Human skeletal muscle-specific hypertrophy with exercise training and aging: a comprehensive review

Caroline S Vincenty, Gilhyeon Yoon, Kaitlyn Rogers, Masatoshi Naruse, Scott Trappe, Todd A Trappe

Human Performance Laboratory, Ball State University, Muncie, IN

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Corresponding Author:

Todd Trappe, PhD
Human Performance Laboratory
Ball State University
Muncie, IN 47306 USA
ttrappe@bsu.edu
+1 765 285-4456

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ABSTRACT

Age-related skeletal muscle atrophy is a muscle group-specific process. Therefore, we were interested in understanding exercise-induced hypertrophy across different muscles in older individuals. This review provides a comprehensive summary of the available information on muscle-specific hypertrophy responses to exercise training with aging (≥60y). In total, 6018 peer-reviewed publications were reviewed for inclusion (e.g., supervised resistance (RE) or aerobic (AE) exercise training; MRI, CT, or ultrasound determined muscle size), resulting in 1417 individuals from 68 studies (RE: n=1254; AE: n=163). Data were divided across age (60-69y, 70-79y, 80-89y, ≥90y) and duration (≤9, 10-14, 15-19, 20-24, ≥25wks), with the majority coming from the sexa- and septuagenarians (n=1335, 94%) and 10-14wks of training (n=806, 57%). The number of muscle groups (RE: 7, AE: 8) and subcomponent muscles (RE: 10, AE: 16) were a low representation of the whole-body musculature, with 79% of the data (n=1113) coming from the quadriceps. The 10-14wk responses showed a range of unique muscle-specific hypertrophy and atrophy (RE: 60-69y: 2-14% across six muscles; 70-79y: 1-12% across nine muscles; AE: 70-79y: -6% to +9% across 22 muscles). The large quadriceps-only resistance exercise training dataset (60-79 yrs) showed that no additional hypertrophy was observed with increased training repetitions (i.e., dose), and that men and women elicited an equivalent hypertrophic training response. The optimal exercise training mode(s) and dose(s) for all of the skeletal muscles of sexa-, septa-, octo-, and nonagenarian women and men is far from being elucidated based on the current scientific literature.

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INTRODUCTION

There is evidence that muscles atrophy at different rates as humans age (1). Considering that exercise has a powerful impact on offsetting or reversing age-related muscle atrophy (2-13), an important follow-on question to these summary findings is whether exercise responsiveness is muscle specific. The answer to this question has implications for exercise protocol development and guidelines for older women and men to attenuate or reverse the decline in aging skeletal muscle health and improve overall quality of life.

There is strong evidence for muscle-specific exercise responsiveness from the literature on human microgravity exposure, where muscle atrophy approaches, and in some cases exceeds, the magnitude observed with aging. For example, muscles of the lower leg are less responsive to an exercise dose compared with muscles of the upper leg (14-17). As a result, muscle-specific approaches to exercise countermeasures are needed to maintain astronaut skeletal muscle health when exposed to the microgravity environment of space (17). There is also evidence from younger adults that different muscles of the body respond differently to exercise at the whole muscle, metabolic, and molecular level (18-21), which is also supported by data from animal investigations (22).

The goal of this review is to provide a comprehensive assessment of the current state of the literature regarding muscle-specific hypertrophy responses to exercise training in older adults. Our focus was the two most common forms of exercise training recommended for aging individuals, resistance exercise and aerobic exercise (23-25). We recognized *a priori* that the majority of the studies in the literature were likely focused on the quadriceps muscle, given its functional importance in older adults and the relative ease of targeting this muscle with common resistance (e.g., knee extension) and aerobic (e.g., cycling) exercise for scientific

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studies (1, 5, 9, 13, 26-32). However, the appropriateness of applying the knowledge obtained from these "quadriceps-only" studies to other muscle groups, in the context of exercise responsiveness in older adults, is unknown. We also considered that the potentially large data set associated with the quadriceps-only studies may provide some additional insight into the responsiveness of aging skeletal muscle to exercise training (e.g., dose-, age-, or sex-specific influences). The expectation is that a more complete understanding of the responsiveness of different muscles across the whole-body musculature will lead to more comprehensive exercise programming recommendations for older adults to counteract age-related atrophy.

LITERATURE REVIEW PARAMETERS AND SUMMARY

To compile the existing literature that had assessed the effect of longitudinal exercise training on muscle-specific cross-sectional area (CSA) or volume in older individuals, a total of 6018 peer-reviewed articles were reviewed. These articles were obtained from PubMed searches performed on or before October 1, 2024, as well as from an exhaustive review of the reference lists of any articles obtained from the PubMed search and any subsequently obtained articles and associated reference lists. The PubMed searches used the following search criteria: ("muscle size" or "muscle mass" or "muscle volume") AND ("training" or "intervention" or "treatment") AND ("old" or "aging" or "older" or "elder" or "elderly") AND ("exercise" or "activity" or "physical activity") AND ("magnetic resonance" or "MRI" or "computed tomography" or "CT" or "ultrasound"). Only articles published in English were included for this review. Articles were included if the study assessed muscle- or muscle group-specific mass in older participants (i.e., 60 years or older) undergoing an exercise intervention. Muscle-specific training responses were quantified through the percent change in muscle size

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(presented numerically in the article, or calculated from the pre and post training data presented numerically in the article) via anatomical CSA, volume, or volume-derived mass that was measured using CT, MR, or ultrasound (US) (33) imaging. Articles that estimated muscle size based on muscle architecture (e.g., “muscle thickness”) or assessed muscle CSA or volume through regional size (e.g., “thigh”) were excluded. Exercise interventions were required to be supervised by research staff and to have employed either traditional resistance training (e.g., free weights or weight stack machines) or aerobic training (e.g., cycling or walking). Articles which made use of high-intensity interval training, elastic resistance bands, and exercise interventions that combined resistance and aerobic exercise within the same training group were excluded. Articles with exercise training interventions coupled with supplement or medication administration were also excluded from this review; however, if a placebo or control exercise training group was included, these articles were considered.

In total, 75 articles were identified to be included in this review, of which 15 had data that were duplicated in multiple papers from the same research team (6, 34-47). Thus, 63 articles with unique data sets were ultimately identified as eligible for this review (3-5, 11, 28-30, 37, 43, 46, 48-100). Some articles included multiple timepoint assessments of muscle size in the same individuals during exercise training. As a result, each different timepoint was considered a “study” to allow for compilation of the data while minimizing the confusion between the article and study nomenclature.

