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EVIDENCE-BASED RESISTANCE TRAINING RECOMMENDATIONS FOR MUSCULAR HYPERTROPHY

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Abstract

Objective: There is considerable interest in attaining muscular hypertrophy in recreational gym-goers, bodybuilders, older adults, and persons suffering from immunodeficiency conditions. Multiple review articles have suggested guidelines for the most efficacious training methods to obtain muscular hypertrophy. Unfortunately these included articles that inferred hypertrophy markers such as hormonal measurements, used older techniques that might not be valid (e.g. circumference) and failed to appropriately consider the complexity of training variables.

Methods: The present commentary provides a narrative review of literature, summarising main areas of interest and providing evidence-based guidelines towards training for muscular hypertrophy.

Conclusions: Evidence supports that persons should train to the highest intensity of effort, thus recruiting as many motor units and muscle fibres as possible, self-selecting a load and repetition range, and performing single sets for each exercise. No specific resistance type appears more advantageous than another, and persons should consider the inclusion of concentric, eccentric and isometric actions within their training regime, at a repetition duration that maintains muscular tension. Between set/exercise rest intervals appear not to affect hypertrophy, and in addition the evidence suggests that training through a limited range of motion might stimulate similar results to full range of motion exercise. The performance of concurrent endurance training appears not to negatively affect hypertrophy, and persons should be advised not to expect uniform muscle growth both along the belly of a muscle or for individual muscles within a group. Finally evidence suggests that short (~3 weeks) periods of detraining in trained persons does not incur significant muscular atrophy and might stimulate greater hypertrophy upon return to training.

Key words: *muscular size, bodybuilding, intensity, genetics, concurrent, endurance*

Introduction

Muscular growth and hypertrophy is of considerable interest to athletes and lay persons wishing to increase their muscularity. As a result there have been multiple publications reviewing the mechanisms [1], as well as providing guidelines and training recommendations. [1-5]. The most recent of these papers [1] includes meta-analytical studies [2,5], and associated position stand publications [6], as well as the opinion of authors via text-books [7] as *evidence* to support their claims. Such a review should be considering only original, empirical, peer-reviewed research articles. The inclusion of studies measuring a hormonal response, which only infers potential for hypertrophic adaptations, is also cause for concern as discussed herein. Many other publications [2,4,5] have received criticism for a lack of scientific rigour [e.g. 8-10] and thus there appears need for a more scrupulous review. The present piece is not aimed as a critique of previous publications, but rather aims to discuss the research and provide evidence-based recommendations for muscular hypertrophy.

Symptomatic, Aging, and Special Populations

Sarcopenia (muscle wastage) and thus, muscle hypertrophy, are of considerable interest for special populations e.g. older adults [11-13], persons suffering from immunodeficiency conditions [14,15], and bodybuilders [16]. However, the present article is concerned only with the hypertrophic adaptations to resistance training for asymptomatic adults. Whilst the nature of these more complex areas, specifically bodybuilding, might seem unwise to dismiss, bodybuilders, weightlifters and the like should be considered an elite population, likely with genetics that are favourable to muscular growth, and potentially using powerful supplementation [17] or anabolic steroids [18], and/or growth hormones [19,20]. As a result their training routines and growth are not considered to be within expected ranges for the general population. Indeed, older or symptomatic persons likely do not respond to resistance training in the same way as asymptomatic persons, therefore, the present article has excluded research considering any specialised population sample group.

Physiological Biomarkers

We can also consider the biomarkers linked to, or assumed to mediate, hypertrophy and muscle remodelling. This includes but is not limited to: hormone levels, e.g. IGF-1, testosterone, and growth hormone, [21-23]; satellite cell activation, proliferation and differentiation [23,24]; protein synthesis [26,27], and genetic variation [28]. These markers are discussed in detail in several articles (e.g. 1,29-31] and some authors have made recommendations from these inferred markers [1,4]. However, multiple publications have provided extensive critical analysis of these hypotheses and the associated complexities [e.g. 32-36]. Whilst we recognise the importance of understanding hypertrophic mechanisms, we suggest that these physiological biomarkers only infer a hypertrophic response. As such the present article does not discuss the measurement of these variables or other mechanisms, but rather is focused upon research examining the manipulation of training techniques/variables and their effects upon *in vivo* hypertrophic measurement.

Acute and Chronic Hypertrophy and Methods of Measurement

Muscular hypertrophy can be defined as acute, i.e. as a result of sarcoplasmic hypertrophy [37-39], or chronic, i.e. as a result of an increased number of sarcomeres and myofibrils [40-42]. It is important that hypertrophy is measured using a method that can differentiate between acute changes and chronic adaptation therefore the present study will consider research using the most accurate techniques, such as magnetic resonance imaging (MRI), computerised tomography (CT) and ultrasound, all of which are well-validated [43-45]. In measurement of hypertrophy several studies have reported muscle CSA or muscle thickness (MT) from a single 'slice' measurement whilst others have taken multiple measurements through the length of a muscle and calculated and reported a volume. Since in the present review we make no attempt to compare statistical values between studies using different techniques, CSA, MT and volume are considered adequate reporting for muscle size and thus hypertrophic changes. With these criteria defined, the aim of the present article is to provide readers with a series of scientifically-validated recommendations for resistance training for healthy, asymptomatic adults looking to increase muscular hypertrophy.

Methods

A literature search was completed up to the end of May 2013, using MEDLINE, SportDiscus and Google Scholar databases. In addition, the reference list of each article gathered was used to broaden the literature search, as well as previous reviews [1-6,46-53]. The previously detailed inclusion and exclusion criteria were applied to groups within research studies considering hypertrophy. In addition the exclusion of groups performing any irregular forms of training, e.g. hypoxic or occluded training[1] was also applied. Articles manipulating training supplementation as a variable were also excluded.

Whilst review articles [2,3,5] have served to try to compile all the statistical data from respective studies into single results, the present piece makes no such attempt due to the complex individual methods and disparity of reporting data between the studies. Thus given the broad area of this review, a narrative approach has been utilised, discussing the between group differences of each study in their own merit, and grouping similar studies in an attempt to provide recommendations based on the evidence. Finally, it is worth mentioning that several papers were excluded from the present review due to unclear methodological manipulation of variables including: exercises performed, volume (including sets and repetitions), load, and repetition duration [55-59]. Such studies should be commended for their attempt to provide *'real-life'* training regimes but ultimately are limited in any application due to the lack of detail/control of variables [60].

Having applied the inclusion and exclusion criteria the present piece presents results from 57 different peer-reviewed journal articles in an attempt to provide evidence-based resistance training recommendations for hypertrophy. The following sub-sections have been discussed and summarized:

- Intensity of Effort, Load and Repetition Range
- Repetition Duration and Rest Intervals
- Volume and Concurrent Resistance and Endurance Training
- Range of Motion, Contraction Types and Resistance Types
- Non-Uniform Muscle Growth, Contralateral Effects and Training and Detraining Time Course
- Training Status and Genetics

Intensity of Effort, Load and Repetition Range

Intensity

Intensity of effort has previously been considered to be perhaps the single most influential controllable variable for enhancing muscular strength [61]. Evidence suggests that, through the size-principle, i.e. the sequential recruitment of motor units [62], that training to momentary muscular failure maximizes enrolment of muscle fibres to catalyse adaptation. Two studies have considered hypertrophic measurements using electrical stimulation of muscle contraction [63,64]. Ruther, et al., [63] reported favourable increases in hypertrophy as measured by MRI pre- and post-intervention for a training group receiving electrical stimulation (10%) compared to a group performing voluntary muscle activation (4%). Whilst both groups trained at maximal effort, this article

[1] The long term health implications of hypoxic/occluded training have not been thoroughly tested, whilst the effects of cuff pressure and moderate/complete occlusion have implications for muscle activation [54]

suggests that the diminished ability of untrained subjects to recruit motor units limits their potential for hypertrophy, and that recruiting a greater number of muscle fibres (even through electrical stimulation) increases hypertrophic gains. In support Gondin et al. [64], reported significant increases in muscle CSA for a group of participants performing electrically stimulated isometric knee extension exercises. The stimulated contraction equated to approximately 68 ±13% of maximal voluntary contraction (MVC), whilst the training intervention lasted 8-weeks. This suggests that regardless of the stimulus, it is the activation of motor units and muscle fibres that catalyses hypertrophic increases.

