Muscle strength and hypertrophy occur independently of protein supplementation during short-term resistance training in untrained men

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Abstract

Short-term resistance training (RT) has consistently demonstrated gains in muscular strength, but not hypertrophy. Post-RT protein ingestion is posited to augment the acute anabolic stimulus, thus potentially accelerating changes in muscle size and strength. The purpose of this investigation was to examine the effects of four weeks of RT with protein supplementation on strength and muscle morphology changes in untrained men.

Participants (N = 18; 22.0 ± 2.5y; 25.1 ± 5.4kg·m⁻²) were randomly assigned to a RT + protein (PRO; n = 9; whey [17g] + colostrum [3g] + leucine [2g]) or RT + placebo group (PLA; n = 9). One-repetition maximum (1RM) strength in the leg press (LP) and leg extension (LE) exercises, maximal isometric knee extensor strength (MVIC), and muscle morphology (thickness [MT], cross-sectional area [CSA], pennation angle [PA]) of the dominant rectus femoris (RF) and vastus lateralis (VL) was assessed before and after training. Participants performed LP and LE exercises (3 × 8-10; @ 80%1RM) 3 d/wk for 4 weeks. Data were analyzed using two-way ANOVA with repeated measures.

Four weeks of RT resulted in significant increases in LP (p < 0.001), LE (p < 0.001), MVIC (p < 0.001), RF MT (p < 0.001), RF CSA (p < 0.001), VL MT (p < 0.001), and VL CSA (p < 0.001). No between-group differences were observed.

Although nutrition can significantly affect training adaptations, these results suggest that short-term RT augments muscle strength and size in previously untrained men with no additive benefit from post-exercise protein supplementation.

Key words: Supplementation, Muscle strength, Hypertrophy, Muscle morphology, Protein
Introduction

It is well established that chronic resistance training enhances muscle strength. Additionally, the mechanical stress imposed on the working muscles during resistance training is purported to augment whole muscle and muscle fiber size (Staron et al. 1994; Wilkinson et al. 2006). In an untrained population, the early improvement in strength preceding muscle hypertrophy is reportedly due to increased neural drive resulting in enhanced maximal voluntary activation of the exercised muscle (Gabriel et al. 2006; Moritani 1979; Staron et al. 1994). Although the precise duration of training necessary to evoke hypertrophy is still unclear, previous research suggests a period of 6-7 weeks for significant increases in muscle fiber diameter (Phillips 2000; Staron et al. 1994). More recently, however, detectable changes in whole muscle size have been reported following as little as three weeks of resistance training in both active and sedentary individuals (Defreitas et al. 2011; Malas et al. 2013; Seynnes et al. 2007).

Acute resistance training with sufficient intensity has been shown to increase skeletal muscle net protein balance for up to 48 hours which may influence changes in muscle fiber size over time (Phillips et al. 1997). Interestingly, when essential amino acids or milk proteins are supplemented following resistance training, a significantly greater acute anabolic response has been observed when compared to training alone (Biolo et al. 1995; Phillips et al. 1997; Tipton et al. 2004; Tipton et al. 1999). In support, several studies reported that ingesting protein-based supplements before and/or after resistance training resulted in significantly greater gains in strength and muscle hypertrophy over placebo controls in both trained and untrained individuals (Coburn et al. 2006; Hulmi et al. 2010; Walker et al. 2009; Willoughby et al. 2007). However, others have observed no added benefit of amino acid or protein supplementation on muscle mass and/or strength following 6-10 weeks of resistance training in both trained and untrained
individuals (Antonio et al. 2000; Hoffman et al. 2009). The conflicting results may be the result of differing methods of strength and muscle morphological assessment, participant training status, training program, and/or the amount or type of protein used. The potential benefits of protein supplementation in conjunction with resistance training over a four week period in untrained men are currently unclear; however, we hypothesized that protein supplementation during a short-term resistance training program would further augment muscle strength and hypertrophic gains. The purpose of this study was to examine the short-term effect of resistance training with and without protein supplementation on changes in muscle morphology and strength in untrained young men.