Ultimately, data were compiled from 68 studies with exercise interventions that included 1417 older individuals. Overall summary information from these studies is presented in Figure 1 and Table 1, as well as Supplemental Tables S1 and S2 (https://figshare.com/s/5353d9a331949da610fa). Data were considered based on the type of

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training (resistance or aerobic exercise), duration of training (≤9, 10-14, 15-19, 20-24, and ≥25 weeks), decade of aging (60-69y, 70-79y, 80-89y, ≥90y), sex (men, women, or uncategorized by the original authors), and the specific muscle(s) studied. Training duration ranged from 6-48 weeks for resistance exercise (only two studies exceeded 25 weeks of training: 42 and 48 weeks) and from 6-18 weeks for aerobic exercise. The data were separated into duration and age group categories to minimize any influence that training duration (i.e., dose) and age might have on interpretation of the literature data. The most common duration for both resistance and aerobic exercise training was 10-14 weeks, and the most common age groups studied were the two youngest cohorts (60-69y and 70-79y). As a result, these training and age group categories were the focus of the review because they provided the largest sample sizes in conjunction with the number of muscles studied. The quadriceps femoris was the most common muscle group analyzed for both the resistance and aerobic exercise studies; thus, the literature data were also considered based on the quadriceps-only studies. Most studies of either mode of exercise investigated only one muscle group or subcomponent muscle.

A total of seven muscle groups were investigated across all the resistance exercise training studies: the elbow extensor muscle group (i.e., triceps brachii), the elbow flexor muscle group (i.e., biceps brachii, brachialis), the hip adductors muscle group (i.e., adductor longus, adductor magnus), the hamstrings muscle group (i.e., biceps femoris, semimembranosus, semitendinosus), the upper leg muscle group (i.e., hamstrings, gracilis, sartorius, hip adductors), the quadriceps femoris muscle group (i.e., vastus lateralis, vastus intermedius, vastus medialis, rectus femoris), and the triceps surae muscle group (i.e., gastrocnemius lateral head, gastrocnemius medial head, soleus). A total of eight muscle groups were examined across all the aerobic training studies: an alternate hip adductor muscle group (i.e.,

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adductor longus, adductor magnus, gracilis), the hamstrings muscle group, the upper leg muscle group, the quadriceps femoris muscle group, the anterior tibial muscle group (i.e., tibialis anterior, extensor digitorum longus, extensor hallucis longus), the peroneal muscle group (i.e., peroneus longus, peroneus brevis), the anterior lower leg muscle group (i.e., anterior tibial muscle group, peroneal muscle groups, tibialis posterior, flexor digitorum longus), and the triceps surae muscle group.

Ten subcomponent muscles were analyzed within the resistance exercise training studies that included the adductor longus, the adductor magnus, the vastii muscles both individually (i.e., vastus lateralis, vastus intermedius, vastus medialis) and grouped, the rectus femoris, the gastrocnemius lateral head, the gastrocnemius medial head, and the soleus. Aerobic exercise training studies investigated a total of 16 subcomponent muscles which included the rectus abdominus, the adductor longus, the adductor magnus, the vastii muscles grouped-only, the rectus femoris, the sartorius, the biceps femoris long-head, the biceps femoris short-head, the semimembranosus, the semitendinosus, the gracilis, the gastrocnemius lateral head, the gastrocnemius medial head, the soleus, the flexor digitorum longus, and the tibialis posterior.

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MUSCLE-SPECIFIC HYPERTROPHIC RESPONSE IN OLDER ADULTS

Overall, it appears that different muscles do hypertrophy in a muscle-specific fashion in response to either resistance or aerobic exercise training in older individuals. This muscle-specific conclusion is based primarily on the 60-69y and 70-79y categories and the 10-14 week training duration (Figures 2 and 3, Supplemental Tables S3-S8 (https://figshare.com/s/5353d9a331949da610fa)). These two youngest aging categories represent 94% (n=1335 of 1417) of all studies and 91% (n=734 of 806) of the studies within the 10-14 week duration. In addition, the 10-14 week studies represent 57% (n=806 of 1417) of the studies across all durations, irrespective of age (Figure 1, Supplemental Tables S1 and S2 (https://figshare.com/s/5353d9a331949da610fa)). The general exercise training programs from these 10-14 week studies are presented in Supplemental Tables S9-S11 (https://figshare.com/s/5353d9a331949da610fa). The majority of the resistance exercise training studies utilized training sets to fatigue or to achieve a repetition maximum with linear periodization for training intensity throughout the intervention. Similarly, the majority of the aerobic exercise training studies implemented progressive training intensity based on prescribed heart rate (or heart rate reserve). It can also be concluded that this area of scientific inquiry has been largely overlooked by the peer-reviewed literature, evidenced by the very few muscles of the body studied beyond the quadriceps and its subcomponent muscles, and the dearth of muscle-specific investigations in the 80-89y and ≥90y age groups. While quadriceps studies dominate this literature (79%, n=1113 of 1417), there is no evidence that we are aware of that suggests quadriceps exercise training responses are directly translatable to all muscles. Data from this comprehensive review and other non-aging studies (14-20) support this suggestion.

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The resistance exercise data from the 60-69y group (Figure 2) shows a range of responsiveness from 2% to 14% hypertrophy across six different muscle groups or subcomponent muscles. Similarly, data from the 70-79y group (Figure 2) shows a range of 1% to 12% hypertrophy across nine different muscle groups or subcomponent muscles. Even when looking at the subcomponent muscles within a muscle group, there can be a substantial range in hypertrophy across the muscles (60-69y quadriceps: vastus intermedius: 2%, vastus lateralis: 11%; 70-79y triceps surae: soleus 1%, lateral gastrocnemius: 12%). Thus, in response to chronic exercise loading a muscle group like the triceps surae, one subcomponent muscle may be relatively unresponsive, while another may undergo substantial hypertrophy. The basis for this variation across and within muscles is likely multifactorial, involving elements like: 1) specific muscle loading pattern(s) of the exercise movement and related musculoskeletal mechanics (18, 19, 74, 101-103), 2) underlying fiber-type related contractile, metabolic, and molecular characteristics (18, 20-22, 26, 104-108), and 3) relative daily activity and training status of a muscle (17, 18, 109-112).