Goto et al. [65] considered the effects of either strength (S) or combination (C) regimes on muscular hypertrophy. Both groups performed an identical workout for 6 weeks. However, from week 7 the protocol for the S group consisted of 5 sets at 90% 1RM with 3-minutes rest between each set, whereas the C group performed the same regime with an additional sixth set performed 30 seconds after the fifth set using 50% 1RM. The authors commented that each set was taken to muscular failure. Muscle CSA of the mid-thigh revealed no significant differences between groups S and C at both week 6 and week 10 suggesting that when training to failure there appears no difference in load or repetitions used. However, the authors commented that that there was a greater hypertrophy for the C group which approached significance (P = 0.08). Due to the nature of the decreased rest interval before the final set within the C group, this might provide evidence for the use of drop-sets, or break-down sets, e.g. where muscular force is no longer sufficient to lift a load the load is reduced and repetitions are almost immediately continued. Future research should consider hypertrophic changes as a result of advanced techniques such as drop-sets, and pre-exhaustion, amongst others.

Whilst between-set rest periods will be discussed in a later section, a study by Goto et al. [66] considered the effect of a within-set rest period on muscular hypertrophy of the quadriceps. Participants were divided into three groups: no rest (NR), with rest (WR) and control (CTR). Each training group performed 3 sets of 10RM for lat pull-down and shoulder press, and 5 sets of 10RM for bilateral knee extension. The NR group were permitted 1 minutes' rest between sets and exercises, whereas the WR group were instructed to take an additional 30 seconds of rest midway through each set (e.g. between the 5^{th} and 6^{th} repetitions). The increases in muscle CSA of the thigh was significantly greater in NR compared to WR groups (12.9 ±1.3 % vs. 4.0 ±1.2% respectively). This suggests that the continuous and sequential recruitment of muscle fibres for the NR group enhanced hypertrophy, whilst the rest in the WR group allowed some motor units recovery time preventing the need for recruitment of higher threshold motor-units.

Load and Repetition Range

In association with the discussion of intensity of effort, we should consider how the load lifted (%1RM) or the number of repetitions performed affects muscular hypertrophy. For example Hisaeda et al. [67] considered two different resistance training protocols described as being typical for strength (S; high load, low repetition) and hypertrophy (H; low load, high repetition). Participants trained 3 x / week for 8 weeks using an isotonic knee extension exercise. Group H performed 5-6 sets of 15-20RM with 90 seconds interval between sets, whilst group S performed 8-9 sets of 4-5RM with *'sufficient'* rest between each set. Pre- to post-test results revealed a significant increase in CSA for the quadriceps femoris for both groups with no significant difference between training interventions. Reporting similar results, Kraemer et al. [68], considered the effect of multiple resistance training protocols on hypertrophy in physically active, but untrained women. Participants were divided into either total- or upper-body training programs, and further divided in to two groups; one using heavier load and lower repetition range (starting at 8RM and progressing to 3RM) and the other using a lighter load and higher repetition range (starting at 12RM and progressing to 8RM). Muscle CSA was measured for the mid-thigh and upper arm of the dominant limbs at weeks 0, 12 and 24 using MRI. All training groups showed a significant increase in upper arm CSA from weeks 0 to 12, with no significant difference between groups. In addition all training groups showed a further significant increase in CSA of the upper arm from weeks 12 to 24, once again with no significant difference between the groups. Mid-thigh CSA showed a significant increase from weeks 0 to 12, and 12 to 24 in the whole body training groups only, with no significant difference between the groups.

Additional support comes from Popov et al. [69], and Tanimoto et al., [70,71], who considered the effects of low and high load training on muscular hypertrophy. Each of these studies compared groups training at ~50% 1RM to ~80% 1RM. All groups trained to repetition maximum (RM), and results of MRI showed no significant differences in hypertrophy between the groups. Ogasawara et al., [72] also compared low- (30% 1RM) and high-load (75% 1RM) resistance training, using the same participants with a 12 month detraining period between each 6-week intervention. Participants trained to volitional fatigue in the bench press exercise and post-intervention MRI results revealed similar increases in pectoralis major and triceps brachii cross sectional area with no significant differences between groups. In addition Léger et al., [73] considered groups training with high load and low reps (3-5RM), and low load and high reps (20-28RM). Following an 8-week intervention of leg press, squat and leg extension training MRI revealed ~10% increases in cross sectional area of the quadriceps in both groups with no significant differences between high- and low-repetition groups.

Finally an article that is discussed in greater detail in a later section [74] considered rest intervals between sets. In this study the group with a decreasing rest interval performed fewer repetitions, and also used a lighter load as a result of decreased rest. This amounted to a significantly ($P < 0.05$) lower total training volume throughout the 8-week intervention. However, both the continuous interval and decreasing interval groups showed significant hypertrophy measured by MRI with no significant difference between the groups.

Summary

The evidence presented supports previous research suggesting that it is the activation of muscle fibres that appears to stimulate muscular responses [61,62] causing hypertrophy. Thus, recruiting as many motor units as possible through training to momentary muscular failure appears optimal for muscular hypertrophy. From the research discussed there appears no substantiation of the claim that training using either light or heavy loads is better for attaining hypertrophic adaptations when training to MMF.

Repetition Duration & Rest Intervals

Repetition Duration

The area of repetition duration[2] and use of explosive lifting has been equivocal with regard to strength gains, although previous recommendations have suggested a velocity that maintains muscular tension throughout the range of movement [61,75]. This section will consider the research regarding repetition duration and hypertrophic gain. Young and Bibby [78] considered fast and slow training groups for a half squat exercise. The fast group performed a controlled eccentric phase followed by an explosive concentric phase, and the slow group performed both concentric and eccentric phases in a '*slow and controlled manner*'. Muscle thickness (MT) of the mid-thigh was measured using ultrasound, where results revealed significant hypertrophy in both fast and slow groups with no significant differences between these groups. In addition, the aforementioned studies by Tanimoto et al. [70,71] considered the effects of repetition duration and load using a knee extension exercise, on quadriceps hypertrophy. Participants in the first study [70] were divided in to three groups: low-load and high repetition duration (LST; 3 seconds concentric: 3 seconds eccentric with 1 second pause and no relaxation phase at ~50% 1RM), high-load and *normal* repetition duration (HN; 1 second concentric: 1 second eccentric and 1 second for relaxing with ~80% 1RM0 and low-load and *normal* repetition duration (LN; 1 second concentric: 1 second eccentric and 1 second for relaxing with ~50% 1RM)[3]. The second study did not include a LN group but did utilise a control group. The authors state that exercise intensity was determined at 8RM. In the first study [70] muscle CSA of the quadriceps was measured using MRI and in the second study MT was measured using ultrasound. The LST and HN groups reported significantly greater hypertrophy than the LN group in the first study [70] and the control group in the second study [71] with no significant difference between LST and HN in either study [70,71]. We might consider that if either increased repetition duration or an increased load caused participants to reach MMF around 8RM, as to how the LN group using both a lighter load and lower repetition duration also reached MMF at around 8RM. It seems more logical that the LN group did not perform repetitions to MMF, which might be a cause for their lack of hypertrophic gains compared to LST and HN.

The evidence appears to suggest that repetition duration makes no significant difference to hypertrophic gain. However, we might further consider a study by Friedmann et al. [79] whose protocol required control participants perform 25 repetitions with 30% 1RM within 45 seconds. Following 6 sets of 3 x / week training cross sectional area results using MRI revealed no significant increases in strength or hypertrophy. Previous reviews have suggested that muscular tension appears necessary to actively recruit muscle fibres to cause increases in strength [e.g. 61,75], therefore we can consider that explosive training of 25 repetitions in 45 seconds (e.g. <1 second per concentric/eccentric muscle action), with a load of 30% 1RM does not provide sufficient stimulus for strength or hypertrophic gains. Thus, whilst repetition duration appears to have no significant effect on hypertrophy, it appears that muscular tension is a requirement. In support, a latter study by the same authors [80] considering eccentric overload (see later section on contraction types for more details) used the same research design of 25 leg extension repetitions in 45 seconds. Once again none

[2] Repetition duration makes reference to the time taken to perform concentric and eccentric phases (CON: ECC) of a single repetition. Previous research has clarified the importance of the term repetition duration as opposed to velocity or speed, which makes reference to distance and time [76,77].