Materials and Methods

Participants

Twenty untrained young men volunteered to participate in this investigation and were randomly assigned to either a resistance training + protein (PRO; 21.4 ± 1.9y, 75.3 ± 15.7kg) or resistance training + placebo (PLA; 22.9 ± 3.1y, 76.8 ± 14.4kg) group. Eighteen (N = 18) completed the intervention and were included in the current results. Volunteers who did not complete the study reported personal reasons (n = 1) and/or issues of time commitment (n = 1). All participants were untrained as determined by the ACSM’s guidelines for aerobic physical activity. Additionally, none had any lower body resistance training experience within the year prior to this investigation. Prior to data collection, all participants completed a health history questionnaire, PAR-Q, and medical and activity questionnaire to assess physical activity level, health status, and possible risk factors. Participants were asked to avoid any ergogenic supplement use (e.g., protein or creatine) and refrain from participation in any other clinical/investigational trials.
throughout the duration of this experiment. The New England Institutional Review Board’s approval was obtained before any data collection was conducted. All participants signed an informed consent form prior to any data collection.

Research Design

A randomized, double-blinded, mixed-factorial design was used to examine the effects of four weeks of lower body unilateral resistance training on (a) muscle morphology [cross-sectional area, muscle thickness, pennation angle], (b) lower body power output, (c) maximal dynamic strength, and (d) maximal isometric strength of the dominant, trained leg knee extensors. Limb dominance was assessed using the Waterloo Footedness Questionnaire. All participants were asked to visit the university’s Human Performance Lab a total of 14 times (twice to complete pre- and post-testing, 12 times to complete training sessions).

Dietary Recall

Participants were asked to provide a 3-day dietary recall at pre- and post-testing while maintaining their regular diet for the duration of the investigation. FoodWorks® nutrient analysis software (McGraw-Hill, New York, NY) was used to analyze the self-reported dietary recalls for total kilocalorie intake and macronutrient distributions (carbohydrate, protein, and fat).

Familiarization and Testing Protocol

Pre- and post-testing occurred during the week immediately preceding and following the intervention period, respectively. A minimum of 48 hours was allotted between testing and training sessions. Assessments consisted of non-invasive ultrasound examination (General Electric LOGIQ P5, Wauwatosa, WI, USA) of the vastus lateralis and rectus femoris muscles, power testing via linear transducer during unilateral countermovement jumps (Tendo™ Power...
Units, Tendo Sports Machines, Trencin, Slovak Republic), maximal voluntary isometric contraction (MVIC) of the knee extensors (Biodex Medical Systems, Shirley, NY, USA), and one-repetition maximum (1RM) testing of the leg press and leg extension exercises (Power Lift, Jefferson, IA, USA). Exercise familiarizations were conducted prior to 1RM testing, wherein all participants were instructed on proper form for each of the required exercises.

**Training Protocol**

For the duration of the intervention period, participants reported to the university’s Strength and Conditioning Lab on three nonconsecutive days per week for training sessions. In the event that a training session was missed, make-up sessions were scheduled with laboratory staff to ensure that 12 total sessions were completed during the four weeks while still maintaining appropriate rest periods between training sessions. Prior to training, participants performed a general warm-up – five minutes of non-fatiguing aerobic activity on a cycle ergometer at a self-selected resistance and cadence – followed by a specific warm-up – body weight squats, alternating lunges, walking knee hugs, and glute kicks (10 each). Each training session consisted of unilateral countermovement jumps (CMJ), leg press (LP), and leg extension (LE) using the dominant leg. CMJ were performed for a total of three sets of 8 repetitions with maximal effort. The LP and LE exercises were performed for a total of three sets of 8-10 repetitions at 80% of the participant’s previously determined 1RM with 90 seconds allotted between sets and exercises. If a participant was unable to perform the minimum amount of repetitions during the first or second sets of LP or LE, weight was decreased to an intensity deemed appropriate by a certified trainer. Consequently, if the participant was able to perform all repetitions with proper form and minimal strain, weights were progressively increased during the subsequent training session at the certified trainer’s discretion. All participants were asked to refrain from any other
form of structured resistance exercise and to maintain their usual recreational activities for the
duration of this investigation.

Supplementation

Participants were randomly assigned to either a training + protein (PRO) or a training + placebo
group (PLA). The PRO group was asked to ingest a protein blend containing 17g of whey
protein concentrate (WPC-80), 3g of bovine colostrum extract, and 2g of leucine. The PLA
group was asked to ingest a non-nutritive, iso-volumetric placebo containing 20g resistant
maltodextrin that was similar in appearance and taste of the PRO. Third party laboratory testing
by the sponsoring company was conducted on the PRO to ensure contents were determined to be
accurate. Participants were instructed to supplement once per day for the duration of the 28-day
investigation. On training days, either the placebo or supplement was administered by one of the
coi-investigators immediately after the training session. At the end of each training session,
participants were given a single-serving sachet of their respective supplement to be consumed ad
libitum on non-training days; sachets were returned (empty) on the subsequent training day to
monitor compliance.

