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Does habitual dietary intake influence myofiber hypertrophy in response to resistance training? A cluster analysis

Anna E. Thalacker-Mercer,
UAB Departments of Physiology and Biophysics and Nutrition Sciences, 1530 3rd Ave S., Birmingham, AL 35294-0005

John K. Petrella[2], and
UAB Department of Physiology and Biophysics, 1530 3rd Ave S., Birmingham, AL 35294-0005

Marcas M. Bamman[1]
UAB Departments of Physiology and Biophysics and Nutrition Sciences and Geriatric Research, Education, and Clinical Center, Birmingham Veterans Affairs Medical Center, 1530 3rd Ave S., Birmingham, AL 35294-0005

Anna E. Thalacker-Mercer: athalack@uab.edu; John K. Petrella: jkpetrel@samford.edu; Marcas M. Bamman: mbamman@uab.edu

Abstract

While resistance exercise training (RT) is a common intervention to stimulate muscle protein synthesis and increase skeletal muscle mass, the optimal daily protein and total energy intakes to support RT-mediated muscle growth are yet unclear. Further, the efficacy of RT varies widely among adults of all ages but whether this is attributable to inter-individual differences in nutrition is not known. To determine if self-selected daily intake of macronutrients and specific components of dietary protein and fat are predictive of the magnitude of RT-mediated muscle growth, detailed 4-d dietary records were analyzed on 60 subjects previously clustered (K-means cluster analysis) as non-, modest-, and extreme-responders (Non, n=16; Mod, n=29; Xtr, n=15) based on the magnitudes of change in vastus lateralis myofiber cross-sectional area (CSA) following 16-wk, 3-d/wk, high-intensity RT. Despite the marked contrast between 60% myofiber hypertrophy in Xtr and zero growth in Non, we found no differences among response clusters in daily intakes of energy (Mean ± SEM: Non 102 ± 8; Mod 111 ± 6; Xtr 109 ± 5 $kJ \cdot kg^{-1} \cdot d^{-1}$), protein (Non 0.97 ± 0.08; Mod 1.07 ± 0.07; Xtr 1.05 ± 0.06 $g \cdot kg^{-1} \cdot d^{-1}$), carbohydrate (Non 3.02 ± 0.24; Mod 3.18 ± 0.20; Xtr 3.14 ± 0.17 $g \cdot kg^{-1} \cdot d^{-1}$), and fat (Non 0.95 ± 0.09; Mod 1.05 ± 0.08; Xtr 1.03 ± 0.08 $g \cdot kg^{-1} \cdot d^{-1}$), which generally met or exceeded dietary recommendations. There were no cluster differences in intakes of BCAA known to stimulate muscle protein synthesis. Using the novel K-means clustering approach, we conclude from this preliminary study: 1) protein and energy intakes were sufficient to facilitate modest and extreme muscle growth during RT; and 2) intrinsic or extrinsic factors other than nutrient ingestion apparently impaired the anabolic response in Non.

Keywords

diet; amino acids; exercise; muscle hypertrophy

[1]Address all correspondence to M.M. Bamman, UAB Dept. of Physiology and Biophysics, 1530 3rd Ave S., Birmingham, AL 35294-0005; tele: 205.996.7937; fax: 205.996.9286; mbamman@uab.edu.
[2]Current affiliation: Samford University Department of Exercise Science and Sports Medicine, 800 Lakeshore Dr., Birmingham, AL 35229-2244; jkpetrel@samford.edu

Introduction

Resistance exercise training (RT) induces skeletal muscle hypertrophy and increases strength, power, and quality in younger and older adults and has been identified as the most promising method to regenerate and re-grow muscle in populations suffering from atrophy such as aging adults (Fiatarone et al. 1990; Brown et al. 1990; Frontera et al. 1988). The degree of reported variation in skeletal muscle hypertrophy in response to RT has been large (Kosek et al. 2006; Petrella et al. 2006; Cribb et al. 2007). Inter-individual variation could be a product of not only intrinsic factors (e.g., autocrine growth factors and transcription factors (Bamman et al. 2007; Kim et al. 2007a)), but also extrinsic factors, such as daily dietary intake.