[3] The authors incorrectly cite the groups as low or high *intensity*, where in fact they make reference to load (kg). Since all groups were training to RM we suggest that all groups trained at the same intensity of effort but rather differed in load. In addition the authors make reference to slow or normal *speed* where they did not cite a speed but rather repetition duration (see previous footnote).

of the training groups reported any significant increase in hypertrophy. Interestingly, the authors state that multiple participants dropped out of the study citing muscle soreness or injury. Later within the present review we will discuss time-course of hypertrophy where evidence has shown chronic adaptation in as short as 3 weeks of resistance training [81,82]. However, we must also recognise that not all participants will respond in the same time-scale, therefore the 4-week interventions by Friedmann et al. [79,80] simply might not have been of sufficient duration.

Rest Intervals

The American College of Sports Medicine (ACSM) [4] discussed rest intervals between sets and exercises, suggesting that both short (30 second) and long (90 second) rest intervals are equally efficacious. Two studies [74,83] directly examining the effects of different between set rest intervals have supported the idea that these have little effect upon hypertrophy. Ahtiainen et al. [83] compared the effects of between-set rest intervals on muscle hypertrophy of the quadriceps whilst controlling for total volume (a lower load and additional sets was used during a short-rest protocol to create a similarity in total volume - load x sets x repetitions - between the protocols). Their 6-month intervention consisted of a crossover design where two training groups completed a short-rest (SR; 2 minutes) and a long-rest (LR; 5 minutes) 3-month intervention. Muscle volume of the quadriceps was measured using MRI, and results revealed that neither the 3-month SR or LR group alone produced significant increases. However, after the 6-month intervention (including both LR and SR) both groups 1 and 2, showed significant increases in muscle volume.

De Souza et al. [74] considered the effects of between set rest intervals on muscular hypertrophy without controlling for total volume. Participants were randomly assigned to either continuous interval (CI) or decreasing interval (DI). After 2-weeks of standardized training the CI group continued to have 2-minute rest intervals where the DI group reduced their between set/exercise rest interval as follows; weeks 3, 4, 5, 6, 7, and 8 accommodated 105, 90, 75, 60, 45, and 30 seconds of rest, respectively. As a result of this decreased rest interval the load lifted and thus total training volume (load x sets x repetitions) for the DI group also decreased. The authors reported statistically significant differences for the free-weight back squat (CI=27,248.2 ±293.8kg vs. DI=23,453.6 ±299.4kg) and free-weight bench press (CI=21,257.9 ±172.7kg vs. DI=19,250.4 ±343.8kg). Interestingly this additional rest and training load did not enhance pre- to post-test 1RM strength for the squat or bench press to any greater degree in the CI group than for the DI group. Muscle CSA of the right thigh and upper arm revealed significant hypertrophy pre- to post-intervention in both groups with no significant between-group differences.

Overall, it appears that although rest intervals can have an acute impact upon total training volume this bears little effect upon hypertrophic adaptation. Additionally, different rest intervals appear to bear little effect independently where volume has been controlled between groups.

Summary

From the evidence presented it appears that muscular tension is a necessity in stimulating hypertrophic gains. Whilst studies considering high and low repetition duration generally have found no significant difference, we can conclude that it is the sequential recruitment of muscle fibres and training to momentary muscular failure that stimulates hypertrophic response rather than the load being lifted or repetition duration used. In addition the evidence suggests that whilst rest interval appears to play a role in acute performance e.g. both the repetitions performed and load lifted, it did not affect the chronic strength or hypertrophic gains acquired.

Other studies have considered repetition duration and shall be discussed herein where appropriate to their other independent variables (e.g. concentric vs. eccentric muscle actions); however, we caution the interpretation of those studies with regard to repetition duration due to the use of isokinetic dynamometry. See later for a more thorough discussion.

Volume and Concurrent Resistance and Endurance Training

Volume

A recent meta-analysis suggested that significantly greater gains in hypertrophy can be obtained by the performance of multiple sets of exercise compared to single sets [5]. However, a critique of that meta-analysis suggested that the disparity between studies, as well as inclusion of studies which did not meet inclusion/exclusion criteria, prevented such a simple conclusion [10]. With this in mind it is prudent that the present review consider the area of volume of training for muscular hypertrophy.

Starkey et al. [84] divided 39 (19 males, 20 females) healthy untrained participants in to either 1 set, 3 set or control groups for bilateral knee extension and flexion exercises. Ultrasound measures of muscle thickness revealed significant hypertrophy pre- to post-test for the quadriceps muscles; medialis (3 set) and lateralis (1 set). In addition muscle thickness increased in the hamstrings muscles from pre- to post-test, measured at 40% and 60% from greater trochanter to lateral epicondyle of the tibia, for both 1 set and 3 sets groups with no significant difference between the groups.

Ostrowski et al. [85] also considered volume, dividing 35 trained males into 1 of 3 groups (1 set, 2 sets, and 4 sets, of each exercise). This equated to 3, 6, or 12 sets of exercise per muscle group, performed for 4 different workouts each week; (i) legs, (ii) chest and shoulders, (iii) back and calves and (iv) biceps and triceps. Ultrasound was used to measure cross-sectional area for the rectus femoris (RF) and muscle thickness for the triceps brachii (TB). After 10 weeks of resistance training ultrasound measurements revealed significant increases in cross-sectional area for RF and muscle thickness for TB within all the groups, but no significant differences in the gains between the groups. Since this study utilizes a split routine of training different body parts on different days it likely replicates what many gym goers looking to increase muscle mass might perform. Thus the absence of significant differences between 1, 2, and 4 set training groups represents an important finding. A final study considering the lower body is that of Bottaro et al. [86] who compared 3 sets of knee extension and 1 set of elbow flexion (3K-1E) to 1 set of knee extension and 3 sets of elbow flexion (1K-3E). Muscle thickness was measured using ultrasound pre- and post- intervention, and results revealed significant increases in muscle thickness in the elbow flexors in both groups with no significant difference between groups. However, the authors also reported no significant increases in muscle thickness for the knee extensors in either group from pre- to post- intervention.

Sooneste et al. [87] considered volume of training in a crossover designed study, comparing 1 and 3 sets of seated dumbbell preacher curl over a 12 week period. Each participant trained 2 x / week, performing 1 set of biceps curl on one arm, and 3 sets on the other arm. Each set was performed at 80% 1RM for 10 repetitions or to muscular failure. Cross sectional area was measured using MRI pre- and post- 1RM testing. The authors reported a statistical significance in hypertrophy over the 12 week period for both groups (1 set; 8.0 ±3.7%, 3 set; 13.3 ±3.6%), with a statistically significant between group increase in favour of the 3 set training intervention.

The studies presented herein appear to be conflicting, with some research supporting multiple set training [87] whilst others suggest no significant difference in hypertrophic gains between single and multiple sets [84-86]. Perhaps a significant consideration might be that of total training volume; i.e. the number of sets that activate an intended muscle group as opposed to the number of sets of a specific exercise. For example Gentil et al. [88] considered the addition of single joint (SJ) exercises to a multi-joint (MJ) resistance training program. Participants were divided into MJ or MJ+SJ groups in which they performed either bench press and lat pull-down exercises (MJ), or bench press, lat pull-down, triceps extension and elbow flexion exercises (MJ+SJ) for 3 sets of 8-12 repetitions, 2 x / week for 10 weeks. All sets were performed to concentric failure. The authors comment *"Because the purpose of the study was to evaluate the effects of adding supplemental SJ exercises to a MJ exercise program, total training volume between the two groups was not equated."* Muscle thickness of the elbow flexors was measured using ultrasound revealing significant increases in hypertrophy for both MJ and MJ+SJ groups (6.46% and 7.04%, respectively) with no significant difference between groups. Thus, the addition of an isolated elbow flexion exercise to a training program which already incorporated the use of the elbow flexors in a lat pull-down exercise made no significance to the increases in hypertrophy of said muscles. It would be interesting for researchers in the future to compare the effects of multiple sets of the same exercise with single sets of different exercises.