Ultrasound Measurements

During testing sessions, participants reported to the Human Performance Lab for non-invasive
ultrasound examination of the quadriceps musculature. Participants were asked to lay supine on
an examination table with both legs fully extended for a minimum of 15 minutes to allow fluid
shifts to occur. Images of the rectus femoris (RF) were captured midway between the anterior
inferior iliac crest and proximal patellar border. Images of the vastus lateralis (VL) were
captured on the midline halfway between the greater trochanter and lateral epicondyle. The
following measurements were obtained from the images of the RF and VL: cross-sectional area
(CSA), muscle thickness (MT), and pennation angle (PA). All measures were obtained by passing a 12MHz linear probe (General Electric LOGIQ P5, Wauwatosa, WI, USA) coated with water-soluble transmission gel (Aquasonic® 100, Parker Laboratories, Inc., Fairfield, NJ) over the surface of the thigh at the predetermined anatomical locations. Images of muscle CSA were captured using extended-field-of view ultrasonography, while MT and PA were captured using B-mode ultrasonography. For all images, gain was set at 50, dynamic range was set at 72 to optimize spatial resolution, and depth was fixed at 5 cm$^4$. Further analyses of all ultrasound images was performed using ImageJ (National Institutes of Health, USA, version 1.45s) to quantify CSA, PA, MT. To ensure consistency, the same investigator performed all ultrasound measurements and analyses. Intra-class correlation coefficients were as follows: RF CSA (0.93; $SEM = 0.613$ cm$^3$), VL CSA (0.96; $SEM = 0.792$ cm$^3$), MT RF (0.95; $SEM = 0.090$ cm), MT VL (0.85; $SEM = 0.080$ cm), PA RF (0.95, $SEM = 0.579^\circ$), and PA VL (0.93; $SEM = 0.441^\circ$).

**Maximal Strength Assessment**

During pre- and post-testing sessions, maximal isometric strength of the dominant leg was assessed using a Biodex™ isokinetic dynamometer. Each participant performed three, six-second maximal-effort isometric contractions separated by three minutes of rest. Knee and hip angle were positioned at 110°. One-repetition maximum testing followed methods previously outlined by Hoffman (2006). Relative strength was calculated as strength relative to body weight. Specific strength, reported as strength relative to the sum of muscle cross-sectional areas, was calculated for MVIC and leg press and extension 1RM strength:

$$\text{Specific Strength} = \frac{\text{Strength}}{\text{RF CSA} + \text{VL CSA}}$$

(Kent-Braun and Ng 1999)

Prior to strength testing, each participant completed the previously described general and specific warm-up protocols. During 1RM testing, the trainer/investigator monitored and instructed proper
exercise form to ensure that each participant met the desired range of motion for each exercise.

Attempts not meeting the range of motion criterion for each exercise were discarded.

Power Assessment

Lower body power output was quantified during unilateral countermovement jumps. Each participant was asked to complete three maximal effort countermovement jumps from the dominant leg with hands placed on his hips to rule out extraneous force generation. Power output was quantified using a Tendo™ Power Unit which consists of a transducer attached to the waist of the participant to measure linear displacement over time. Subsequently, velocity was calculated and power was determined. Mean and peak power output were recorded from each jump and used for later analysis.

Statistical Analyses

Data were considered normally distributed as assessed by the Shapiro-Wilk test. Baseline differences at Pre- and Post-testing were identified using independent samples t-tests. If no significant between-group baseline differences were identified, data were analyzed using separate two-way, mixed-factorial [group (protein [PRO] vs. placebo [PLA]) × time (pre-intervention [PRE] vs. post-intervention [POST]), repeated-measures analysis of variance (ANOVA). If there was a significant F ratio for main effects, a Fisher’s Least Significant Difference (LSD) post-hoc test was performed to determine change for each group. Results were considered significant at an alpha level of \( p \leq 0.05 \). All data were reported as mean ± SD. Data were analyzed via SPSS (Version 20.0, SPSS Inc., Chicago, IL).

Results
Anthropometric and dietary intake changes are displayed in Table 1. All participants were similar in body mass ($p = 0.850$), total caloric ($p = 0.176$), carbohydrate ($p = 0.432$), fat ($p = 0.628$), protein ($p = 0.582$), and relative protein intake ($p = 0.765$) at pre-testing. No significant changes in body mass ($p = 0.960$), total caloric ($p = 0.262$), carbohydrate ($p = 0.902$), fat ($p = 0.482$), protein ($p = 0.095$), or relative protein intake ($p = 0.106$) were observed between groups over the four-week intervention period.