The quantities of daily protein and total energy intakes which are sufficient to support RT-mediated muscle growth are as yet unclear. Acute response studies involving a single resistance exercise bout, with or without nutrient ingestion, indicate that protein or amino acid ingestion augments the post-exercise anabolic response (Biolo et al. 1997; Tipton et al. 2004), which could theoretically lead to greater gains in skeletal muscle mass over an extended period of RT. However, findings regarding the impact of dietary intake on long-term RT-mediated skeletal muscle growth are equivocal. Some studies suggest that higher daily intakes of dietary protein and essential amino acids (EAA) enhance the magnitude of skeletal muscle hypertrophy and gains of lean body mass (LBM) during RT (Cribb et al. 2007; Campbell et al. 1999). By contrast, others report that muscle mass or LBM gain during long-term RT was not enhanced by higher quantities (e.g., 1.6 $g \cdot kg^{-1} \cdot d^{-1}$) and source (e.g., animal vs. vegetable protein) of dietary protein (Andrews et al. 2006; Campbell et al. 1995; Haub et al. 2002).

These equivocal findings call into question whether daily consumption of protein drives the anabolic response to RT in a dose-dependent manner. As suggested by some published results (Andrews et al. 2006; Campbell et al. 1995; Haub et al. 2002), the quantity of dietary protein to support muscle growth during RT may need not be excessive if recommended daily needs are met; however, this has yet to be tested in humans across a wide range of RT “responsiveness”. Nitrogen balance studies demonstrate that resistance exercise does not increase the need for dietary protein but in fact improves utilization of protein which may actually lower the protein requirement during training (Hartman et al. 2006; Moore et al. 2007). Further, it is unclear whether the magnitude of RT-mediated skeletal muscle hypertrophy is affected by constituents of daily dietary intake in addition to protein.

Typically, investigators apply a stimulus to initiate the hypertrophic response and then determine the magnitude of change in the muscle to test stimulus efficacy. Post hoc cluster analysis is unique in that it clusters subjects based on each individual’s magnitude of change in skeletal muscle fiber size in response to RT, enabling investigators to then identify what factors may have caused these differential responses. Given the constraints inherent in human research models, cluster analysis offers an attractive alternative to models only possible in lower animals (e.g., genetic manipulations). The purpose of this study was therefore to determine whether differences in myofiber hypertrophy among response clusters following 16 wk of RT may have been driven, at least in part, by differences in the constituents of daily dietary intake (e.g., energy, macronutrients, amino acids). We tested the hypothesis that differences in daily ingestion of key nutrients would be found between subjects failing to experience muscle hypertrophy (non-responders, Non) and those responding with modest (Mod) or extreme (Xtr) muscle growth.

Methods

Subjects

Sixty-six untrained healthy men (n=35) and women (n=31) recruited from the Birmingham, Alabama metropolitan area completed a 16-wk RT program. Subjects were recruited in two age ranges: 20–35 yr (16 women, 21 men) and 60–75 yr (15 women, 14 men). All subjects completed health history and physical activity questionnaires. Older adults passed a comprehensive physical exam conducted by a geriatrician and a diagnostic, graded exercise stress test with 12-lead ECG reviewed by a cardiologist. Of the 66 participants (described in (Bamman et al. 2007)), 60 (32 men, 28 women) completed 4-day dietary records and were therefore studied herein. Subjects were excluded for any musculoskeletal or other disorders that might have affected their ability to complete RT and testing for the study; obesity (BMI > 30.0 kg/m^2); knee extensor RT within the past 5 yr; and for treatment with exogenous testosterone or other pharmacological interventions known to influence muscle mass. The study was approved by the Institutional Review Boards of both the University of Alabama at Birmingham (UAB) and the Birmingham Veterans Affairs Medical Center. All subjects provided written informed consent before participating.