Concurrent Resistance and Endurance Training

The completion of multiple exercises for similar muscle groups should not solely refer to the use of typical resistance exercises. Many traditional endurance exercise modalities use the same muscles as resistance training exercises. Thus, when considering exercise volume we should also consider concurrent resistance and conventional cardiovascular training. McCarthy et al. [89] compared the hypertrophic effects of performing strength (S), endurance (E) and concurrent strength and endurance (SE) exercise. The S group performed 8-weight training exercises for 3 sets of each for 5-7RM. The E group performed 50 minutes of continuous cycling at 70% maximum heart rate. The SE training group performed both training protocols in their entirety each training day (with alternating order) with 10 to 20 minutes of rest between each session. Muscle CSA of the knee extensors and knee flexors/adductors was measured using CT scan pre- and post- intervention. Results showed significant hypertrophy for the knee extensors in all groups, with significantly greater increases in S and SE compared to E groups. In addition, significant hypertrophy was reported in the knee flexors/adductors in both the S and SE groups, with no significant between group differences.

Izquiredo et al. [90] also compared the hypertrophic effects of strength (S), endurance (E), and strength and endurance (SE) training. Groups trained 2 x / week performing either 2 x strength (S), 2 x endurance (E), or 1 x strength and 1 x endurance (SE) workouts, for 16 weeks on non-consecutive days. The authors noted that the training programs used in this study were similar to those reported previously [91]. These are both complex and vague, including unquantified ranges (e.g. 10-15 repetitions, 3-5sets, 50-70%

1RM) as well as failing to clarify whether exercise was taken to muscular failure, and the inclusion of '*and/or*' when describing the exercises performed suggested a lack of parity between participants/groups. The endurance element consisted of a progressive cycle task at a constant 60rpm for 30-40 minutes per session, increasing in wattage based on individual blood lactate profiles. All groups showed significant hypertrophy in the quadriceps with no significant difference between groups. The S group significantly increased biceps brachii CSA where no significant increases were reported for SE and E groups. Whilst this article suggests that a frequency of 1 x / week is not sufficient to stimulate hypertrophy in the elbow flexors, we raise concern about the publication of vague (and consequently impossible to duplicate) training regimes.

Finally Lundberg et al. [92] considered the effects of resistance exercise and aerobic exercise versus just resistance exercise upon hypertrophy of the knee extensors. Each participant performed unilateral leg extension resistance exercise on a flywheel[4] ergometer 2 x / week for weeks 1, 3 and 5, and 3 x / week for weeks 2 and 4 for both limbs. In addition they performed aerobic exercise on a unilateral cycle ergometer 3 x / week for one of the lower body limbs, consisting of 40 minutes continuous cycling at 70% of max wattage (WMax) at a cadence of 60 rpm. After 40 minutes the workload was increased by ~20W and subjects were encouraged to cycle until failure, which occurred within 1-5 minutes. Thus, one leg belonging to each participant performed aerobic exercise and resistance training (AE+RT) or resistance training only (RT). The results reported significant increases within and between legs in quadriceps volume for AE+RT, and RT only (13.6% and 7.8%, respectively). The authors reported a consistent response across all 10 subjects. Whilst the present article is primarily concerned with resistance training recommendations to increase muscular hypertrophy, Lundberg et al.'s [92] findings suggest that preceding exhaustive AE for the quadriceps might further enhance hypertrophy above that of RT alone. Notably participants performing AE were encouraged to cycle until failure as a result of increased resistance, which supports previous evidence that training to muscular failure appears to maximally stimulate muscle fibres for hypertrophic response. Future research might consider this with regard to kayaking, rowing or arm cranking tasks for the upper body.

Summary

The research considered within the present section suggests that volume of training (e.g. the number of sets performed) does not show a relationship to hypertrophic gains. Based on the present evidence discussed and the likelihood that most persons perform multiple exercises that activate the same muscle group, our recommendations are to perform a single set of each exercise to MMF. In addition, the research has supported that persons wishing to include endurance exercise in their training regime can do so without negatively affecting their hypertrophic gains. Further research should consider this area with regard to frequency and rest intervals/days.

Range of Motion, Contraction Types and Resistance Types

Range of Motion

The ACSM [4] failed to discuss range of motion (ROM) in regard to muscular hypertrophy, which might have been a result of a lack of available research. Two studies have been published since the 2009 ACSM recommendations [4] which are discussed herein. Pinto et al. [94] investigated muscular hypertrophy of the elbow flexors for partial and full range of motion (ROM) repetitions for a bilateral bicep 'preacher' curl exercise. Untrained participants were divided in to one of three groups; full ROM (where movement was controlled at 0° to 130° flexion), partial ROM (where movement was controlled as the mid part of the repetition [50-100° flexion]) and a control group who did no exercise. The authors did not mention repetition duration, and as such it is unclear as to whether they controlled for the presumably longer contraction time of a greater ROM repetition against a smaller ROM. Using ultrasound, the authors reported no statistically significant difference between the increases for full and partial ROM muscle thickness (9.5% and 7.4% respectively). It is therefore puzzling that the authors concluded that a full ROM is essential for muscle mass gains, even though their evidence does not support this conclusion. Further evidence to support limited ROM training comes from Eugene-McMahon and Onambélé-Pearson [95] who examined the effects of knee ROM using free weights, resistance machines and bodyweight exercises for the lower body. Participants were randomised to either a partial ROM (full extension to 50° knee flexion), full ROM (full extension to 90° knee flexion), or a non-training control group. Muscle CSA was measured at baseline, 8, 10 and 12 weeks at 25%, 50% and 75% of femur length. Both training groups showed significantly greater CSA at 8 weeks at all sites. For training groups hypertrophy was still significantly greater than baseline at both 10 and 12 weeks at 50% and 75%. No significant changes were found for controls at any time point. Between group

[4] This equipment works on the principle that the concentric movement unwinds a strap and initiates a flywheel. Upon reaching full extension the strap begins to rewind as a product of the kinetic energy of the rotating fly-wheel, thus pulling the lever arm back through the ROM. Participants resist this secondary motion of the lever arm performing an eccentric phase to this exercise. See Norrbrand et al. [93] for further details.

comparisons revealed only one significant difference in favour of the full ROM group for CSA at 75% site at week 8 compared to partial ROM.

Evidently significant hypertrophy occurs using limited ROM resistance exercise; however, there is contrasting evidence as to whether this differs from the improvements induced by full ROM exercise either for muscle thickness or site specific CSA [94,95]. Persons with injuries or diminished ROM might be interested to find that this evidence suggests that partial ROM repetitions can still produce significant hypertrophic gains, with no discernible difference to the gains made from repetitions performed through a full ROM.

Contraction Types

The concept of contraction type is of important consideration with regard to achieving optimal hypertrophic gains. When performing an exercise dependent upon gravity to provide resistance (e.g. a free-weight or traditional weight stack orientated resistance machine) there is a difference in muscle-fiber recruitment and activation in favour of the concentric (CONC) lifting of a weight compared to the eccentric (ECC) lowering of a weight [96]. However, when using flywheel (see previous footnote) or isokinetic equipment the ability to overload the ECC phase by providing a greater load to resist applies a different resistance type. The biomechanical nature of ECC training with an isokinetic dynamometer means that the lever arm is *pulled* away and the participant maximally *resists* that movement. With a traditional resistance machine or free weight the ECC phase is generally the lowering of a load under control, rather than resisting the movement. Of course an advanced technique in resistance training, is to use a supra-maximal load (e.g. >1RM) and perform negative repetitions, where persons might apply force to resist the load, but be performing an ECC repetition since their force production is lower than that of the load. Ultimately this might best be considered in terms of *intent*. An isokinetic ECC muscle action or supra-maximal negative repetition is more like an intended CONC contraction, whereas the ECC phase of a normal repetition is an intended ECC muscle action. In fact, Blazevich et al. [97] stated exactly this in their study of concentric and eccentric muscle actions using isokinetic dynamometry for leg extension exercises; that the ECC group *"maximally extended the knee to resist the downward movement of the lever arm of the dynamometer"*. Indeed, Moore et al. [98] stated that due to the nature of eccentric isokinetic training (e.g. resisting a load by attempting to perform a concentric contraction) there is a greater muscular force than concentric training. With this in mind the present section has divided training with isokinetic, isoinertial and isometric contractions.