**Maximal Dynamic Strength**

Changes in dynamic strength are displayed in Table 2. No significant between-group differences were observed for LP ($p = 0.585$) or LE ($p = 0.559$) at pre-testing. The two-way [group (PRO vs. PLA) × time (PRE vs. POST)] repeated-measures ANOVA for LP indicated no significant ($F = 0.010, p = 0.921, \eta^2 = 0.001$) group × time interaction but a significant ($F = 215.103, p < 0.001, \eta^2 = 0.931$) main effect of time. Similarly, there was no significant ($F = 0.084, p = 0.776, \eta^2 = 0.005$) group × time interaction for LE, but a significant ($F = 117.789, p < 0.001, \eta^2 = 0.880$) main effect of time was observed.

**Maximal Isometric Strength**

No significant between-group difference was observed for MVIC ($p = 0.197$) at pre-testing. The two-way [group (PRO vs. PLA) × time (PRE vs. POST)] repeated-measures ANOVA for MVIC indicated no significant ($F = 2.074, p = 0.169, \eta^2 = 0.115$) group × time interaction, but a significant ($F = 36.948, p < 0.001, \eta^2 = 0.698$) main effect of time was observed.

**Specific Strength**

No significant between-group differences were observed for specific LP strength ($p = 0.601$) strength, specific LE strength ($p = 0.524$), or specific MVIC strength ($p = 0.606$) at pre-testing.
The two-way [group (PRO vs. PLA) × time (PRE vs. POST)] repeated-measures ANOVA for specific LP strength indicated no significant ($F = 0.601, p = 0.450, \eta^2 = 0.036$) group × time interaction, but a significant ($F = 90.107, p < 0.001, \eta^2 = 0.849$) main effect of time was observed. Likewise, no group × time interaction ($F = 2.379, p = 0.143, \eta^2 = 0.129$), but a significant ($F = 82.715, p < 0.001, \eta^2 = 0.838$) main effect of time was observed for specific LE strength. No significant group × time interaction ($F = 1.071, p = 0.360, \eta^2 = 0.089$) or time effect ($F = 0.367, p = 0.553, \eta^2 = 0.022$) was observed for specific MVIC strength.

**Power Output**

Changes in power output are displayed in Table 3. No significant between-group differences were observed for mean ($p = 0.672$) or peak power output ($p = 0.166$) at pre-testing. The two-way [group (PRO vs. PLA) × time (PRE vs. POST)] repeated-measures ANOVA for mean power output indicated no significant group × time interaction ($F = 0.106, p = 0.750, \eta^2 = 0.007$) or main effect of time ($F = 0.044, p = 0.837, \eta^2 = 0.003$). Similarly, no significant group × time interaction ($F = 1.493, p = 0.239, \eta^2 = 0.085$) or main effect of time ($F = 1.578, p = 0.227, \eta^2 = 0.090$) was identified for peak power output.

**Muscle Morphology**

Changes in muscle morphology are displayed in Table 4. No significant between-group differences were observed in RF (MT: $p = 0.212$, PA: $p = 0.088$, CSA: $p = 0.916$) or VL (MT: $p = 0.229$, PA: $p = 0.212$, CSA: $p = 0.894$) at pre-testing. Separate two-way [group (PRO vs. PLA) × time (PRE vs. POST)] repeated-measures ANOVAs indicated a significant group × time interaction for RF CSA ($F = 5.096, p = 0.038, \eta^2 = 0.242$), but not RF MT ($F = 0.791, p = 0.388, \eta^2 = 0.050$), RF PA ($F = 0.611, p = 0.447, \eta^2 = 0.039$), VL CSA ($F = 0.791, p = 0.388, \eta^2 = 0.050$), VL MT ($F = 0.791, p = 0.388, \eta^2 = 0.050$), or VL PA ($F = 0.791, p = 0.388, \eta^2 = 0.050$).
Results of the LSD post-hoc test revealed no significant group difference for RF CSA ($p = 0.817$). A significant main effect of time was identified for RF MT ($F = 68.761, p < 0.001, \eta^2 = 0.464$), RF CSA ($F = 13.841, p = 0.002, \eta^2 = 0.683$), VL MT ($F = 29.557, p < 0.001, \eta^2 = 0.683$), and VL CSA ($F = 106.885, p < 0.001, \eta^2 = 0.870$, but not RF PA ($F = 1.217, p = 0.287, \eta^2 = 0.075$) or VL PA ($F = 3.872, p = 0.069, \eta^2 = 0.217$).

