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ARTICLE

Strategic creatine supplementation and resistance training in healthy older adults

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Abstract: Creatine supplementation in close proximity to resistance training may be an important strategy for increasing muscle mass and strength; however, it is unknown whether creatine supplementation before or after resistance training is more effective for aging adults. Using a double-blind, repeated measures design, older adults (50–71 years) were randomized to 1 of 3 groups: creatine before (CR-B: $n = 15$; creatine (0.1 g/kg) immediately before resistance training and placebo (0.1 g/kg cornstarch maltodextrin) immediately after resistance training), creatine after (CR-A: $n = 12$; placebo immediately before resistance training and creatine immediately after resistance training), or placebo (PLA: $n = 12$; placebo immediately before and immediately after resistance training) for 32 weeks. Prior to and following the study, body composition (lean tissue, fat mass; dual-energy X-ray absorptiometry) and muscle strength (1-repetition maximum leg press and chest press) were assessed. There was an increase over time for lean tissue mass and muscle strength and a decrease in fat mass ($p < 0.05$). CR-A resulted in greater improvements in lean tissue mass (Δ 3.0 ± 1.9 kg) compared with PLA (Δ 0.5 ± 2.1 kg; $p < 0.025$). Creatine supplementation, independent of the timing of ingestion, increased muscle strength more than placebo (leg press: CR-B, Δ 36.6 ± 26.6 kg; CR-A, Δ 40.8 ± 38.4 kg; PLA, Δ 5.6 ± 35.1 kg; chest press: CR-B, Δ 15.2 ± 13.0 kg; CR-A, Δ 15.7 ± 12.5 kg; PLA, Δ 1.9 ± 14.7 kg; $p < 0.025$). Compared with resistance training alone, creatine supplementation improves muscle strength, with greater gains in lean tissue mass resulting from post-exercise creatine supplementation.

Key words: aging, sarcopenia, timing, muscle mass, strength, strategies.

Résumé : La supplémentation en créatine associée de près à l'entraînement en résistance pourrait s'avérer une stratégie importante pour accroître la masse musculaire et la force; toutefois, on ne sait pas si la supplémentation en créatine est plus efficace avant ou après une séance d'entraînement en résistance chez des personnes âgées. On répartit aléatoirement des personnes âgées (50–71 ans) selon un devis à double insu avec mesures répétées dans l'un des trois groupes suivants : (*i*) créatine avant (CR-B: $n = 15$; créatine (0,1 g/kg) immédiatement avant l'entraînement en résistance et placebo (0,1 g/kg de maltodextrine d'amidon de maïs) immédiatement après l'entraînement en résistance), (*ii*) créatine après (CR-A: $n = 12$; placebo immédiatement avant l'entraînement en résistance et créatine immédiatement après l'entraînement en résistance) ou (*iii*) placebo (PLA: $n = 12$; placebo immédiatement avant et immédiatement après l'entraînement en résistance); l'intervention est d'une durée de 32 semaines. Avant et après l'intervention, on évalue la composition corporelle (masse maigre, masse adipeuse, absorptiométrie à rayons X en double énergie) et la force musculaire (1RM au développé couché et des jambes). Au long de l'intervention, on observe une augmentation de la masse maigre et de la force musculaire et une diminution de la masse grasse ($p < 0,05$). Le groupe CR-A présente une plus grande amélioration de la masse maigre (Δ 3,0 ± 1,9 kg) comparativement au groupe PLA (Δ 0,5 ± 2,1 kg; $p < 0,025$). La supplémentation en créatine suscite une plus grande amélioration de la force musculaire que le placebo, et ce, indépendamment du moment de l'ingestion du supplément (développé des jambes : CR-B Δ 36,6 ± 26,6 kg; CR-A Δ 40,8 ± 38,4 kg; PLA Δ 5,6 ± 35,1 kg; développé couché : CR-B Δ 15,2 ± 13,0 kg; CR-A Δ 15,7 ± 12,5 kg; PLA Δ 1,9 ± 14,7 kg; $p < 0,025$). Comparativement à l'entraînement en résistance sans supplément, la supplémentation en créatine suscite une plus grande augmentation de la force musculaire avec un meilleur gain en masse maigre quand la créatine est prise à la suite de l'exercice. [Traduit par la Rédaction]

Mots-clés : vieillissement, sarcopénie, moment, masse musculaire, force musculaire, stratégies.