Data from the aerobic exercise literature also support the muscle-specificity of the exercise response, but provide an interesting additional consideration (Figure 3). That is, while the literature shows a range of 15% change in muscle size across 22 different muscles (70-79y age group), this range is a result of some of the muscles atrophying in response to exercise, by as much as -6%. Some of the muscles that atrophied were part of muscle groups that were specifically targeted by the exercise (e.g., the rectus femoris of the quadriceps during cycling exercise), while others were part of muscle groups that are known to be less engaged in the exercise (e.g., the calf muscles during cycling exercise (19)). This may be more of a consideration with aerobic exercise due to the associated energy requirements that may lead

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to an unplanned net energy deficit or if aerobic exercise is coupled with a weight reduction goal (43, 113, 114). Thus, muscle-specific assessments are not only useful for understanding the muscles that are targeted to respond positively to an exercise intervention, but may also help elucidate how the body is responding in a way that may be detrimental to other non-targeted muscles.

Unfortunately, the upper body muscle-specific data in the literature are very limited (Table 1 and Figures 2 and 3, as well as Supplemental Tables S4, S5, S7, S8 (https://figshare.com/s/5353d9a331949da610fa)), which in turn provides limited scientific exercise guidance for older individuals regarding a large number of muscles. However, the amount of hypertrophy of the elbow flexors (+14%) and extensors (+7%) following resistance exercise training (60-69y age group, Figure 2) suggests that at least some of the upper body musculature of older individuals is responsive to hypertrophic stimuli. Overall, these summarized exercise response data strongly support the need for a more comprehensive approach to better understand how to appropriately target the large number of different muscles across the body with resistance and aerobic exercise.

INSIGHTS INTO DOSE, AGE, AND SEX-SPECIFIC RESPONSES

We separated the overall data into different training durations and age categories to minimize any potential confounding influence of these parameters on our muscle-specific questions. However, it is not completely clear what influence these parameters actually have on the exercise training response. For example, based on smaller sample size studies there is somewhat conflicting evidence regarding the decline in the hypertrophic response to resistance exercise with advancing age (3, 41, 115, 116). Thus, we leveraged the large

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literature data set on the quadriceps to address non-muscle specific questions related to dose (training duration and total muscle contractions), advancing age (decade of aging over 60y), and sex (men and women) in the context of exercise countermeasures for aging individuals.

Dose. The influence of exercise dose on skeletal muscle hypertrophy was examined using the quadriceps resistance exercise data from the five training durations, as well as within the two durations that had the largest data set. To provide adequate sample size across the five durations (n=970, 44 studies), the 60-69y (n=527) and 70-79y (n=443) age groups were combined, while the two older age groups were excluded (80-89y: n=61, ≥90y: n=21) due to sporadic and limited representation across the durations (Supplemental Table S1 (https://figshare.com/s/5353d9a331949da610fa)). In general, resistance exercise training targeting the quadriceps was completed across a range of durations (6 to 42 weeks) and training volumes (i.e., total repetitions; 384 to 4872). Interestingly, even though there was a general increase in the average total number of repetitions completed with the resistance exercise training across the five durations (≤9wks: 971 reps, 10-14wks: 1703 reps, 15-19wks: 2087 reps, 20-24wks: 3488 reps, ≥25wks: 2520 reps), there was no additional increase in quadriceps hypertrophy beyond what was observed in the shortest duration and the lowest number of repetitions (≤9wks: 9%, 10-14wks: 8%, 15-19wks: 6%, 20-24wks: 7%; ≥25wks: 6%) (Figure 4).

These dose related findings were also supported by the quadriceps resistance exercise data within the relatively narrow training durations of 10-14 weeks (n=553) and 15-19 weeks (n=163) across a wide range of resistance exercise repetitions (10-14wks: 600 to 3492, 15-19wks: 444 to 3588). That is, there was no relationship between the number of repetitions and the amount of quadriceps hypertrophy within either the 10-14 or 15-19 week durations (Figure

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5). We do recognize that not all studies completed the resistance exercise repetitions at the same intensity; however, given the relatively high sample size, repetition range, and studies represented, this likely does not alter the general conclusion. Thus, this summary data from the available scientific literature regarding resistance exercise training responses in older adults suggests that more repetitions and/or longer duration of training does not necessarily provide greater skeletal muscle hypertrophy. While more research is needed in this area (8, 117-120), the available data do suggest a relatively small dose of resistance exercise may provide maximal skeletal muscle hypertrophy, at least with regards to the quadriceps of older adults over 60y.

Decade of Aging. The influence of advancing age (i.e., decade of aging) over the age of 60y was examined with the quadriceps resistance exercise data, within the 10-14 weeks training duration and across the four decades of aging (n=625; 338M, 279W, 8 uncategorized): 60-69y (n=373; 189M, 176W, 8 uncategorized), 70-79y (n=180; 117M, 63W), 80-89y (n=61; 29M, 32W), ≥90y (n=11; 3M, 8W) (Supplemental Table S3 (https://figshare.com/s/5353d9a331949da610fa)). The reduction in sample size by ~50-80% with each advancing decade limit the overall interpretation of the existing body of literature with respect to the whole muscle hypertrophic response with advancing age in men and women. From the available data, it appears all four older age groups were able to mount a significant quadriceps hypertrophic response to resistance exercise training over 10-14 weeks (60-69y: 8%, 70-79y: 6%, 80-89y: 7%, ≥90y: 4%) (Supplemental Table S3 and S9 (https://figshare.com/s/5353d9a331949da610fa)). Interestingly, the nonagenarian response, albeit somewhat lower than the younger age groups, was achieved with only a fraction (~25%) of the repetitions (~36 repetitions per week) compared with the three younger age groups

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(~160 repetitions per week) (Supplemental Table S3 (https://figshare.com/s/5353d9a331949da610fa)). This further highlights the need for a better understanding of the aforementioned effects of dose on aging skeletal muscle responsiveness. It also appears that the sexa-, septua-, and octogenarian individuals had a similar quadriceps hypertrophy responsiveness to resistance exercise training (Supplemental Table S3 (https://figshare.com/s/5353d9a331949da610fa)). While this does not completely fit with previous literature data (3, 41, 115, 116), the sample size of these three groups does suggest a larger study into this question is needed.