**Discussion**

Following four weeks of resistance training, all participants experienced significant improvements in strength (1RM) and isometric force (MVIC) (Table 2). Similarly, muscle thickness (MT) and cross-sectional area (CSA) of the dominant rectus femoris (RF) and vastus lateralis (VL) were significantly increased (Table 4). Four weeks of resistance training, however, did not affect pennation angle (PA), or mean and peak power output (Tables 3 & 4).

Following four weeks of resistance training, leg press 1RM was improved by $75.8 \pm 32.1\%$ and $72.6 \pm 44.4\%$ in the PRO and PLA group, respectively. In addition, leg extension 1RM significantly increased by $46.3 \pm 18.4\%$ (PRO) and $45.3 \pm 15.8\%$ (PLA) (Table 2). These results were similar to those of Seynnes and colleagues (2007) who reported strength improvements of $38.9 \pm 5.7\%$ in the leg extension exercise among recreationally active adults following three weeks of resistance training. Additionally, Blazevich and colleagues (2003) observed significant lower body strength improvements reaching as high as $42.8\%$ in recreationally active adults following five weeks of resistance training. However, Malas and colleagues (2013) reported no significant strength improvements following three weeks of dynamic resistance training in osteoarthritic adults. The dissimilarity in results among previous studies may be attributed to differences in training intensity/modality, length of training intervention, and/or population enrolled.
Previous research suggests that performance adaptations are specific to the velocities and movement patterns employed during training (Kannus et al. 1992; Malas et al. 2013). Because the training program used in this investigation did not incorporate specific power exercises, it is not surprising that we observed strength improvements with no significant change in power measures. Interestingly, four weeks of resistance training resulted in an $11.4 \pm 5.0\%$ and $16.8 \pm 8.8\%$ increases in VL CSA and RF CSA, respectively, for the combined PRO and PLA groups. Similar increases in muscle hypertrophy of the RF ($11.4 \pm 5.0\%$) and VL CSA ($13.8 \pm 3.1\%$) have been observed via magnetic resonance imaging following just 35 days of knee extensor training (Seynnes et al. 2007). Additionally, DeFreitas and colleagues (2011) reported a $6.7\%$ increase in thigh muscle CSA after four weeks of resistance training as assessed by computed tomography. The variation in findings between these studies may be due to differences in the methods used to assess muscle morphology and/or differences in training protocols. Participants in the PRO and PLA group also experienced significant increases in MT (RF: $13.2 \pm 6.4\%$ and $16.6 \pm 8.5\%$; VL: $32.0 \pm 22.9$ and $21.9 \pm 20.7\%$, respectively). This is consistent with Malas and colleagues (2013) who reported a significant increase in muscle thickness ($2.9\%$) of the VL using ultrasound imaging after three weeks of dynamic resistance training, but contrasts with Blazevich and colleagues (2003) who reported no change in VL thickness as assessed by ultrasound imaging following five weeks of isokinetic concentric and eccentric training. The greater increase in MT observed in this present study compared to previous investigations may be related to differences in the training protocols employed. Malas and colleagues (2013) instructed their participants to perform 90 knee extensions per day with $1.5\text{kg}$ added to the distal portion of his or her trained leg; whereas Blazevich and colleagues (2003) implemented a 3 day/week ($4-5$ sets $\times 6$ sets).
repetitions) isokinetic, concentric-eccentric knee extension training program with a velocity of 60°/s⁻¹. In contrast to the present investigation, the aforementioned studies did not include a hypertrophy-style training regimen – 6-12 repetitions for 3-6 sets at 67-85% 1RM (Ratamess et al. 2009). Thus, differences in the muscle hypertrophy response between these investigations were likely the result of the differences seen in training program design.

Seynnes and colleagues (2007) reported significant changes in PA following short-term resistance training, while others have reported no change following three to five weeks of lower body resistance training (Blazevich et al. 2003; Malas et al. 2013). Although it has been suggested that intrinsic myofiber rearrangement occurs prior to muscle hypertrophy during short-term training interventions (Seynnes et al. 2007), our observation of significant muscle hypertrophy with no change in pennation angle appears to be contradictory. Adaptations to training occur with great inter-individual variability, but the discrepancies may be further attributed to differences in instrumentation used to analyze skeletal muscle morphology, training modality employed, participant training status and/or gender.