Isokinetic

Higbie et al. [99] considered the effects of concentric (CONC) and eccentric (ECC) training of the knee extensors on an isokinetic dynamometer. The authors state that the previous maximal force was displayed on a screen and participants were encouraged to reach or exceed that marker. Post-test MRI revealed significantly greater increases in hypertrophy for the ECC group (6.6%) compared to the CONC group (5.0%). In contrast Blazevich et al. [97] reported no significant differences in hypertrophy between CONC and ECC groups performing an isokinetic knee extension exercise at 30°/s, equating to approximately 3-seconds for each concentric/eccentric muscle action. Finally Farthing and Chilibeck [100] considered the effects of concentric (CONC) and eccentric (ECC) training at two different velocities (180°/s and 30°/s). Participants performed either CONC or ECC training of the elbow flexors on an isokinetic dynamometer. Following a 5-week washout period each participant performed the opposite muscle action type on the opposing arm. Muscle CSA was measured using ultrasound pre- and post- intervention and results showed that ECC fast training caused significantly greater hypertrophy (13 ±2.5%) compared to CONC slow (5.3 ±1.5%), CONC fast (2.6 ±0.7%), and both control group arms. In addition ECC slow training significantly increased CSA (7.8 ±1.3%) compared to both control group arms. Neither fast nor slow concentric training velocities showed any significant increase in CSA when compared to the control group. The high velocity (180°/s) likely equated to higher forces than the slower velocity (30°/s) when resisted. This research suggests that eccentric actions which require high muscular forces might be beneficial in increasing muscular hypertrophy. However, due to the unnatural nature of eccentric training with using isokinetics, as well as the risks associated with supra-maximal loads we should be cautious of inferring practical application from this research.

Isoinertial

Housh et al. [101,102] conducted two separate studies considering the effects of unilateral CONC [101] and ECC [102] training using dynamic constant external resistance (DCER) on the leg extensors. We can consider both studies individually but also in comparison since they utilised the same protocol for testing and training whilst controlling the same independent variables. For CONC training [101], participants trained at 80% 1RM but the repetition duration was not stated by the authors. Muscle CSA of the thigh was measured by MRI where post-test results revealed significant hypertrophy in the training group only. In the second study, considering ECC training [102], the same authors utilised an identical protocol to previously [101], with the only change in variable being the use of ECC training as opposed to CONC training. The lever arm and load was raised manually and then the participant lowered the lever arm for approximately 1-2seconds. Cross-sectional area was measured via MRI, revealing no significant increases in hypertrophy in the training or control groups pre- to post-intervention. In comparison between these studies it appears that the CONC training attained significant hypertrophy where the ECC training did not. However, we should consider that in the CONC training study [101] the repetition duration was not detailed, whilst the 1-2 seconds ECC training [102], whilst prompting significant increases in 1RM, might not be sufficient time-under-tension to promote growth in muscle CSA in the quadriceps. As suggested [96] CONC contractions appear to stimulate higher motor unit activation than ECC muscle actions where loads are equal, suggesting that the ECC group in the study by Housh et al. [102] did not train to the same intensity of effort as the CONC group [101]. Therefore, greater gains in hypertrophy might have been possible if performing ECC training with a greater load, or to a higher intensity of effort.

In consideration of exactly this Smith and Rutherford [103] compared the effects of unilateral CONC versus ECC training of the knee extensors on muscle hypertrophy. The ECC exercise was performed with a load 35% greater than CONC, and both ECC and CONC repetitions were controlled at 3 seconds' duration. Cross sectional area was measured using a CT scan, revealing significant hypertrophy pre- to post-intervention for both ECC and CONC groups (4.0% and 4.6% respectively) with no significant difference between limbs. In contrast Norrbrand et al. [93] reported significantly greater increases for a group training with ECC overload using a flywheel (FW) compared to traditional loading (WS). The FW and WS group performed 4 sets of 7 maximal repetitions in ~3s (FW; 1.5 seconds concentric: 1.5 seconds eccentric, WS; 1 second concentric: 2 seconds eccentric). Muscle volume of the quadriceps was measured using MRI, revealing significant hypertrophy in both WS and FW groups pre- to post- intervention. Whilst the authors suggest a greater increase in hypertrophy for whole quadriceps as a result of FW compared to WS they reported no statistically significant difference between the groups (6.2% vs. 3.0%, respectively). However, results for individual quadriceps muscles revealed significant increases for vastus lateralis (VL), vastus intermedius (VI), vastus medialis (VM) and rectus femoris (RF) for the FW group, as opposed to only RF for the WS group.

Other research with the lower body has been performed by Walker et al. [104] who compared the effects of CONC versus CONC and ECC (CONC + ECC) training on muscle CSA in the gastrocnemius muscle. Participants were randomly assigned to two training groups, and each subject acted as his own control. The CONC group performed 40° of plantar-flexion from an ankle angle of 90°-130° for 2 seconds per repetition with a 2 second rest between repetitions. whilst the CONC + ECC group performed an identical protocol with the addition of a 2 second eccentric phase as opposed to the 2 second rest. Muscle CSA of the gastrocnemius measured by MRI revealed significant increases in the CONC + ECC group only. Research has also considered upper body muscles; Brandenburg and Docherty [105] compared the effects of accentuated eccentric loading on muscle hypertrophy of the elbow flexors and extensors. Trained participants were divided between dynamic constant external resistance (DCER) and dynamic accentuated external resistance (DAER). Participants in both groups performed either 4 sets of 10 repetitions at 75% 1RM (DCER) or 3 sets of 10 repetitions at 75% 1RM for the concentric phase, and 125% concentric 1RM for the eccentric phase (DAER). Repetition duration was controlled at 2 seconds concentric: 2 seconds eccentric for both groups. Muscle CSA was measured pre- and post-intervention using MRI at the mid-point of the humerus. However, results revealed no significant hypertrophy in either flexors or extensors in either DCER or DAER. The authors attributed the lack of significant increases in CSA to the trained status of the participants.

This evidence suggests that both concentric and eccentric muscle actions are required to stimulate muscle hypertrophy. In addition, since muscle fibre recruitment appears diminished in an eccentric compared to concentric action when using the same load [96], this research supports methods which increase the intensity of effort, and thus muscle fibre recruitment, in eccentric phases of a movement (e.g. by increasing repetition duration or load).

Isometric

Finally multiple studies have considered isometric training; Jones and Rutherford [106] compared the effects of concentric (CONC), eccentric (ECC) and isometric (ISO) training of the knee extensors. The ISO group performed 4 second contractions at a knee angle of 90° and a target of 80% MVC. Muscle CSA was measured pre- and post-intervention revealing significant hypertrophy, with no significant differences between training intervention groups. Similar results have been reported for isometric training of the knee extensors by Garfinkel and Cafarelli [107] and Kubo et al. [108]. The training group within Garfinkel and Cafarelli [107] performed thirty unilateral maximal voluntary isometric contractions (MVIC) of the knee extensors. Muscle CSA measured by CT scan showed significant hypertrophy pre- to post-intervention (14.6%). The participants within Kubo et al. [108]

performed two different unilateral isometric knee extension regimes; either 3 sets of 50 repetitions for 1 second contraction and 2 second relaxation (short duration), or 4 sets of a contraction for 20 seconds and relaxation for 1 minute (long duration). Muscle volume was calculated from MRI revealing significant increases in hypertrophy in both legs (short duration = 7.4 ±3.9%, and long duration = 7.6 ±4.3%) with no significant between group differences.

Research also supports the use of isometric training for the upper body. For example Ikai and Fukunaga [109] measured muscle hypertrophy following unilateral isometric training of the elbow flexors (at an angle of 90°). Participants performed 3 x 10 second maximal isometric contractions every day (except Sunday) for 100 days. Ultrasound results revealed significant hypertrophy pre- to post-test, in the trained arm only, at 40 and 100 days ($P < 0.05$ and $P < 0.001$, respectively). Davies et al. [110] also considered the effects of unilateral isometric (IM) elbow flexion, this time at 80% of maximal isometric torque. At 90° of elbow flexion each participant performed 4 sets of 6 IM contractions, with each contraction lasting for 4 seconds. Maximal IM torque was tested each week to accommodate a progressive increase throughout the 6-week programme. Cross-sectional area was measured using CT scan revealing significant hypertrophy in the trained arm only. In addition, and as discussed previously Gondin et al. [64] reported data that suggested that electrically stimulated isometric training of the quadriceps at ~68% MVC is sufficient to stimulate hypertrophic gains.

