ugrinowitsch C, Libardi CA. Crescent pyramid and drop-set systems do not promote greater strength gains, muscle hypertrophy, and changes on muscle architecture compared with traditional resistance training in well-trained men. Eur J Appl Physiol. 2017;117:359–69.
29. Fink J, Schoenfeld BJ, Kikuchi N, et al. Effects of drop set resistance training on acute stress indicators and long-term muscle hypertrophy and strength. J Sports Med Phys Fitness. 2017. doi:10.23736/S0022-4707.17.06838-4.
30. Klemp A, Dolan C, Quiles JM, et al. Volume-equated high- and low-repetition daily undulating programming strategies produce similar hypertrophy and strength adaptations. Appl Physiol Nutr Metab. 2016;41:699–705.
31. Chestnut JL, Docherty D. The effects of 4 and 10 repetition maximum weight-training protocols on neuromuscular adaptations in untrained men. J Strength Cond Res. 1999;13:353–9.
32. Ribeiro AS, Schoenfeld BJ, Silva DRP, et al. Effect of two-versus three-way split resistance training routines on body composition and muscular strength in bodybuilders: a pilot study. Int J Sport Nutr Exerc Metab. 2015;25:559–65.
33. Conlon JA, Newton RU, Tufano JJ, et al. The efficacy of periodised resistance training on neuromuscular adaptation in older adults. Eur J Appl Physiol. 2017;117:1181–94.
34. Mangine GT, Hoffman JR, Gonzalez AM, et al. The effect of training volume and intensity on improvements in muscular strength and size in resistance-trained men. Physiol Rep. 2015;3:e12472.
35. Mitchell CJ, Churchward-Venne TA, West DWD, et al. Resistance exercise load does not determine training-mediated hypertrophic gains in young men. J Appl Physiol (1985). 2012;113:71–7.
36. de Salles BF, Simão R, Miranda F, et al. Rest interval between sets in strength training. Sports Med. 2009;39:765–77.
37. Willardson JM, Burkett LN. The effect of different rest intervals between sets on volume components and strength gains. J Strength Cond Res. 2008;22:146–52.
38. Schoenfeld BJ, Pope ZK, Benik FM, et al. Longer inter-set rest periods enhance muscle strength and hypertrophy in resistance-trained men. J Strength Cond Res. 2015;30:1805–12.
39. Buford TW, Kreider RB, Stout JR, et al. International Society of Sports Nutrition position stand: creatine supplementation and exercise. J Int Soc Sports Nutr. 2007;4:6.
40. Burke DG, Silver S, Holt LE, et al. The effect of continuous low dose creatine supplementation on force, power, and total work. Int J Sport Nutr Exerc Metab. 2000;10:235–44.
41. Vandenberghe K, Goris M, Van Hecke P, et al. Long-term creatine intake is beneficial to muscle performance during resistance training. J Appl Physiol (1985). 1997;83:2055–63.
42. Volek JS, Rawson ES. Scientific basis and practical aspects of creatine supplementation for athletes. Nutrition. 2004;20:609–14.
43. Chrusch MJ, Chilibeck PD, Chad KE, et al. Creatine supplementation combined with resistance training in older men. Med Sci Sports Exerc. 2001;33:2111–7.
44. Devries M, Phillips S. Creatine supplementation during resistance training in older adults—a meta-analysis. Med Sci Sports Exerc. 2014;46:1194–203.
45. Goto K, Nagasawa M, Yanagisawa O, et al. Muscular adaptations to combinations of high- and low-intensity resistance exercises. J Strength Cond Res. 2004;18:730–7.
46. Aguiar AF, Buzzachera CF, Pereira RM, et al. A single set of exhaustive exercise before resistance training improves muscular performance in young men. Eur J Appl Physiol. 2015;115:1589–99.
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. 2005;37:964–72.
48. Churchward-Venne TA, Tieland M, Verdijk LB, et al. There are no nonresponders to resistance-type exercise training in older men and women. J Am Med Dir Assoc. 2015;16:400–11.