Results of this study indicated that the PRO and PLA groups experienced similar changes in performance and muscle morphology suggesting that protein supplementation did not provide any additional benefits. Similarly, previous investigations have reported no significant group differences in muscle size or strength gains when comparing protein to placebo controls following four to eight weeks of resistance training (Herda et al. 2013; Lemon et al. 1992). While the rapid increase in training-induced strength and muscle size was not surprising, the observation that protein supplementation offered no additional benefit was unexpected. These results, however, may be attributed to a few limitations in our study design. Firstly, all participants in the PRO group supplemented with an identical dose of protein regardless of total...
or lean body mass. In a recent investigation, Moore et al. (2014) reported that ingesting a 20g
dose of whey protein was sufficient to stimulate maximal muscle protein synthesis (MPS) in
resistance trained young men weighing approximately 80kg. Further, it has been suggested that
untrained individuals have a lower dietary protein requirement as compared to their trained
counterparts (Hartman et al. 2006). Therefore, we hypothesized that the PRO supplement (17g
whey) was sufficient to stimulate MPS among all participants (75.3 ± 15.7kg) in our
investigation. Although resistance training has been shown to increase whole-body nitrogen
balance, thus creating an anabolic environment appropriate for muscle hypertrophy (Hartman et
al. 2006), the addition of whey protein (~21g) has demonstrated further enhancement of MPS
rates in trained young men (Tang et al. 2009). Assuming the supplement provided a sufficient
dosage of high quality protein and post-exercise MPS was maximally stimulated, we anticipated
a further degree of muscle hypertrophy in the PRO group; however, no meaningful group
differences were detected (Table 4). This observation may be attributed to variations in body
weight (i.e., three participants in the PRO group weighed more than 80kg) or the lack of dietary
control throughout the investigation. Although total energy and macronutrient intake remained
relatively constant (Table 1), it should be noted that the PRO group consumed an additional 17g
of protein each day for the duration of the investigation. Moreover, participants were not given
any advisement in regards to optimal nutrient quality, quantity, or timing – all of which
purportedly influence lean body mass (Phillips and Van Loon 2011). Therefore, without
accounting for these variables we cannot rule out that variations in individual diet (i.e. timing
and food selection) elicited differences in results.

The current results suggest that untrained men will experience significant muscle hypertrophy
and strength adaptations following resistance training regardless of post-exercise protein
supplementation. Although a number of researchers report positive effects (i.e., augmented training adaptations) of protein supplementation with resistance training, it should be noted that ingestion occurred both pre- and post-training (Coburn et al. 2006; Cribb et al. 2007) suggesting that additional supplementation proximal to training may be necessary for optimal hypertrophic adaptations to occur. While post-exercise protein supplementation appears to enhance the acute anabolic response, recent research has observed no correlation between the acute effects of milk protein supplementation and the training-induced muscle hypertrophy seen after chronic resistance training (Mitchell et al. 2014).

In conclusion, the current findings suggest that short-term resistance training resulted in significant increases in muscle strength and size in untrained young men. The addition of a post-exercise protein supplement used in the current investigation was not sufficient to enhance the effect of resistance training, however, more research needs to be done to determine if protein dosage and timing are beneficial for untrained individuals beginning a new resistance training program.

Acknowledgment

The authors thank iSatori, Inc. for generously providing the supplement used in this investigation.


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<th>Pre</th>
<th>Post</th>
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<tr>
<td><strong>Body mass (kg)</strong></td>
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<tr>
<td>PRO (n = 9)</td>
<td>75.3 ± 15.7</td>
<td>76.8 ± 15.9</td>
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<td>PLA (n = 9)</td>
<td>76.8 ± 14.4</td>
<td>78.2 ± 14.0</td>
<td>1.4 ± 1.4</td>
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<td><strong>Total energy intake (kCal)</strong></td>
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<tr>
<td>PRO (n = 9)</td>
<td>2034.0 ± 682.3</td>
<td>2073.8 ± 755.8</td>
<td>4.9 ± 22.6</td>
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<td>PLA (n = 7)</td>
<td>2107.0 ± 370.7</td>
<td>1844.7 ± 286.3</td>
<td>-9.4 ± 23.0</td>
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<tr>
<td><strong>Total carbohydrate intake (g)</strong></td>
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<tr>
<td>PRO (n = 9)</td>
<td>262.9 ± 94.2</td>
<td>267.2 ± 110.7</td>
<td>4.1 ± 25.8</td>
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<tr>
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<td>242.8 ± 67.3</td>
<td>242.5 ± 35.1</td>
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<td><strong>Total protein intake (g)</strong></td>
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<td>PRO (n = 9)</td>
<td>84.9 ± 34.4</td>
<td>93.0 ± 32.6</td>
<td>20.0 ± 37.6</td>
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<td>88.0 ± 29.3</td>
<td>69.9 ± 26.9</td>
<td>-15.7 ± 40.7</td>
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<td><strong>Total fat intake (g)</strong></td>
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<tr>
<td>PRO (n = 9)</td>
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<td>75.6 ± 23.2</td>
<td>36.7 ± 62.1</td>
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<tr>
<td>PLA (n = 7)</td>
<td>82.9 ± 41.1</td>
<td>73.6 ± 18.6</td>
<td>12.3 ± 72.4</td>
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<td><strong>Relative protein intake (g/kg)</strong></td>
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<tr>
<td>PRO (n = 9)</td>
<td>1.2 ± 0.5</td>
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<td>18.2 ± 37.9</td>
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<td>PLA (n = 7)</td>
<td>1.2 ± 0.4</td>
<td>1.0 ± 0.3</td>
<td>-17.1 ± 40.9</td>
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Values are means ± SD. Reduced n size in PLA group due to non-compliance in dietary recall. Total intake values do not include additional calories and/or macronutrients, if applicable, from supplement.
Table 2. Changes in maximal dynamic, isometric, and specific strength following training