Sex. Potential differences in the hypertrophic response to exercise between men and women were examined with the 10-14 week quadriceps resistance exercise data. To provide adequate sample size of both men and women, only the two largest age categories were considered (60-69y: n=287; 153M, 134W; 70-79y: n=171; 110M, 61W). From the available data, there did not appear to be any substantial sex-specific differences with respect to quadriceps hypertrophy following resistance exercise training in the sexagenarians (M: 10%, W: 8%) and septuagenarians (M: 6%, W: 6%). However, data continue to emerge suggesting larger scale, sex-specific investigations are needed (28, 66, 108, 115, 116, 121-129). The lack of sex-specific data for individuals ≥80y in the existing literature support this need.

CONCLUSIONS AND FUTURE DIRECTIONS

From this comprehensive review of the aging and muscle adaptation (i.e., hypertrophy) in response to resistance and aerobic exercise training literature, two overarching conclusions emerge: 1) There have been a large number of aging individuals studied with high-quality medical imaging over the last ~35 years to better understand how exercise can mitigate the

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detrimental aspects of sarcopenia. The majority of the investigations are centered on the quadriceps, but this large amount of useful information also adds to the important body of myocellular literature focused on the quadriceps (vastus lateralis). 2) In the context of understanding the hundreds of skeletal muscles that (likely) undergo sarcopenic changes with aging and alter the quality of life of older individuals, there has been relatively little scientific investigation in this area. A concise summary of the key findings from this literature review is presented in Table 2. In this same table we also provide several key areas of focus for future studies in this area, what could be labeled “a call to action” for scientists in this area of research.

The importance of filling this muscle-specific knowledge gap in the scientific literature relates to understanding and targeting the specific functions and related activities of specific muscles (1). Thus, it is paramount to consider the muscles as they relate to functional tasks such as balance, walking, stair climbing, toileting, lowering and rising to/from a chair, lifting and carrying (e.g., groceries or grandchildren), vacuuming, dressing, laundering clothes, driving, and numerous other activities of daily living. This also translates to hobbies and sport-specific interests of older individuals that contribute to quality of life (126, 127, 130, 131). We recognize that muscle size is not the only indicator of muscle health. However, if investigations are going to expand and encompass nearly all of the muscles of the human body, scientists will have to go beyond the limited number of muscles that are ideally suited for studies of muscle function (i.e., strength, power, endurance) and muscle quality (i.e., strength per unit size), as well as those that can be reasonably accessed with the muscle biopsy procedure for myocellular aging investigations. Thus, muscle-specific health assessment need to be considered that can be employed across a large number of muscles, like MRI or CT

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measures of intra- and inter-cellular adiposity or other approaches that have yet to be defined. Answering questions related to muscle-specific adaptions to exercise training in aging individuals would not only have an impact on the overall health of aging men and women, but it would also likely provide useful information for adults of all ages who would benefit from scientifically-based, regular exercise training.

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SUPPLEMENTAL MATERIALS

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

Conception and design of research: CSV, GY, KR, MN, ST, TAT

Prepared figures: CSV, GY, TAT

Drafted manuscript: CSV, TAT

Edited and revised manuscript: CSV, GY, KR, MN, ST, TAT

Approved final version of manuscript: CSV, GY, KR, MN, ST, TAT

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FIGURE CAPTIONS

Figure 1. Summary data of the resistance and aerobic exercise training studies in the literature that completed muscle size measurements in individuals over the age of 60 years that met the criteria for this review as outlined in the *Literature Review Parameters and Summary* section. M, Men. W, Women. U, Uncategorized (some studies did not specify the breakdown of men and women). [1] Some studies of different durations examined the same muscle group(s) or subcomponent muscle(s); thus, the total number in these columns only reflects unique muscle groups or subcomponent muscles. See article text and Table 1 for description of muscle group and subcomponent muscle specifics. [2] %Total for Quadriceps Only Studies reflects the percentage of the total sample size for that Study Duration. Supporting details are proved in Supplemental Tables S1-S9 (https://figshare.com/s/5353d9a331949da610fa).

Figure 2. Muscle-specific hypertrophy with resistance exercise (10-14 week) in the sexagenarian (n=451) and septuagenarian (n=224) data cohorts (n=675 total). Muscles without a value (bar) were not studied for that age group. See article text and Table 1 for description of muscle group and subcomponent muscle specifics. Supporting details are proved in Supplemental Tables S1, S3-5, S9-S10 (https://figshare.com/s/5353d9a331949da610fa).

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Figure 3. Muscle-specific atrophy or hypertrophy with aerobic exercise (10-14 weeks) in the septuagenarian data cohort (n=59). See article text and Table 1 for description of muscle group and subcomponent muscle specifics. Supporting details are proved in Supplemental Tables S2, S6-8, S11 (https://figshare.com/s/5353d9a331949da610fa).

Figure 4. Quadriceps hypertrophy in response to resistance exercise over the five training durations (bottom) in relation to the average number of repetitions completed during resistance exercise training (top). Muscle hypertrophy did not increase with additional training duration nor number of training repetitions beyond the initial training duration, which contained studies between six and nine weeks and the lowest average number of repetitions. Data represent 970 individuals from the 60-69y (n=527) and 70-79y (n=443) age categories (Supplemental Table S1 (https://figshare.com/s/5353d9a331949da610fa)).

Figure 5. Quadriceps hypertrophy in response to resistance exercise within the 10-14 and 15-19 week training durations in relation to the average number of repetitions completed during resistance exercise training. Muscle hypertrophy did not increase with an additional number of training repetitions within each training duration. Data represent 716 sexa- and septuagenarian individuals from the 10-14 (n=553) and 15-19 (n=163) week training durations (Supplemental Table S1 (https://figshare.com/s/5353d9a331949da610fa)). The dashed and solid lines represent the simple linear regression fit of the data for the two training durations.