Post hoc K-means cluster analysis was performed to classify subjects (independent of sex and age) into one of three response clusters based on the magnitude of change in mean vastus lateralis myofiber cross-sectional area (CSA, μm^2) in response to 16 wk of RT as described (Bamman et al. 2007). K-means cluster analysis identifies a defined number of clusters based on the similarity of a chosen trait (e.g., change in myofiber CSA); the number of cases (e.g., subjects) assigned to a cluster is not pre-determined. The analysis resulted in the following three clusters (mean ± SD myofiber CSA change): non- (Non, −16 ± 99 μm^2), modest (Mod, +1111 ± 46 μm^2), and extreme (Xtr, +2475 ± 140 μm^2) responders. The composition and phenotypic traits of the three clusters have been detailed elsewhere (Bamman et al. 2007). The current report includes dietary analysis on 16 Non (9 women [4 young, 5 old] and 7 men [1 young, 6 old]), 29 Mod (15 women [8 young, 7 old], 14 men [8 young, 6 old]), and 15 Xtr (4 women [2 young, 2 old], 11 men [9 young, 2 old]). Training intensity, training volume, and adherence (~90%) to the exercise protocol did not differ among the three response clusters, as detailed previously (Bamman et al. 2007).

Progressive resistance training program

All subjects completed a 16-wk, 3-d/wk RT protocol. The resistance exercise and warm-up protocols have been described previously (Bamman et al. 2007; Kim et al. 2007a). Briefly, resistance training sessions were performed three days per week and involved three lower body exercises (knee extension, leg press, and squat). Each exercise was performed for three sets to volitional fatigue (8–12 repetitions) using resistance exercise stations or plate-loaded stations. Training loads were initially based on 80% of baseline one repetition maximum (1RM) strength and loads were increased incrementally throughout the study to maintain the repetition range as strength levels improved.

Dietary assessment

Prior to beginning the RT program, subjects were required to meet with the GCRC Head Dietician to learn how to complete accurate 4-day dietary records. Subjects were informed to consume ad libitum and to maintain a fairly consistent intake throughout the study. All subjects were encouraged not to restrict intake for any period of time during the 16 wk RT program. Of 66 adults who completed the RT program, 60 adults (Non, n=16; Mod, n=29; and Xtr, n=15) satisfactorily completed a minimum of one continuous 4-d dietary food record at baseline, mid-study, and/or wk 16 of the study (i.e., complete records of all meals and beverages consumed in the course of 4 consecutive days). Each 4-day dietary record

was collected across two weekend days and two weekdays in succession to account for any weekend changes in dietary habits. A single 4-day food record that includes both weekend days and weekdays is a well-accepted tool, although under-reporting is a known limitation of all self-report tools (Hill and Davies 2001). In most cases (46 of 60 participants), subjects completed records both before and after the training period. There were no changes in energy or macronutrient intakes from wk 0 to wk 16 of training among the response clusters in the 46 subjects (i.e., there was no time-by-cluster interaction). If more than one 4-d food record was collected for a subject, the data for the food records were combined and averaged. Self-selected and reported total energy, macronutrient, micronutrient, and amino acid intakes were determined using Nutrition Data Systems for Research (NDSR software v5.0, Minneapolis, MN, United States). While different dietitians entered the records into the NDSR over the course of the study, standards for foods and beverages were established for consistency among dietitians.

Body composition

Lean mass, fat mass, and thigh lean mass were determined by dual-energy x-ray absorptiometry (DEXA, Lunar Prodigy, GE Lunar Corporation, Madison, WI, USA) at baseline and after 16 wk of thigh RT. DEXA scans were analyzed by a single technician prior to each individual's cluster assignment using enCORE software (version 6.10.029) as described (Bamman et al. 2004).

Muscle biopsy and myofiber size assessment

Percutaneous needle biopsies of the vastus lateralis were taken with a 5-mm Bergstrom biopsy needle under suction (Evans et al. 1982; Chakravarthy et al. 2000). For the cluster analysis based on change in mean myofiber area, biopsies were collected prior to training and 24 h after the final training session 16 wk later. Each biopsy was blotted with gauze and dissected to remove any visible connective and/or adipose tissue. A portion of the muscle sample was mounted cross-sectionally on cork in OCT mounting medium mixed with tragacanth gum and frozen in liquid nitrogen-cooled isopentane for immunohistochemistry. All samples were stored at −80°C. We routinely assess myofiber type distribution (I, IIa, IIx) and type-specific myofiber size via myosin heavy chain (MHC) isoform immunofluorescence microscopy and have published these methods in detail elsewhere (Kosek et al. 2006; Kim et al. 2005). Images were analyzed by a single technician blinded to age, sex, and timepoint (pre- or post-training) of each specimen. Mean myofiber size was determined as a weighted average based on distribution and size of type I, IIa, and IIx myofibers before and after training. Myofiber type distribution was determined from 1009 ± 39 and 851 ± 38 myofibers per specimen pre- and post-training, respectively.