The research considered herein suggests that muscular hypertrophy can be obtained by concentric [97,101,103] eccentric [93,99,100] and isometric muscle actions [64,106-110]. There appears to be some evidence to suggest greater gains are acquired from the disproportionate loading and contraction type during eccentric muscle actions performed using an isokinetic dynamometer [99,100]. However, other studies have shown no significant difference between constant and negative accentuated resistance [105], and others have suggested no significant difference in the hypertrophic gains achieved from isometric, concentric and eccentric muscle actions [106]. Ultimately it, once again, appears that a muscle action type that maximally recruits motor units and thus muscle fibres appears optimal to stimulate hypertrophic gains whether that be eccentric, concentric, or isometric.

Resistance Types

The evidence presented suggests that hypertrophic gains can be acquired by free-weight [78], traditional accommodating resistance machines [65,66,71,86], flywheel machines [93,111,112], and isokinetic dynamometers [97,100]. However, only one published study has specifically considered the differences in hypertrophy between resistance types. O'Hagan et al. [113] considered the effects an accommodating elbow flexion resistance machine (hydraulic; ARD), and the other arm using a weight resistance machine (designed to the same specification as the ARD but using a cable pulley; WRD). It is worth noting that the ARD group only performed contractions in the CONC phase (each repetition at, or near maximal), whilst the WRD group trained using CONC and ECC muscle actions at 80% 1RM[5]. The ARD group performed CONC contractions on the slowest possible setting, which was replicated on the WRD using a metronome. Interestingly the authors commented that they equated workload in *"units"* [page 1213]. However, if the WRD group truly performed their sets to repetition maximum (RM) then the main consideration is simply that both groups trained to maximal effort; the ARD group performed 10 maximal concentric contractions per set, and the WRD group performed 1 maximal concentric contraction as the final repetition of each set. The use of CT scan revealed significant hypertrophy for both groups post-test. They reported no significant between group difference for biceps CSA, or total flexor CSA; however they did report a significantly greater increase in CSA in the brachialis for the WRD group.

Summary

The evidence suggests that muscular hypertrophy can be obtained through concentric, eccentric and isometric muscle actions, with the most significant variable appearing to be that of intensity of effort and thus muscle fibre recruitment. We suggest that use of an isokinetic dynamometer or resisting supramaximal loads (e.g. >1RM) for eccentric muscle actions provides a significant stimulus for growth. However, we urge caution with regard to the safety implications of using supramaximal loads.

In addition, whilst there is minimal research that has directly compared hypertrophy when training with different resistance types, the evidence presented supports the logical conclusion that a muscle does not know what it contracts against; it simply contracts or relaxes [61]. Therefore, we reiterate earlier comments; that it is the recruitment of motor units and muscle fibres that stimulates muscular growth irrespective of what has caused that recruitment. With this in mind, and until further evidence can suggest to the contrary, there appears no scientific reason for suggesting one resistance type above another, but rather to propose

[5] The authors provide a diagrammatic to show that the WRD group trained at 80% of *"maximal contraction"*, however we should clarify that this is a reference to the load lifted in a single repetition (page 1212; e.g. 1RM), in fact the WRD group trained at 8-12RM which by its definition means that the final repetition was a maximal contraction irrespective of the load being lifted.

that it is the method of training that appears more important. We propose that resistance type should be chosen with the consideration of other variables, e.g. safety, time efficiency, and personal preference.

Non-Uniform Muscle Growth, Contralateral Effects, and Training and Detraining Time-Course

Non-Uniform Muscle Growth

In a review of muscular hypertrophy we should also consider the non-uniform growth of both a single muscle along its length and of individual muscles within a group, as it might be expected by some that they should confer uniform hypertrophy from participation in resistance training. Examination of the research in this area suggests need for a more reserved expectation. For example research has supported non-uniform hypertrophy of the quadriceps muscles as a result of resistance training. Research suggests that lower body exercise stimulates the greatest level of hypertrophic growth at the rectus femoris, with lesser and similar results from the vastus medialis and lateralis and the least hypertrophy at the vastus intermedius [92,111,112,114].

In support of non-uniform growth Abe et al. [115] considered whole body hypertrophy. Three physically active, but untrained, males performed 16 weeks of resistance training, performing squat, knee extension, knee flexion, bench press and lat pull-down exercises for 3 sets of 8-12 repetitions to failure. Total body MRI revealed significant pre- to post- intervention increases in muscle volume, with the most significant hypertrophy occurring at the level of the shoulder, chest, and upper portion of the upper arm (m=26%), followed by the mid-thigh (m=18%) and lower leg (m=9%). Matta et al. [116] considered muscle thickness of the biceps brachii (BB) and triceps brachii (TB) following an upper body resistance training intervention. Muscular hypertrophy was measured using ultrasound at proximal (PS), midsite (MS) and distal (DS) positions of the humerus (50, 60, and 70% distance between the acromion and olecranon, respectively). Results revealed significant hypertrophy for BB at all sites after the training intervention. In addition pre- and post- intervention data revealed significant differences in MT at the PS (~12%) and DS (~5%) ($P < 0.05$). Significant hypertrophy was also seen in the TB pre- to post-intervention at PS, MS, and DS sites. However, there was no significant difference in the proportion of hypertrophy between sites on the TB.

Similar research which has considered the activation of muscles has been performed by Wakahara et al. [117] who considered muscle activation and hypertrophy of the triceps in distal, middle and proximal regions. Acute muscle activation was reported as a product of MRI measurements taken before and after a single workout. The authors suggest that brightness of the agonist muscle in a MRI increases immediately after exercise, which can be quantified as an increase in the transverse relaxation time (T2) of a muscle. The authors suggest this has been related to exercise intensity, number of repetitions and electrical activity. Results showed significantly lower activation in the distal region of the triceps compared to middle and proximal regions. Similarly the chronic increases in muscle CSA was significantly lower in the distal region compared to the middle and proximal regions. In a more recent study the same authors [118] followed a similar research design with supportive results. Once again MRI was used to estimate muscle activation of the triceps brachii using transverse relaxation time of the triceps. Pre- to post-intervention hypertrophy supported that the most significantly activated areas of the muscle result in the greatest hypertrophic change. These authors suggested that the chronic adaptations of muscle hypertrophy are attributable to the acute muscle activation during the exercise. Of course it is logical that to stimulate muscular growth we must activate the motor units and muscle fibres.

In review Hedayatpour and Falla [119] suggest that non-uniform muscular adaptations are a product of the individual muscle fibres' mechanical and directional biology, stating that *'architectural complexity'* along with the *'non-uniform distribution of motor unit activation'* during exercise influence this. In summary, it appears that whilst different exercises might activate different areas of a muscle there is a more complex relationship between motor-unit activation, fibre-recruitment and chronic hypertrophy for specific exercises than the present review can consider.

Contralateral effects

As an adjunct to non-uniform growth it is perhaps worth discussing the concept of contralateral effects of unilateral training, i.e. a growth effect in an untrained limb as a result of training the contralateral limb. In the future section on time-course of training and detraining, we discuss a study by Ivey et al. [120], who presented data that unilateral training of the knee-extensors can produce contralateral effects in males. However, other research has suggested that training unilaterally causes significant hypertrophy in the trained limb only considering the elbow flexors [109], elbow extensors 121] and knee extensors [101,102,111,112,122,123].

Further evidence comes from Ploutz et al. [124] who considered the hypertrophic effects of unilateral knee extension training. Cross-sectional area of the thigh was measured pre- and post-intervention using MRI, with results reporting a significant mean increase in hypertrophy in the trained leg only. The CSA of the untrained leg showed no significant change pre-post-intervention (neither hypertrophy nor atrophy).