49. Ahtiainen JP, Walker S, Peltonen H, et al. Heterogeneity in resistance training-induced muscle strength and mass responses in men and women of different ages. Age (Dordr). 2016;38:10.
50. Montero D, Lundby C. Refuting the myth of non-response to exercise training: "non-responders" do respond to higher dose of training. J Physiol. 2017;11:3377–87.
51. Krieger JW. Single vs. multiple sets of resistance exercise for muscle hypertrophy: a meta-analysis. J Strength Cond Res. 2010;24:1150–9.
52. Peterson MD, Sen A, Gordon PM. Influence of resistance exercise on lean body mass in aging adults: a meta-analysis. Med Sci Sports Exerc. 2011;43:249–58.
53. Burd NA, Holwerda AM, Selby KC, et al. Resistance exercise volume affects myofibrillar protein synthesis and anabolic signalling molecule phosphorylation in young men. J Physiol. 2010;588:3119–30.
54. Terzis G, Spengos K, Mascher H, et al. The degree of p70 S6k and S6 phosphorylation in human skeletal muscle in response to resistance exercise depends on the training volume. Eur J Appl Physiol. 2010;110:835–43.
55. McKendry J, Pérez-López A, McLeod M, et al. Short inter-set rest blunts resistance exercise-induced increases in myofibrillar protein synthesis and intracellular signalling in young males. Exp Physiol. 2016;101:866–82.
56. Hackett DA, Johnson NA, Chow C-M. Training practices and ergogenic aids used by male bodybuilders. J Strength Cond Res. 2013;27:1609–17.
57. Correa CS, Teixeira BC, Cobos RCR, et al. High-volume resistance training reduces postprandial lipaemia in postmenopausal women. J Sports Sci. 2015;33:1890–901.
58. Law TD, Clark LA, Clark BC. Resistance exercise to prevent and manage sarcopenia and dynapenia. Annu Rev Gerontol Geriatr. 2016;36:205–28.
59. Wernbom M, Augustsson J, Thomeé R. The influence of frequency, intensity, volume and mode of strength training on whole muscle cross-sectional area in humans. Sports Med. 2007;37:225–64.
60. Ostrowski KJ, Wilson GJ, Weatherby R, et al. The effect of weight training volume on hormonal output and muscular size and function. J Strength Cond Res. 1997;11:148–54.
61. Amirthalingam T, Mavros Y, Wilson GC, et al. Effects of a modified German volume training program on muscular hypertrophy and strength. J Strength Cond Res. 2016. doi:10.1519/JSC.0000000000001747.
62. Strasser B, Siebert U, Schobersberger W. Resistance training in the treatment of the metabolic syndrome: a systematic review and meta-analysis of the effect of resistance training on metabolic clustering in patients with abnormal glucose metabolism. Sports Med. 2010;40:397–415.
63. Umpierre D, Ribeiro PAB, Schaan BD, et al. Volume of supervised exercise training impacts glycaemic control in patients with type 2 diabetes: a systematic review with meta-regression analysis. Diabetologia. 2013;56:242–51.
64. Grøntved A, Rimm EB, Willett WC, et al. A prospective study of weight training and risk of type 2 diabetes mellitus in men. Arch Intern Med. 2012;172:1306–12.
65. Grøntved A, Pan A, Mekary RA, et al. Muscle-strengthening and conditioning activities and risk of type 2 diabetes: a prospective study in two cohorts of US women. PLoS Med. 2014;11:e1001587.
66. Shad BJ, Thompson JL, Breen L. Does the muscle protein synthetic response to exercise and amino acid-based nutrition

diminish with advancing age? A systematic review. Am J Physiol Endocrinol Metab. 2016;311:E803–17.
67. Phillips SM, Glover EI, Rennie MJ. Alterations of protein turnover underlying disuse atrophy in human skeletal muscle. J Appl Physiol. 1985;2009(107):645–54.
68. Faigenbaum AD, Myer GD. Resistance training among young athletes: safety, efficacy and injury prevention effects. Br J Sports Med. 2010;44:56–63.