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58 Resistance Exercise Training Studies

Study Duration (Weeks)	All Studies								Quadriceps Only Studies					
	Studies	Muscle Groups[1]	Sub-Component Muscles[1]	Sample Size					Studies	Sample Size				
				n	%Total	M	W	U		n	%Total[2]	M	W	U
≤9	6	1	2	76	6%	39	37	0	5	64	84%	32	32	0
10-14	33	6	7	747	60%	407	332	8	29	625	84%	338	279	8
15-19	9	4	5	176	14%	76	70	30	8	163	93%	66	67	30
20-24	8	1	2	166	13%	72	44	50	6	124	75%	45	29	50
≥25	2	1	1	89	7%	49	40	0	1	76	85%	39	37	0
Total	58	7	10	1254	100%	643	523	88	49	1052	-	520	444	88

Resistance Exercise
n=1254 (88%)
51% M, 42% W, 7% U

68 Eligible Exercise Training Studies
n=1417

Aerobic Exercise
n=163 (12%)
36% M, 64% W, 0% U

10 Aerobic Exercise Training Studies

Study Duration (Weeks)	All Studies								Quadriceps Only Studies					
	Studies	Muscle Groups[1]	Sub-Component Muscles[1]	Sample Size					Studies	Sample Size				
				n	%Total	M	W	U		n	%Total[2]	M	W	U
≤9	2	2	1	47	29%	12	35	0	1	15	32%	0	15	0
10-14	5	7	16	59	36%	24	35	0	3	21	36%	6	15	0
15-19	3	2	1	57	35%	22	35	0	2	25	44%	10	15	0
20-24	0	0	0	0	-	0	0	0	0	0	-	0	0	0
≥25	0	0	0	0	-	0	0	0	0	0	-	0	0	0
Total	10	8	16	163	100%	58	105	0	6	61	-	16	45	0