Whilst it is not within the scope of this article to consider strength changes as a result of any RT studies, it is perhaps noteworthy that whilst the left quadriceps made greater 1RM strength changes than the right leg (14% vs. 7%), both legs showed a significant increase in 1RM strength pre- post-test, suggesting that there was a strength but not hypertrophic response in the untrained leg. Tesch et al. [112] considered the effects of unilateral unloading with the addition of knee extension resistance exercise over a 5 week period. Muscle volume was measured pre- and post-intervention using MRI, revealing significant hypertrophy in the quadriceps as a result of training. The authors reported significant increases for each quadriceps muscle (VL = 6.2%, VI = 5.3%, VM = 9.3%, and RF = 16.3%) as well as whole quadriceps (7.7%). The other participants who were subject to unilateral unloading without resistance training showed significant reductions in muscle size (VL = -9.3%, VI = -8-8%, VM = -12.1%, RF = 0%, whole quadriceps = -8.8%.

Finally, Hubal et al. [125] considered hypertrophy of males and females performing unilateral biceps and triceps exercise in their non-dominant arm. A large cohort of participants (male=243, female=342) performed biceps preacher curl, biceps concentration curl, standing biceps curl, overhead triceps extension and triceps kickback. Muscle CSA of the elbow flexors was measured pre- and post-intervention using MRI at a site corresponding to the maximum circumference when the elbow was flexed to 90°. Results revealed a significant increase in muscle size for both males (20.4%) and females (17.9%), with a significant difference between groups ($p < 0.001$). No significant increases were seen in the untrained arm in either males or females. Interestingly, due to the large sample size, the authors were able to comment regarding outliers, defined as ±2 SD. They reported that 0.08% of both men ($n = 2$) and women ($n = 3$) were low responders, and that 3% of men ($n = 7$) and 2% of women ($n = 7$) were high responders. Indeed, in Figure. 1 [page 968] the range of percentage increases in CSA change is considerable from -5% to +55%. This shows that inter-individual differences in hypertrophic response to training are substantial.

The evidence generally supports that hypertrophy is not commonplace as a result of contralateral training with the exception of the study by Ivey et al. [120]. Interestingly within their study the authors make clear that *"the untrained leg was kept in a relaxed position throughout the training program… and verified by constant investigator observation"*. In addition whilst the authors do confirm their data in the results section, clarifying that *"the small change seen in untrained limbs in both older and younger men was significant (P < .05)"* they fail to discuss this result at all in the discussion section. As such it is difficult to hypothesise as to why they obtained such abnormal results.

Training and Detraining Time course

For those engaged in resistance training it is of interest to understand how quickly they can expect to begin to acquire hypertrophic adaptations. Similarly, for those presently engaged in resistance training, reasons may arise that may require them to halt their engagement for a period of time, thus leading us to consider to what extent initial adaptations might be maintained or lost. Thus within the present article it seems prudent to discuss expected time-course of muscular growth as a result of resistance training in addition to the expected time-course of muscle response to detraining. For example Seynnes et al. [81] reported significant increases in hypertrophy of the quadriceps muscles (RF, VM, and VL), measured using MRI, after 20 days of resistance training (4 sets of 7 'maximal' repetitions performed on a flywheel bilateral leg extension 3 x / week).

Abe et al. [126] considered the effect of time course and volume of training on whole-body muscular hypertrophy with untrained participants (male=17, female=20), aged 25-50 years. Muscle thickness was measured using ultrasound at the following eight anatomical sites; chest, anterior and posterior upper arm, anterior thigh (30%, 50%, and 70% thigh length from greater trochanter) and posterior thigh (50% and 70% of thigh length) pre- and post-intervention, and at 2 week intervals throughout the 12 weeks. Significant increases occurred in the upper body (males' biceps at 4 weeks, and the males' and females' triceps and chest at 6 weeks, continuing to increase through weeks 8 and 12) and lower body (males' hamstrings muscles; 50% from greater trochanter at 6 weeks, males' and females' hamstrings muscles; 70% from greater trochanter at 6 weeks). Some significant improvements were seen post-intervention compared to weeks 2, 4 and 6 in the upper body. No significant increases in muscle thickness were reported for the quadriceps for males or females. We might consider the motivation of the participants to train to muscular failure, or even consider the potential for low response as a result of genetics as suggested by Hubal et al. [125] as reasons for a lack of hypertrophy.

A more recent study reported that untrained males performing a bench press exercise can significantly ($P = 0.002$) increase muscular hypertrophy of the pectoralis major (PM) after just 1 week of training as measured by ultrasound [82]. Whilst the authors reported PM and TB increases at weeks 1 and 5, respectively; the table shown on page 219 does not provide data for individual weeks, only 3- week intervals. Interestingly from this table we can see that both PM and TB showed significant increases in muscle thickness at week 3, leading us to question why in the results section they state TB increases at week 5. The authors also reported that the pectoralis major showed steady increases in size throughout the duration of the 24-week intervention (weeks 3 and 6 were significantly greater than pre-testing, whilst weeks 9, 12 and 15 were significantly greater than week 6, and week 24 was significantly greater than week 15). Whereas the triceps brachii made early increases in hypertrophy (weeks 3 and 6 were significantly greater than pre-testing, and week 15 was significantly greater than week 6), no significant differences were found when comparing weeks 18, 21 and 24 to week 15. It is perhaps worth noting that participants performed the bench press exercise at 200% of the biacromial distance, which the authors suggest might have resulted in decreased activation of the triceps [127].

In addition multiple studies have considered detraining periods. For example Narici et al. [123] considered hypertrophic changes following 60-days of isokinetic knee extension training, and a 40-day detraining period. Cross sectional area was measured using MRI pre- and post-intervention, revealing significant increases in hypertrophy over the 60 day period (8.5 ±1.4%, equating to approximately 0.14% / day). Similar significant decreases in hypertrophy (0.10% / day) were reported following the 40 day detraining period. In contrast Ivey et al. [120] reported that the significant increases in hypertrophy as a result of 9-weeks of knee extension exercise were still evident after 31 weeks without any additional training, in previously untrained males. However, whilst untrained females also showed a significant increase in muscle volume following the 9-week resistance training intervention the MRI results following detraining suggested that their quadriceps had atrophied to their original size pre-training. A later study by Blazevich et al. [97], reported significant growth following 10 weeks of isokinetic knee extension exercise. In addition, following a further 14 weeks of detraining there was no significant difference in MT between finishing the training intervention and finishing the detraining period. However, data analysis also revealed that there was no statistically significant difference in MT between the starting (pre-training intervention) values, and the values after the detraining period.

Finally Ogasawara et al. published two studies comparing continuous and non-continuous resistance training [128,129]. The earlier study [128] compared two groups, performing either continuous training for 15 weeks (CTR) or a group that trained for 6 weeks, went untrained for 3 weeks, and then retrained for a further 6 weeks (RTR) using free-weight bench press. The initial 6-weeks showed significant increases in hypertrophy of the triceps brachii (TB) and pectoralis major (PM) with no significant difference between CTR and RTR groups. During the 3-week detraining period the RTR group showed no significant atrophy of the TB and PM. Through the final 6 weeks of the intervention the CTR group reported a significantly decreased hypertrophy in the TB and PM when compared to the initial 6 weeks, whereas the RTR group showed no such decrease in rate of growth. At the conclusion of the 15-week intervention there was no significant difference in hypertrophy of the TB and PM between the CTR and RTR groups. In the more recent study Ogaswara et al. [129] again considered TB and PM hypertrophy following a bench press exercise, this time comparing continuous (CTR) and periodized (PTR) training groups. The continuous training group performed the exercise for 24 consecutive weeks, whilst the periodised group performed the exercise for weeks 1-6, 10-15, and 19-24 with 3-week detraining period in between. In the CTR group hypertrophic changes were significantly greater for weeks 1-6, compared to weeks 10-15, and 19-24. However, in the PTR group there was no significant difference in the rate of growth between weeks 1-6, 10-15, and 18-24. When comparing measurements between the groups at week 6, 15 and 24 there were no significant differences for either PM or TB suggesting that any atrophy over the detraining periods was compensated for over the subsequent 6-week training periods.

Summary

The evidence considered within this section suggests that non-uniform muscle growth (in both a single muscle as part of a group, and along the length of a belly of a muscle) is commonplace. We suggest that whilst different exercises/body positions/handgrips might activate different areas of a muscle there is a more complex relationship between motor-unit activation, fibre-recruitment and chronic hypertrophy than the present review can consider. With this in mind our suggestion is to perform a variety of upper and lower body exercises, utilizing divergent grips and body positions (within safe boundaries) to ensure comparable hypertrophy for the entire muscular system.