Statistical analysis

Data are reported as means ± SEM. K-means cluster analysis to classify subjects into one of the three responder groups was performed previously (Bamman et al. 2007) using STATISTICA 6.0. A 3 × 2 repeated measures ANOVA was used to determine differences in body composition among the three response clusters (Non, Mod, and Xtr) across time (baseline and 16 wk). Differences in reported daily dietary intake among the three response clusters were assessed using a one-way ANOVA. When significant main effects or interactions were found, Tukey's honestly significant difference tests were performed post hoc. Linear regression analysis was run to determine if there were associations between the response clusters and components of dietary intake. Statistical significance was accepted at $P<0.05$ for all tests.

Results

Subject Characteristics and Body Composition

The average bodyweight of subjects did not change across 16 wk of RT in any of the clusters (Table 1), suggesting the subjects were consuming weight maintenance diets. There were no differences among the clusters at baseline for lean mass, thigh lean mass, or fat mass. DEXA findings regarding changes in lean mass compartments were in agreement with the cluster assignments based on vastus lateralis myofiber hypertrophy (i.e., there was an increase in lean mass in both the Mod and Xtr following 16-wk RT). A main time effect ($P<0.001$) and cluster × time interaction ($P<0.05$) were found for total body lean mass, which increased overall. Post hoc testing localized this to within-groups increases ($P<0.005$) among Mod (916 g) and Xtr (1,528 g) with no change in Non after 16 wk of training, which drove the significant interaction. As the training regimen focused on knee and hip extensor muscle groups, the majority of the lean mass increases were in the thigh compartment. A main time effect ($P<0.001$) and cluster × time interaction ($P<0.005$) were found for thigh lean mass. Again, the effects were driven by significant increases ($P<0.001$) within Mod (533 g) and Xtr (1129 g) with no changes in Non. There were no changes in fat mass within or among the response clusters from baseline to wk 16 of RT. Average fat mass and percent fat mass decreased from baseline to wk 16 ($P<0.001$) for all subjects combined.

Diet Analysis

Average daily dietary intake by cluster is summarized in Table 2. There were no differences among the three response clusters in average daily consumption of energy (total and on a $kJ \cdot kg^{-1} \cdot d^{-1}$), protein, animal protein, vegetable protein, essential amino acids (EAA), branched chain amino acids (BCAA), leucine, carbohydrate, fat, cholesterol, or any of the micronutrients tested (e.g., vitamin B12, calcium, vitamin D, etc). Daily macronutrient intakes relative to bodyweight were also not different among the clusters. There were no associations between the magnitude of myofiber hypertrophy and any dietary intake component (data not shown). Protein intakes on average exceeded the recommended dietary allowance (RDA, 0.8 $g \cdot kg^{-1} \cdot d^{-1}$) in all three clusters. While a small number of subjects (11 of 60) reported dietary protein intakes less than the RDA, these subjects were found across all three response clusters [Non, n=4 (young male, n=1; young female, n=1; old male, n=1; old female, n=1); Mod, n=5 (young female, n=2; old male, n=3); and Xtr, n=2 (young male, n=2)]. Additionally, two younger female subjects (Non, n=1 and Mod, n=1) were consuming ~1–2 $mg \cdot kg^{-1} \cdot d^{-1}$ less than the RDA for leucine (RDA, 42 $mg \cdot kg^{-1} \cdot d^{-1}$).

DISCUSSION

Our purpose was to determine if constituents of the daily diet (e.g., energy, protein, carbohydrate, fat, and amino acids) augment or inhibit skeletal muscle hypertrophy in response to 16 wk of RT. This is the first study to use the cluster analysis approach to test whether macronutrient or micronutrient intakes influenced RT efficacy. The results indicate that dietary intake on average was not sufficient in itself to distinguish the magnitude of muscle growth following 16 wk of RT as there were no mean differences in dietary intakes among the response clusters. Under-reporting is a well-documented limitation of self-reported dietary records (Hill and Davies 2001), and recently has been found to be most common among so-called “healthy eaters” (Scagliusi et al. 2008; Svendsen and Tonstad 2006). In the current study, since body weight was maintained across 16 wk in all clusters and there were no cluster differences in total energy intake per kg, and based on the finding that both Mod and Xtr subjects gained lean mass, we are confident that energy intake was adequate. Although it may have occurred, our data provide no indication that under-reporting was biased in a particular cluster.