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Figure 2

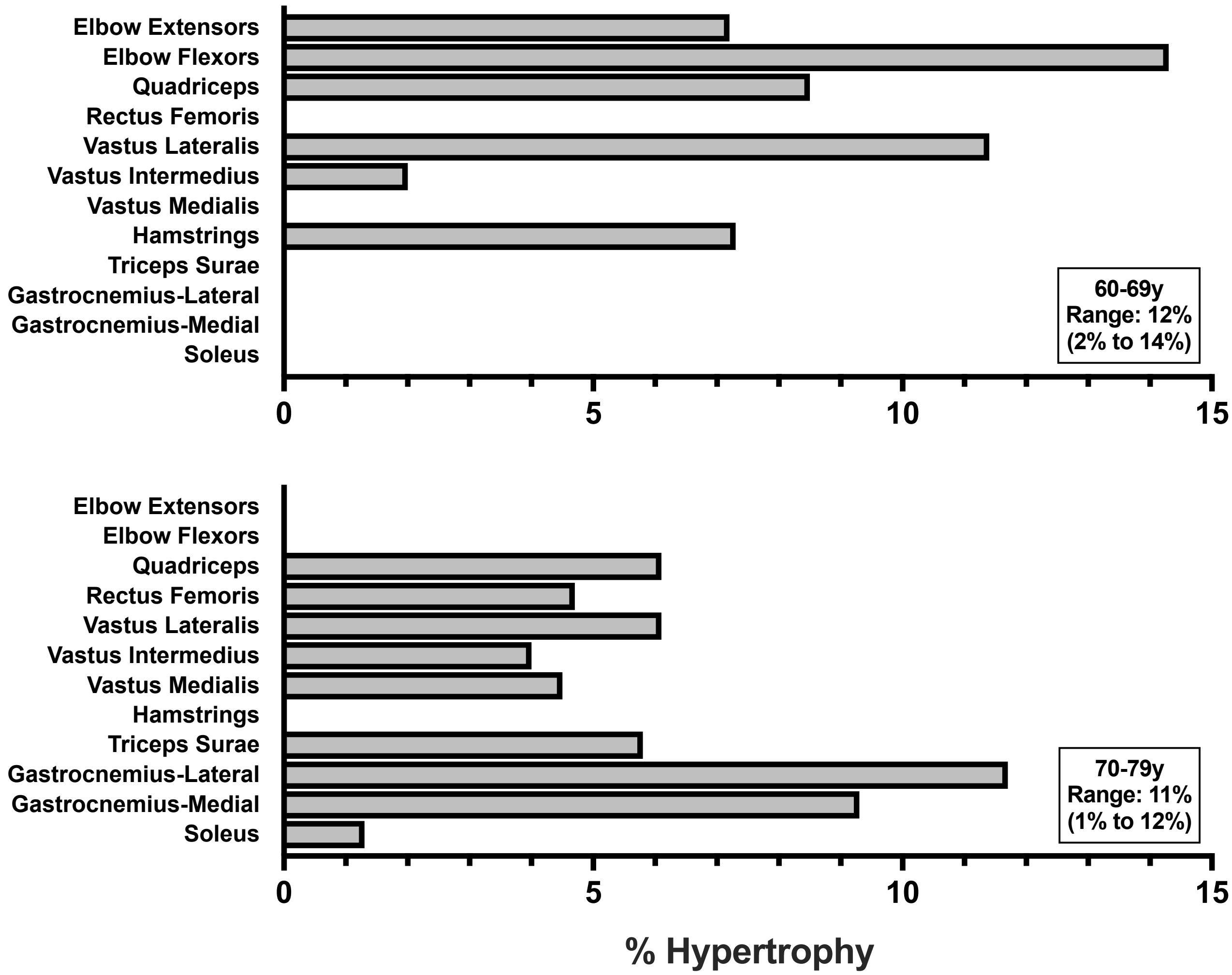

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Figure 3

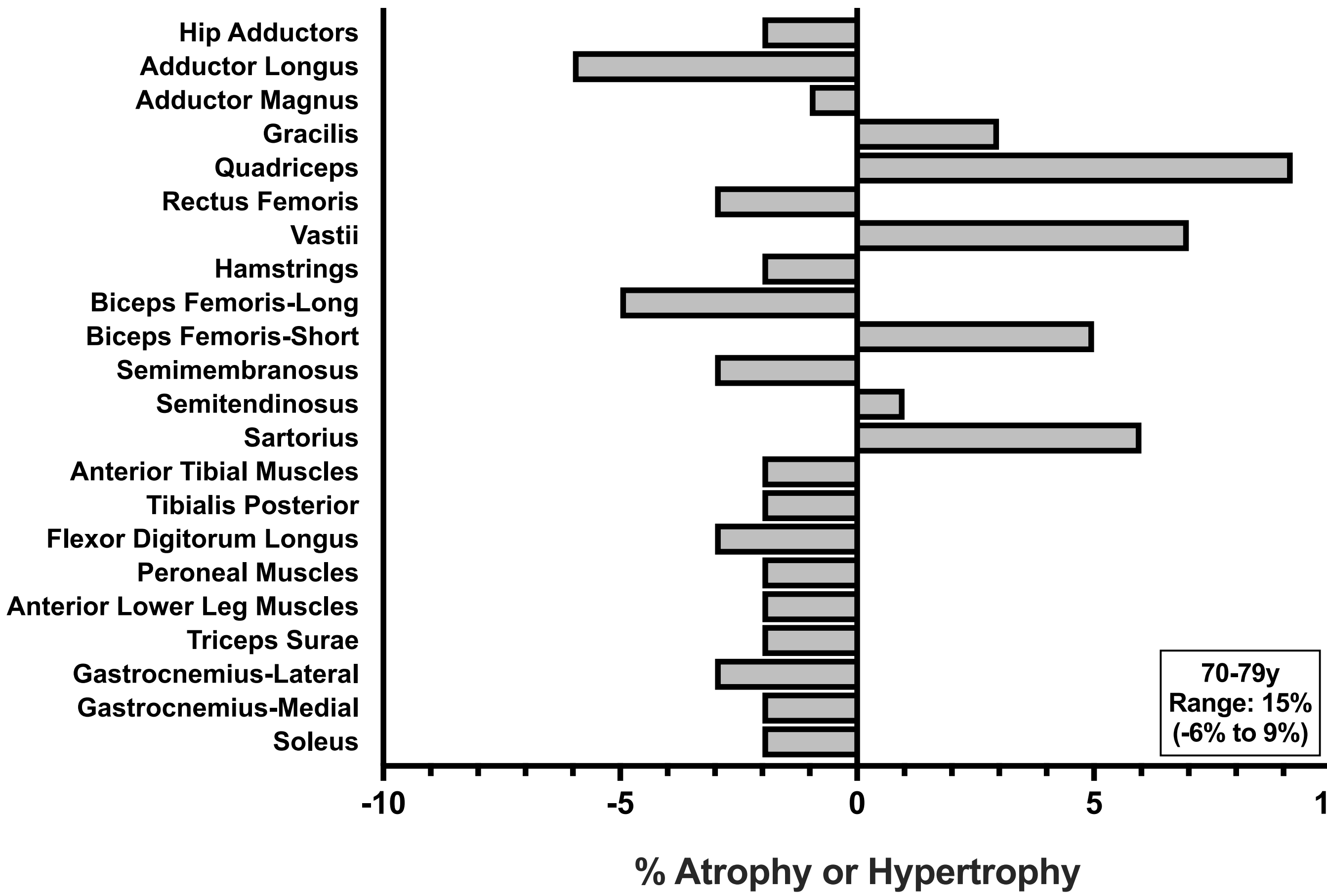

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Figure 4

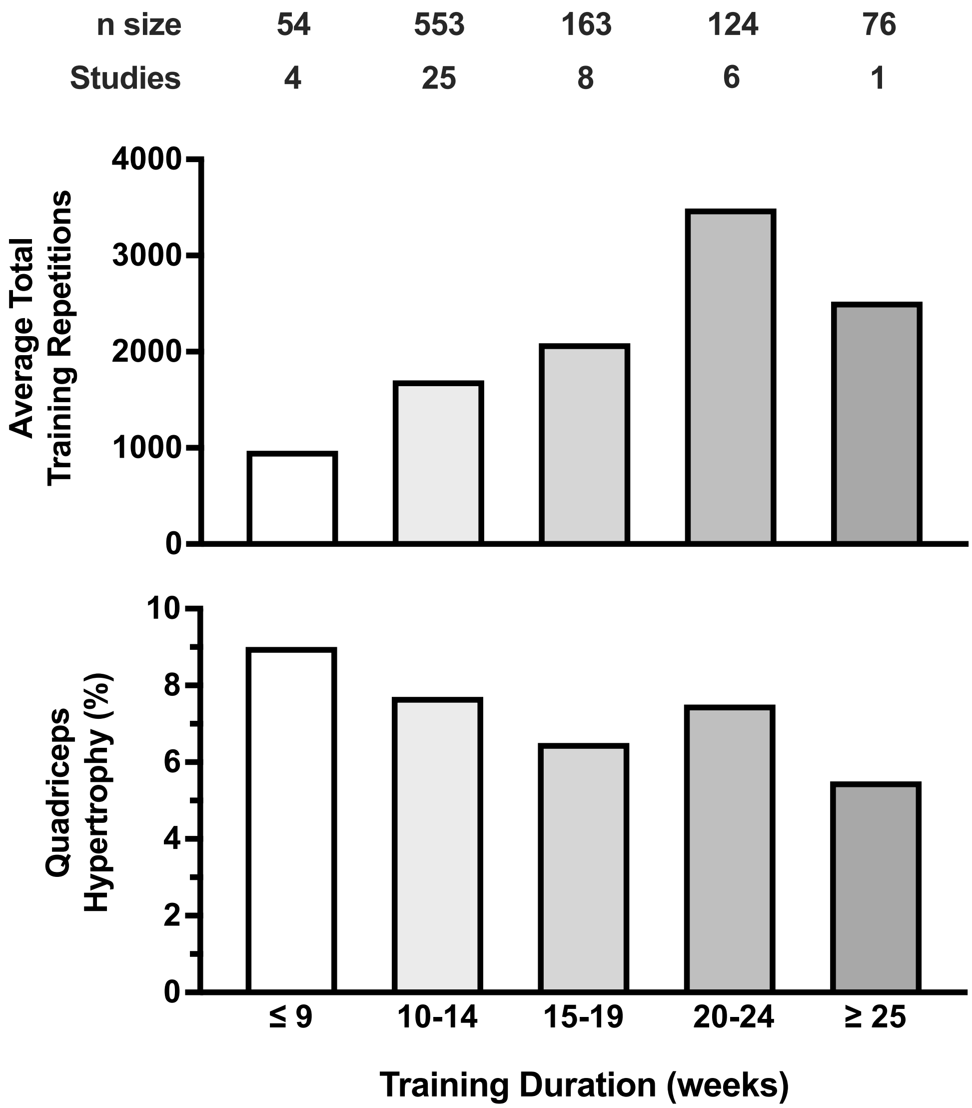

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Figure 5

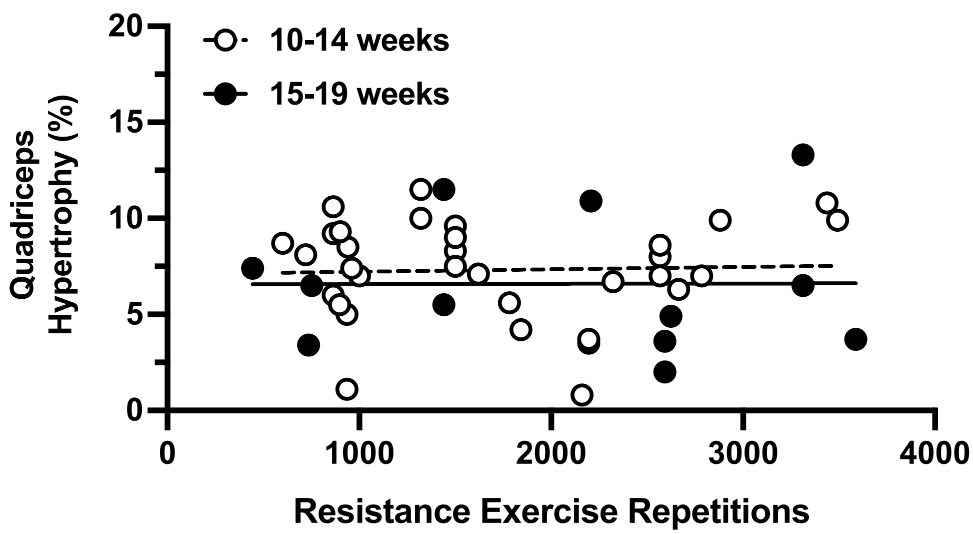

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Table 1. *Muscle summary of studies that completed non-quadriceps muscle group and subcomponent muscle analysis in resistance or aerobic exercise training older adults.*

Exercise Mode	Weeks	Non-Quadriceps Muscle Groups					Subcomponent Muscles				
		Muscle Group	Age	n	M	W	Subcomponent Muscle	Age	n	M	W
Resistance Training	≤9	No studies available	-	0	0	0	Vastus Lateralis (84)	60s & 70s	12	7	5
							Rectus Femoris (84)	60s & 70s	12	7	5
	10-14	Elbow Extensors[1] (11)	60s	14	14	0	Vastus Lateralis (30, 74, 88, 89, 95, 96)	60s & 70s	168	115	53
		Elbow Flexors[2] (11, 59)	60s	22	18	4	Vastus Intermedius (88, 95)	60s & 70s	108	62	46
		Hamstrings[3] (59, 68)	60s	31	12	19	Vastus Medialis (88)	70s	27	27	0
		Triceps Surae[4] (88)	70s	27	27	0	Rectus Femoris (88)	70s	27	27	0
		Hip Adductors[5] (60)	90s	11	3	8	Gastrocnemius – Lateral (88)	70s	27	27	0
							Gastrocnemius – Medial (88)	70s	27	27	0
							Soleus (88)	70s	27	27	0
	15-19	Triceps Surae[4] (64)	60s	16	16	0	Vastus Lateralis (86, 100)	60s & 70s	31	28	3
		Upper Leg Muscle Group[6] (57)	70s	12	0	12	Adductor Longus (81)	70s	37	0	37
		Hamstrings[3] (57, 81)	70s	49	0	49	Adductor Magus (81)	70s	37	0	37
							Vastii[11] (86)	70s	18	18	0
							Rectus Femoris (86)	70s	18	18	0
	20-24	No studies available	-	0	0	0	Vastii[11] (91)	60s	15	0	15
							Vastus Lateralis (97)	60s	27	27	0
	≥25	No studies available	-	0	0	0	Vastus Lateralis (100)	60s	13	10	3