In addition there appears little evidence to suggest that contralateral hypertrophy can be obtained. Finally, the time course for hypertrophy appears to occur following around 3-4 weeks of resistance training. However, more notably, the time course for muscular atrophy appears to vary considerably between persons. It appears that rest from training or a brief detraining period does not result in significant atrophy and can, in fact, increase hypertrophy when returning to resistance training. This seems logical; that the body does not grow during training, but rather whilst recovering from the training stimulus. Brief periods of excessive training require a similar period of no training to allow the body to recover and prepare for further training sessions. Further research should certainly investigate frequency of training to consider optimal timescale for training and recovery between workouts.

Training status and Genetics

The present article has not considered the disparity in hypertrophy between trained and untrained individuals, primarily because most research studies utilize untrained participants, and due to the vague interpretations of *trained, untrained,* and *recreationally trained*.[6] However, we should also recognize that once a person is in some degree of trained state that their rate of response is likely to diminish. We suggest that future research needs to consider this area in greater detail regarding manipulation of the variables discussed herein. However, we should recognise that within the final section discussing detraining, it appears that lengthy recovery from previous training interventions does not cause significant atrophy and can accommodate substantially greater hypertrophy when returning to training. With this regard our recommendation is to monitor training response, perhaps through the use of a training journal, and provide sufficient variation and rest and recovery to allow muscular hypertrophy to occur.

In addition, and as mentioned in the opening section, we should identify that genetic factors will likely be the most significant variable with regard to hypertrophic response to resistance training, [28,29] though unlike the manipulation of training variables these cannot be manipulated. A previous review considering strength training [61] identified and discussed the generally accepted somatotypes and genotypes that appear to affect responsiveness to training. Indeed, as noted previously Hubal et al. [125] reported that 0.08%, and 3% of his 585 participants were low responders and high responders respectively, causing changes in CSA varying between -5% and +55%. In consideration of this, those engaged in resistance training for hypertrophy should mediate their expectations accordingly, though realise that the potential for positive hypertrophic adaptations is inherent in the vast majority of people yet to varying degrees [125].

A final note on methods of measuring muscular development is that of muscle density as measured using Hounsfield units by CT scan. Previous research has reported an increase in muscle density [130,131] as a result of resistance training, which whilst not a measure of muscle cross sectional area (and as such has not been included within the present article) is a change in muscle architecture. Many persons record increases in muscular strength without change in muscle cross sectional area [e.g. 105]; perhaps the unmeasured muscular density needs to be considered more in future research.

Conclusion

This article presents evidence-based recommendations for persons wishing to increase their muscular size. In summary, the evidence discussed herein leads us to suggest that intensity of effort should be maximal to recruit, and thus stimulate the growth of, as many muscle fibres as possible by training to momentary muscular failure [63-66]. Single sets of exercises appear to attain similar results to multiple sets [84-86,88], and load used and number of repetitions performed seems not to affect hypertrophy where sets are taken to MMF [67-74], whilst repetitions should be performed at a pace that maintains muscular tension [70,71,78]. In addition, long rest intervals appear unnecessary [74,83] and the inclusion of concurrent endurance training appears not to significantly influence the hypertrophic gains of resistance training [89,90,92]. In fact, the addition of high intensity cycling might increase muscular hypertrophy [92]. Neither the type of resistance [65,66,71,78,97,100,111-113], range of motion [94,95] nor muscle action (e.g. concentric, eccentric or isometric; [64,97,103-105,108] seem to influence muscular growth, although evidence suggests the likelihood of non-uniform muscle growth both along the length of a muscle and between individual muscles of a muscle group [92,111,112,114-118]. Exercising a contralateral limb appears not to stimulate hypertrophic gains in an untrained limb, although evidence suggests that it might reduce the rate of atrophy [124,125]. Finally untrained persons appear to be capable of making significant hypertrophic gains within 3 weeks of starting resistance training [81,88] whilst trained persons are encouraged to allow adequate rest (up to ~3 weeks) [122,128,129] between training sessions without fear of atrophy.

Future Research

Interestingly, amid the plethora of studies reviewed there was no research that had compared frequency of training, and/or differing routine types (e.g. whole body and split routine) both of which are likely of considerable interest to both exercise physiologists and lay persons wishing to increase muscularity. Future research should certainly consider these areas, along with those others mentioned herein in similarly well-controlled studies. We reiterate earlier comments about the control and detail of independent variables to ensure that published research provides adequate information, rather than simply the publication of data which, whilst attempting to replicate real-life resistance training programs, lacks sufficient scientific rigour to be replicated or utilised optimally.

[6] The ACSM [4] define novice, intermediate and advanced persons by their duration of training experience (novice being untrained or having not trained for several years, intermediate being individuals with ~6 months RT experience, and advanced being individuals with years of RT experience). However, we suggest that this offers little as to clarify their training status and assumes that persons with a greater duration of RT have acquired greater knowledge, experience and physiological adaptations, which might not necessarily be the case.

Table 1. *Evidence for Resistance Training Recommendations*

Topic	Recommendation	Supporting Articles	Suggestions for Future Research
Intensity of Effort	Persons should aim to recruit as many motor units, and thus muscle fibres, as possible by training until momentary muscular failure.	63-66	Future research should consider the use of advanced training techniques such as drop-sets/ breakdown sets, pre-/post-exhaustion training.
Load and Repetition Range	Persons should self-select a weight and perform repetitions to failure. Evidence suggests this is optimal for maximising hypertrophy.	67-74	
Repetition Duration	Persons should perform contractions at a repetition duration that maintains muscular tension.Performing repetitions too briefly appears to unload the muscle and hinder hypertrophic gain	70, 71, 78-80	
Rest Intervals	Length of rest interval between sets and/ or exercises appears to have no significant effect on hypertrophic gain. Persons should self-select rest intervals based on their available time.	74, 83	
Volume and Frequency	Single set training appears to provide similar hypertrophic gains to multiple set training. Frequency of training should be self-selected as there appears no evidence which can support any recommendation. See also 'Training and detraining Time course'	84-87	Future research should investigate frequency of training, for which there appears no current research, as well as multiple sets with a single exercise compared to single sets with multiple exercises.
Concurrent Resistance and Endurance Training	The participation in traditional endurance exercise does not appear to hinder hypertrophic gains from resistance training.	89, 90, 92	Future research should consider concurrent upper/whole- body aerobic exercise, such as arm--cranking/rowing exercise, combined with resistance training.
Range of Motion (ROM)	Persons can self-select the ROM they exercise through. There appears no evidence to suggest that decreased ROM negatively affects muscular hypertrophy.See also 'Non-Uniform Muscle Growth'	94, 95	Future research should consider other muscles; e.g. lower back, knee flexors, and elbow extensors, as well as other exercises; e.g. squat/leg press, chest press, and shoulder press.
Contraction Types	We recommend that persons should complete a range of concentric, eccentric and isometric muscle actions as part of their resistance training programme. There appears no evidence to suggest that one muscle action type is more favourable than another, but rather intensity of effort of said muscle actions appears to be the most significant variable.	64, 97, 103-105, 108	
Resistance Type	Persons should select resistance type based on personal choice. Evidence appears to suggest hypertrophy is attainable using free-weights, machines or other resistance types. However, studies making direct comparisons are minimal.	65, 66, 71, 78, 97, 100, 111-113	Future research should accurately control for intensity of effort and directly compare body-weight training, free-weights, and different resistance machines to further investigate as to whether one resistance type is more efficacious than another

Non-Uniform Muscle Growth	Persons should perform a variety of exercises/body positions/hand-grips to activate different areas of a muscle in attempt to stimulate hypertrophy. Evidence suggests that non-uniform muscle growth in single muscles within a group, and along the belly of a muscle, is commonplace, and potentially beyond the control of an individual.	92, 111, 112, 114-118
Contralateral Effects	Persons cannot obtain hypertrophic increases by training contralateral muscles. However, doing so might cause a reduction in atrophy of an immobilised limb.	124, 125
Training and Detraining Time--Course	Untrained persons appear able to make hypertrophic increases in around 3 weeks of resistance training.Trained persons performing regular resistance training are encouraged to allow adequate rest between training sessions without fear of atrophy. Brief (~3 weeks) absences from training appear not to cause significant atrophy and potentially promote greater hypertrophy upon return to training.	81, 82, 122, 128, 129

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