Dietary protein intake, particularly inadequate protein, has been shown to affect muscle mass, strength, function, metabolism, and mRNA levels (Campbell et al. 2001; Campbell et al. 2002; Castaneda et al. 1995; Castaneda et al. 2000; Thalacker-Mercer et al. 2007). There are relatively limited data on long-term dietary protein during RT-induced muscle growth. Campbell et al. (Campbell et al. 1999) reported that type II, but not type I myofiber CSA increased in older men (51–69 y) with 11 wk of whole body RT independent of dietary protein source (lactoovovegetarian diet (lactoovo) or meat-containing diet); however there was a trend for a greater increase in type II CSA in the meat consuming group compared to the lactoovo group (~+16.2% vs. ~+7.3%, respectively, P>0.05). In a similar study by the same research group, no difference in mid-thigh muscle CSA was reported between the lactoovo and meat protein containing diets. Both groups had significant increases in muscle CSA (lactoovo ~+4.2% and meat ~+6.0%) following 12 wk of whole body RT while consuming diets with adequate energy for body weight maintenance and dietary protein ~125–144% of the RDA for protein (Haub et al. 2002). Corresponding with these reports, the current study shows no difference among the three response clusters for daily consumption of total, animal, or vegetarian proteins at ~125% of the RDA for protein. Comparing diets containing either 0.8 or 1.6 g protein·kg^{-1}·d^{-1}, Campbell et al. (Campbell et al. 1995) found no effects of dietary protein “dosing” on myofiber hypertrophy following 12 wk of whole body RT. However, these data may be interpreted with caution since no measurable hypertrophy was found with either protein dose, suggesting sample size limitations (n=6 in each group).

Overall these prior training studies suggest that, in the presence of adequate nutrition for weight maintenance, skeletal muscle gains following RT are driven by the exercise stimulus with no synergistic effect of increased dietary protein intake (range 0.8 to 1.6 g·kg^{-1}·d^{-1}). Nitrogen balance studies corroborate this, demonstrating that resistance exercise does not increase the need for dietary protein but in fact improves utilization of protein which may actually lower the protein requirement during training (Hartman et al. 2006; Moore et al. 2007). The range of individual “responsiveness” in these prior studies, however, is not known. In the present RT study we have clearly shown that protein consumption above the RDA of ~1 g·kg^{-1}·d^{-1} is adequate (Mod, Xtr) and perhaps even optimal (Xtr) in *some* individuals but such an intake does not guarantee myofiber hypertrophy in others (Non). There are two ways to interpret these findings: 1) Some individuals seeking hypertrophy may benefit from higher protein intake (Non) during RT while others may not (Xtr); or 2) Given adequate total energy intake and some minimum amount of protein (perhaps the RDA), each individual’s propensity for myofiber hypertrophy is determined by factors independent of macronutrient intake. We tend to support the latter interpretation based on: 1) prior findings of cluster differences in load-mediated growth factor expression (Bamman et al. 2007; Kim et al. 2007b) and satellite cell recruitment (Petrella et al. 2008); and 2) current findings that protein intake ~1 g·kg^{-1}·d^{-1} was sufficient for most (Mod + Xtr = 73% of cohort) but not all (Non) individuals attempting myofiber hypertrophy. It seems highly unlikely that the remarkable differences in myofiber responsiveness for Xtr vs. Mod, and for Non vs. all others, would be corrected by cluster-specific adjustments in protein intake. We therefore suspect that factors other than daily nutrient intake were responsible for the lack of hypertrophy among Non.

We were also interested whether differences in hypertrophy across clusters were driven by the building blocks of intact dietary proteins (i.e., EAA, BCAA, and leucine) as these factors have also been shown to stimulate muscle protein synthesis (Paddon-Jones et al. 2005; Paddon-Jones et al. 2004; Volpi et al. 2003; Volpi et al. 1998) and have an additive effect when coupled with acute resistance exercise (Tipton et al. 2001). These studies show that the quantity of leucine in the dose of EAA is an important factor influencing the stimulation of protein synthesis, although some found this effect only among elderly (Katsanos et al.