(N = 18)

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<th>Pre</th>
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<td><strong>Leg press 1RM (kg)</strong></td>
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</tr>
<tr>
<td>PRO (n = 9)</td>
<td>84.7 ± 34.5</td>
<td>140.1 ± 34.9 *</td>
<td>75.8 ± 32.1</td>
</tr>
<tr>
<td>PLA (n = 9)</td>
<td>93.0 ± 37.9</td>
<td>147.7 ± 33.3 *</td>
<td>72.6 ± 44.4</td>
</tr>
<tr>
<td><strong>Leg extension 1RM (kg)</strong></td>
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</tr>
<tr>
<td>PRO (n = 9)</td>
<td>43.9 ± 10.8</td>
<td>63.3 ± 13.9 *</td>
<td>46.3 ± 18.4</td>
</tr>
<tr>
<td>PLA (n = 9)</td>
<td>42.9 ± 13.2</td>
<td>61.3 ± 15.5 *</td>
<td>45.3 ± 15.8</td>
</tr>
<tr>
<td><strong>Specific leg press strength (kg/cm^2)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PRO (n = 9)</td>
<td>2.1 ± 0.6</td>
<td>3.1 ± 0.6 *</td>
<td>55.7 ± 21.4</td>
</tr>
<tr>
<td>PLA (n = 9)</td>
<td>2.3 ± 0.7</td>
<td>3.2 ± 0.4 *</td>
<td>49.8 ± 42.1</td>
</tr>
<tr>
<td><strong>Specific leg extension strength (kg/cm^2)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PRO (n = 8)</td>
<td>1.1 ± 0.2</td>
<td>1.4 ± 0.2 *</td>
<td>27.0 ± 11.7</td>
</tr>
<tr>
<td>PLA (n = 9)</td>
<td>1.1 ± 0.2</td>
<td>1.3 ± 0.2 *</td>
<td>25.3 ± 11.7</td>
</tr>
<tr>
<td><strong>Maximal isometric strength (N)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PRO (n = 8)</td>
<td>818.3 ± 180.4</td>
<td>939.3 ± 187.1 *</td>
<td>15.4 ± 10.7</td>
</tr>
<tr>
<td>PLA (n = 9)</td>
<td>835.8 ± 255.2</td>
<td>910.4 ± 248.7 *</td>
<td>10.0 ± 7.8</td>
</tr>
<tr>
<td><strong>Specific isometric strength (N/cm^2)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PRO (n = 8)</td>
<td>20.5 ± 3.2</td>
<td>21.1 ± 3.5</td>
<td>3.2 ± 13.6</td>
</tr>
<tr>
<td>PLA (n = 9)</td>
<td>20.6 ± 4.5</td>
<td>19.4 ± 3.3</td>
<td>-4.7 ± 10.2</td>
</tr>
</tbody>
</table>

Values are means ± SD. *Significant change from Pre to Post (p < 0.05).
Table 3. Changes in mean and peak power output following training

\( (N = 18) \)