Aerobic Training	≤9	No studies available	-	0	0	0	Rectus Abdominus (92)	60s	32	12	20
	10-14	Hip Adductors[7] (43)	70s	6	6	0	Rectus Abdominus (92)	60s	32	12	20
		Hamstrings[3] (43)	70s	6	6	0	Adductor Longus (43)	70s	6	6	0
		Anterior Tibial Muscles[8] (43)	70s	6	6	0	Adductor Magnus (43)	70s	6	6	0
		Peroneal Muscles[9] (43)	70s	6	6	0	Vastii[11] (43)	70s	6	6	0
		Anterior Lower Leg Muscles[10] (43)	70s	6	6	0	Rectus Femoris (43)	70s	6	6	0
		Triceps Surae[4] (43)	70s	6	6	0	Sartorius (43)	70s	6	6	0
							Biceps Femoris – Long (43)	70s	6	6	0
							Biceps Femoris – Short (43)	70s	6	6	0
							Semimembranosus (43)	70s	6	6	0
							Semitendinosus (43)	70s	6	6	0
							Gracilis (43)	70s	6	6	0
							Flexor Digitorum Longus (43)	70s	6	6	0
							Tibialis Posterior (43)	70s	6	6	0
							Gastrocnemius – Lateral (43)	70s	6	6	0
							Gastrocnemius – Medial (43)	70s	6	6	0
							Soleus (43)	70s	6	6	0
	15-19	Hamstrings[3] (57)	70s	21	6	15	Rectus Abdominus (92)	60s	32	12	20
		Upper Leg Muscle Group[6] (57)	70s	15	0	15					
	20-24	No studies available	-	0	0	0	No studies available	-	0	0	0
	≥25	No studies available	-	0	0	0	No studies available	-	0	0	0

Studies were categorized into an age group (60s=60-69y, 70s=70-79y, 80s=80-89y, 90s=90y or more) based on the mean age (y). M, Men; W, Women; [1] triceps brachii; [2] biceps brachii, brachialis; [3] biceps femoris, semimembranosus, semitendinosus; [4] gastrocnemius lateral head, gastrocnemius medial head, soleus; [5] adductor longus, adductor magnus; [6] hamstrings, gracilis, sartorius, hip adductors; [7] hip adductors, gracilis; [8] tibialis anterior, extensor digitorum longus, extensor hallucis longus; [9] peroneus longus, peroneus brevis; [10] anterior tibial muscles, peroneal muscles, tibialis posterior, flexor digitorum longus; [11] vastus lateralis, vastus intermedius, vastus medialis.