2006). In the current study, there were no differences in dietary intake of EAA, BCAA, or specifically leucine among the three response clusters. These results suggest that while subjects may have an acutely elevated anabolic response following resistance exercise coupled with immediate amino acid intake, acute responses may not translate to augmented myofiber hypertrophy over the course of several weeks of training. Although we suspect other factors are primarily responsible, we cannot rule out the possibility that Non and even Mod could have a blunted acute response to anabolic dietary stimuli (vs. Xtr) that could be overcome with higher dietary intake. If this were the case, it would be difficult if not impossible to identify an "optimal" protein intake to promote muscle hypertrophy during RT in all persons. Non, and perhaps Mod, may require a higher protein intake than Xtr to maximize rates of growth; whereas Xtr clearly consumed sufficient amounts of protein and other nutrients. Future research on optimizing the anabolic response to RT and dietary intake in non-responders is warranted.

Several studies suggest that there is enhanced skeletal muscle metabolism and accretion when intact dietary protein and/or amino acids are consumed within the immediate time frame of the resistance exercise bout (Biolo et al. 1997; Tipton et al. 2004; Tipton et al. 2001; Cribb and Hayes 2006; Esmarck et al. 2001; Tipton et al. 2007; Roy et al. 2000; Hartman et al. 2007; Wilkinson et al. 2007; Andersen et al. 2005). The results from these studies theoretically suggest that a long-term dietary protein and RT prescription would lead to greater muscle accretion than either dietary protein or RT alone. However, few studies have tested whether these acute responses translate into greater gains in skeletal muscle mass. Cribb and Hayes (Cribb and Hayes 2006) reported greater increases in lean body mass and type II muscle fiber area following 10 wk of RT when subjects consumed a protein and glucose supplement immediately before and after exercise compared to persons consuming the same supplement in the morning and evening of exercise training. A limitation of the current study is that subjects did not report the time of dietary ingestion before and after each bout of exercise; therefore, we cannot determine if the magnitude of response was influenced by substrate availability during exercise recovery.

Research investigating the long-term effects of dietary carbohydrate and fat intake on skeletal muscle hypertrophy is sparse. Acute studies suggest that carbohydrate ingestion within the immediate time frame of resistance exercise can stimulate an anabolic response (Roy et al. 1997; Borsheim et al. 2004), but the response does not parallel that of dietary protein and/or amino acids (Hartman et al. 2007; Borsheim et al. 2002) and does not further stimulate muscle protein synthesis when consumed with amino acids (Koopman et al. 2007). To our knowledge there have been no studies looking specifically at the long-term effects of carbohydrate consumption on RT related muscle hypertrophy. There were no differences among the response clusters for carbohydrate intake, suggesting that dietary carbohydrate does not play a pivotal role in maximizing RT-mediated muscle hypertrophy. Similarly, we also found that fat and cholesterol intakes do not differ among the response clusters. This contrasts a recent study by Riechman et al. (Riechman et al. 2007) which showed that cholesterol intake, adjusted by lean mass (mg dietary cholesterol/kg lean mass), had an effect on the change in lean mass over 12 wk of RT (75% 1RM); there was a greater increase in lean mass with higher dietary cholesterol intake. They did not adjust for RT; therefore, the results should be taken with caution.

While we feel that the novel results presented here are valuable, some limitations warrant discussion. For a subject's 4-d diet records to be included in the analysis, one complete record had to be provided. We cannot rule out the possibility that there may have been changes in dietary intake from the beginning to the end of the 16-wk study. However, previous studies suggest that dietary habits do not change over the course of long-term RT (Cribb et al. 2007; Esmarck et al. 2001; Willoughby et al. 2007). Additionally, we did not

ask our participants to record the time of dietary ingestion before or after each exercise bout; therefore, we cannot determine if timing of intake affected our results. Future studies need to address the long-term effects of dietary ingestion before and/or after exercise bouts to determine if responses to RT are maximized with substrate availability. Taking advantage of the metabolic synergism between nutrition and resistance exercise in the acute response phase should theoretically maximize growth rates. Identifying non-responders in the presence of such optimum anabolic conditions would be extremely useful toward identifying intrinsic factors unique to the non-responders.