<table>
<thead>
<tr>
<th></th>
<th>Pre</th>
<th>Post</th>
<th>%∆</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean power output (W)</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>PRO ((n = 9))</td>
<td>646.7 ± 151.7</td>
<td>651.0 ± 146.3</td>
<td>3.7 ± 26.0</td>
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<tr>
<td>PLA ((n = 8))</td>
<td>696.6 ± 139.5</td>
<td>676.7 ± 181.5</td>
<td>-1.1 ± 24.6</td>
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<tr>
<td>Peak power output (W)</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>PRO ((n = 9))</td>
<td>1819.1 ± 399.9</td>
<td>1642.3 ± 335.7</td>
<td>-8.2 ± 16.0</td>
</tr>
<tr>
<td>PLA ((n = 9))</td>
<td>1623.6 ± 296.6</td>
<td>1621.1 ± 329.2</td>
<td>0.3 ± 14.8</td>
</tr>
</tbody>
</table>

Values are means ± SD.
### Table 4. Changes in muscle morphology following training

*(N = 18)*

<table>
<thead>
<tr>
<th></th>
<th>Pre</th>
<th>Post</th>
<th>%Δ</th>
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</thead>
<tbody>
<tr>
<td><strong>Rectus femoris</strong></td>
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<tr>
<td>Cross-sectional area (cm²)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PRO (n = 8)</td>
<td>13.4 ± 4.2</td>
<td>13.8 ± 3.0 *</td>
<td>4.0 ± 12.7</td>
</tr>
<tr>
<td>PLA (n = 9)</td>
<td>12.5 ± 2.1</td>
<td>14.8 ± 3.2 *</td>
<td>15.3 ± 7.4</td>
</tr>
<tr>
<td>Muscle thickness (cm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PRO (n = 8)</td>
<td>2.5 ± 0.4</td>
<td>2.8 ± 0.4 *</td>
<td>13.2 ± 6.4</td>
</tr>
<tr>
<td>PLA (n = 9)</td>
<td>2.4 ± 0.3</td>
<td>2.8 ± 0.2 *</td>
<td>16.6 ± 8.5</td>
</tr>
<tr>
<td>Pennation angle (˚)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PRO (n = 7)</td>
<td>12.1 ± 5.0</td>
<td>13.3 ± 2.7</td>
<td>16.5 ± 24.6</td>
</tr>
<tr>
<td>PLA (n = 9)</td>
<td>12.3 ± 2.6</td>
<td>12.5 ± 2.1</td>
<td>3.4 ± 17.2</td>
</tr>
<tr>
<td><strong>Vastus lateralis</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Cross-sectional area (cm²)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PRO (n = 9)</td>
<td>26.8 ± 5.1</td>
<td>30.9 ± 3.9 *</td>
<td>16.8 ± 8.8</td>
</tr>
<tr>
<td>PLA (n = 9)</td>
<td>27.5 ± 5.6</td>
<td>31.8 ± 5.7 *</td>
<td>16.3 ± 7.6</td>
</tr>
<tr>
<td>Muscle thickness (cm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PRO (n = 7)</td>
<td>1.5 ± 0.2</td>
<td>2.0 ± 0.3 *</td>
<td>32.0 ± 22.9</td>
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<tr>
<td>PLA (n = 9)</td>
<td>1.8 ± 0.4</td>
<td>2.2 ± 0.5 *</td>
<td>21.9 ± 20.7</td>
</tr>
<tr>
<td>Pennation angle (˚)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>PRO (n = 7)</td>
<td>11.4 ± 1.9</td>
<td>13.8 ± 3.3</td>
<td>20.8 ± 19.8</td>
</tr>
<tr>
<td>PLA (n = 9)</td>
<td>9.5 ± 6.0</td>
<td>13.0 ± 2.7</td>
<td>10.0 ± 18.0</td>
</tr>
</tbody>
</table>

Values are means ± SD. *Significant change from Pre to Post (p < 0.05).
Table 1: Participant characteristics and dietary analysis at pre- and post-testing. Values are means ± SD. PRO, protein + training group; PLA, placebo + training group; %Δ, percent change from pre- to post-testing.

Table 2: Changes in maximal dynamic, isometric, and specific strength following four weeks of resistance training. Values are means ± SD. *Significant difference from Pre to Post (p < 0.05). PRO, protein + training group; PLA, placebo + training group; 1RM, one-repetition maximum; %Δ, percent change from pre- to post-testing.

Table 3: Changes in mean and peak power output following four weeks of resistance training. Values are means ± SD. PRO, protein + training group; PLA, placebo + training group; %Δ, percent change from pre- to post-testing.

Table 4: Changes in cross-sectional area, muscle thickness, and pennation angle of the trained rectus femoris and vastus lateralis following four weeks of resistance training. Values are means ± SD. *Significant difference from Pre to Post (p < 0.05). PRO, protein + training group; PLA, placebo + training group; %Δ, percent change from pre- to post-testing.