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Table 2. *Key literature summary points and future studies considerations.*

Key Literature Summary Points

1. The aging exercise training and muscle-specific size adaptations literature (1417 subjects, ≥60y) is heavily focused on: a) the quadriceps (~80% of subjects) and lower body muscles (>97% of subjects), b) resistance exercise (~90% of subjects), c) sexa- and septuagenarians (>90% of subjects), and d) training durations of 10-19 weeks (~75% of subjects; 57% for 10-14 weeks).
2. Less than 20% of the human skeletal muscles have been examined, but the existing data strongly suggest a muscle-specific responsiveness to resistance and aerobic exercise in older adults.
3. Muscle-specific exercise responsiveness even occurs within the subcomponent muscles of a muscle group (e.g., the four muscles of the quadriceps or the three muscles of the triceps surae).
4. Quadriceps-only exercise findings likely do not directly translate to all human skeletal muscles.
5. Skeletal muscle daily activity may play a role in muscle-specific responsiveness (e.g. one of the most active muscles on a daily basis, the soleus, was the least responsive to resistance exercise training).
6. Within the large quadriceps resistance exercise training dataset (60-79y): a) hypertrophy did not increase with increased repetitions (i.e., dose), b) men and women had an equivalent hypertrophic response.
7. The optimal exercise training mode(s) and dose(s) for all of the skeletal muscles of sexa-, septa-, octo-, and nonagenarian men and women is far from being elucidated based on the current scientific literature.

Future Muscle-Specific Aging and Exercise Studies Considerations

1. Studies need to include many more muscle groups and subcomponent muscles, including those not-targeted by specific exercise training movements.
2. Studies need to focus on aspects of muscle health in addition to muscle size, while also allowing for muscle-specific measurements across a large number of muscles.
3. Studies need to examine muscle-specific exercise dose. This includes muscle-specific loading within a given exercise movement, training duration, and factoring in overall muscle-specific daily activity.
4. More studies of octo- and nonagenarians are needed.
5. More studies that examine sex-specific responses are needed.
6. Studies need to consider nutritional aspects (e.g., macronutrient levels, energy deficit/surplus).
7. Studies need to consider muscle-specific health as it relates to daily function and quality of life.

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Human skeletal muscle-specific hypertrophy with exercise training and aging: a comprehensive review

Literature Review

58 Resistance Exercise Training Studies

Study Duration (Weeks)	All Studies								Quadriceps Only Studies					
	Studies	Muscle Groups[1]	Sub-Component Muscles[1]	Sample Size					Studies	Sample Size				
				n	%Total	M	W	U		n	%Total[2]	M	W	U
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	Studies	Muscle Groups[1]	Sub-Component Muscles[1]	Sample Size					Studies	Sample Size				
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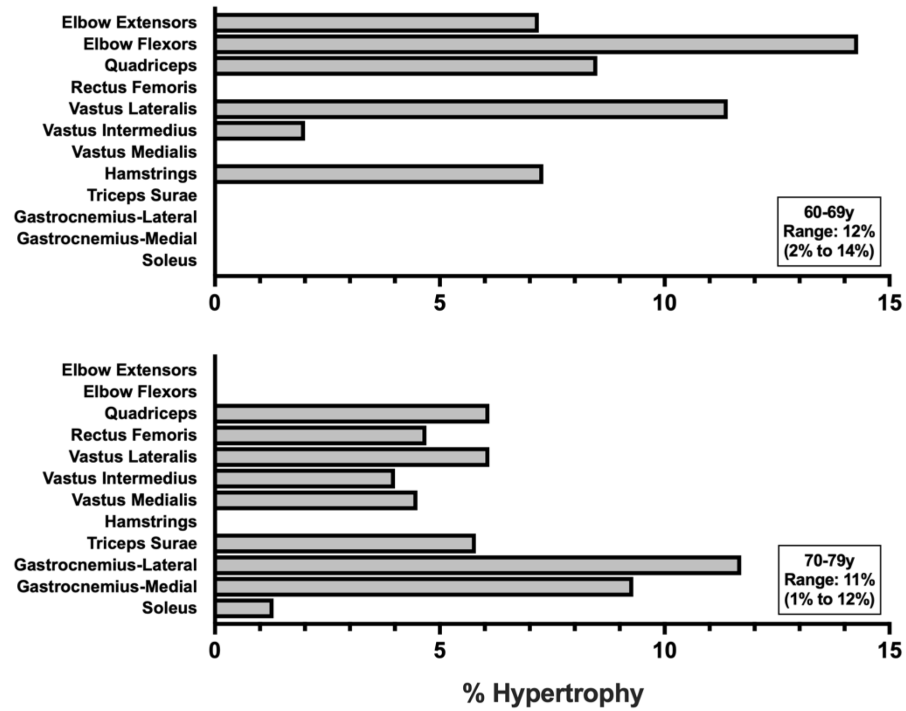
≤9	2	2	1	47	29%	12	35	0	1	15	32%	0	15	0
10-14	5	7	16	59	36%	24	35	0	3	21	36%	6	15	0
15-19	3	2	1	57	35%	22	35	0	2	25	44%	10	15	0
20-24	0	0	0	0	-	0	0	0	0	0	-	0	0	0
≥25	0	0	0	0	-	0	0	0	0	0	-	0	0	0
Total	10	8	16	163	100%	58	105	0	6	61	-	16	45	0

The aging exercise training and muscle-specific size adaptations literature (n=1417, ≥60y; Men (M), Women (W), Uncategorized (U)) is heavily focused on: a) the quadriceps (~80% of subjects) and lower body muscles (>97% of subjects), b) resistance exercise (~90% of subjects), c) sexa- and septuagenarians (>90% of subjects), and d) training durations of 10-19 wks (~75% of subjects; 57% for 10-14 wks).



Muscle-specific hypertrophy following 10-14 weeks of resistance exercise training in the sexagenarian (n=451) and septuagenarian (n=224) data cohorts (n=675 total). Muscles without a value (bar) were not studied for that age group.

Summary

- Less than 20% of the human skeletal muscles have been examined, but the existing data strongly suggest a muscle-specific responsiveness to resistance and aerobic exercise in older adults.
- The optimal exercise training mode(s) and dose(s) for all of the skeletal muscles of sexa-, septa-, octo-, and nonagenarian men and women is far from being elucidated based on the current scientific literature.

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