In conclusion, we found, in this preliminary study, that no components of self-selected, daily, dietary intake predicted the magnitude of RT-mediated myofiber hypertrophy. Although all groups consumed, on average, the same amount of energy, macronutrients, and amino acids, there were marked differences in muscle hypertrophy among the clusters, which suggests, in the presence of apparently adequate nutrition, dietary intake was not a major determinant of gains in skeletal muscle mass during RT. Further, the results do suggest that daily energy and protein intakes were sufficient during RT, at least among responders. Specific extrinsic or intrinsic factors that define individual hypertrophy responsiveness to RT are only beginning to be revealed (Petrella et al. 2008). Future follow-up studies of nutrition-related parameters in responders and non-responders should carefully consider factors such as the source(s) of protein and the timing of feeding relative to each exercise bout.

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Table 1

Subject characteristics at baseline and following a 16-wk resistance exercise training program.

	Non	Mod	Xtr
	n = 16	**n = 29**	**n = 15**
Height, *cm*	169.1 ± 2.5	172.6 ± 1.9	171.8 ± 2.5
Weight, *kg*			
Baseline	73.0 ± 3.0	75.1 ± 3.1	79.6 ± 3.5
16 week	71.5 ± 3.0	75.9 ± 3.1	81.0 ± 3.6
†§ Lean mass, *kg*			
Baseline	45.912 ± 2.485	47.866 ± 2.181	54.000 ± 2.800
16 week	46.196 ± 2.443	48.782 ± 2.203*	55.708 ± 2.891*
†§ Thigh lean mass, *kg*			
Baseline	10.767 ± 0.630	11.525 ± 0.586	13.065 ± 0.821
16 week	11.164 ± 0.677	12.058 ± 0.607*	14.194 ± 0.911*
† Fat mass, *kg*			
Baseline	23.703 ± 1.349	23.557 ± 1.612	22.088 ± 2.295
16 week	22.741 ± 1.352	23.173 ± 1.634	21.080 ± 2.265

Note: Values are means ± SEM. Response clusters: Non, non-responders; Mod, modest responders; and Xtr, extreme responders.

† Main time effect, P<0.05;

§ Cluster × time interaction, P<0.05. Post-hoc analysis using Tukey's HSD test was performed to localize differences following main effects or interactions.

* Change across time within cluster, P<0.05.

Table 2

Energy and nutrient intakes of response clusters reported on four-day dietary records during a 16-wk resistance training program.

	Non	Mod	Xtr
n	16	29	15
Energy, $MJ \cdot d^{-1}$	7.36±0.53	8.07±0.44	8.19±0.36
Energy, $kJ \cdot kg^{-1} \cdot d^{-1}$	102.09±7.80	111.20±6.23	108.93±5.39
Total protein, $g \cdot d^{-1}$	69.7±4.9	77.4±4.4	79.0±3.7
Protein, $g \cdot kg^{-1} \cdot d^{-1}$	0.97±0.08	1.07±0.07	1.05±0.06
Animal protein, $g \cdot d^{-1}$	45.6±3.8	53.5±3.3	56.0±2.8
Animal protein, $g \cdot kg^{-1} \cdot d^{-1}$	0.62±0.06	0.74±0.04	0.75±0.05
Vegetable protein, $g \cdot d^{-1}$	23.7±2.5	23.5±1.9	22.8±1.5
Vegetable protein, $g \cdot kg^{-1} \cdot d^{-1}$	0.33±0.04	0.33±0.03	0.30±0.02
EAA, $g \cdot d^{-1}$	27.1±1.9	30.2±1.8	30.9±1.5
BCAA, $g \cdot d^{-1}$	12.2±0.9	13.5±0.8	13.9±0.7
Leucine, $g \cdot d^{-1}$	5.4±0.4	6.0±0.4	6.2±0.3
Carbohydrate, $g \cdot d^{-1}$	218.1±17.1	228.4±14.5	234.5±8.5
Fat, $g \cdot d^{-1}$	68.1±5.7	76.7±5.6	78.0±6.5
Cholesterol, $mg \cdot d^{-1}$	221.7±23.0	287.7±20.5	270.6±21.1

Note: Values are mean ± SEM. Response clusters: Non, non-responders; Mod, modest responders; Xtr, extreme responders; EAA, essential amino acids; BCAA, branched chain amino acids.