Introduction

Sarcopenia, the age-related loss of muscle mass and strength (Cruz-Jentoft et al. 2010; Fielding et al. 2011), decreases the ability to perform activities of daily living (Short and Nair 2001). Contributing factors of sarcopenia include changes in muscle morphology (Giresi et al. 2005; Larsson et al. 2001), satellite cell activity (Brack and Rando 2007), hormonal kinetics (Balagopal et al. 1997), and oxidative stress (Greenlund and Nair 2003). The combination of resistance training and creatine, a nitrogen-containing compound found in red meat and seafood (Wyss and Kaddurah-Daouk 2000), has shown promise for improving aging muscle mass and strength (for reviews see Candow et al. 2012, 2014*a*; Devries and Phillips 2014; Forbes et al. 2012).

The timing of creatine ingestion may be an important factor contributing to the physiological benefits observed with creatine supplementation (Candow and Chilibeck 2008). For example, ingestion of creatine (0.1 g/kg or ~8 g) immediately before and immediately after resistance training sessions for 12 weeks increased muscle mass and strength in healthy older adults (Candow et al.

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2014*b*). Comparing the effects of creatine supplementation (5 g) immediately before and immediately after resistance training (20 sessions) in young males, Antonio and Ciccone (2013) found slightly greater increases in muscle mass and strength with post-exercise creatine ingestion. Furthermore, consumption of a supplement containing creatine (~6 g) before and after resistance training sessions for 10 weeks resulted in greater increases in lean tissue mass and cross-sectional area of type II fibers than consumption of the creatine supplement in the morning and evening on exercise training days (Cribb and Hayes 2006). While these results suggest the timing of creatine ingestion is important, a limitation of these studies was that a placebo (control) group was not included, which negates the ability to conclude that creatine was more beneficial than resistance training alone. Therefore, the purpose of this study was to compare the effects of creatine supplementation immediately before and after resistance training sessions with the effect of a placebo in healthy older adults. Since muscle contractions may lead to increased blood flow and greater creatine delivery and uptake into skeletal muscle (Harris et al. 1992), it was hypothesized that post-exercise creatine supplementation would lead to greater gains in muscle mass and strength compared with pre-exercise creatine supplementation. It was also hypothesized that creatine supplementation would be more beneficial than placebo, independent of the timing of ingestion. These results may have application for the design and implementation of optimal creatine supplementation strategies for aging adults.

Materials and methods

Study population

Sixty-four adults ≥50 years of age (38 postmenopausal women, 26 males) volunteered for the study. Female participants verbally confirmed that they were postmenopausal (i.e., their last menstrual cycle had occurred ≥1 year prior to the start of the study). Males and females were included to increase the applicability of our findings to the general population. Participants were not engaged in supervised resistance training for 16 weeks prior to the start of the study. We chose to recruit non-resistance-trained adults because it has been shown that they respond more favorably to creatine supplementation and resistance training (Candow et al. 2011). At baseline, participants were performing mild-intensity physical activity 1–4 times per week (e.g., walking, gardening). Participants were excluded if they had supplemented with creatine ≤12 weeks prior to the start of the study, as it has been shown that aging adults may experience residual beneficial effects after creatine supplementation ceases (Candow et al. 2004). Participants were also excluded if they were vegetarians, had pre-existing kidney or liver abnormalities, had taken medications that affect muscle biology (e.g., corticosteroids) ≤12 weeks prior to the start of the study, or suffered from severe osteoarthritis. Participants were instructed not to change their diet or engage in additional physical activity that was not part of their normal daily routine or consume nonsteroidal anti-inflammatory drugs during the study, as these interventions could have affected muscle protein synthesis (Trappe et al. 2002) and influenced our outcome measures. The study was approved by the university ethics review board for research in human subjects at the University of Regina. Participants were informed of any risks and the purpose of the study before their written consent was obtained.

Experimental procedures

The study was a double-blind, repeated measures study in which participants were randomized on a 1:1:1 basis to supplement with creatine before, creatine after, or placebo before and after training (3 days per week) for 32 weeks. Participants were instructed to refrain from physical activity for 48 h, alcohol for 24 h, and food and drink for 2 h prior to training sessions. The primary dependent variables measured before and after 32 weeks were body composition (lean tissue, fat mass) and muscle strength (leg press and chest press, 1 repetition maximum). A secondary dependent variable was habitual dietary intake. Participants completed dietary records for 3 days during the first and final weeks of resistance training and supplementation to assess nutrient intake differences between groups.

Randomization and supplementation

A research assistant who was not involved in any other aspect of the study was responsible for randomizing the participants to groups to ensure all participants and investigators remained blinded throughout the study. Participants were randomly assigned to 1 of 3 groups: creatine before (CR-B: n = 15; 8 females, 7 males; 53.2 ± 2.5 years, 77.2 ± 15.6 kg, 170.1 ± 9.9 cm; creatine (0.1 g/kg) immediately before resistance training and placebo (0.1 g/kg cornstarch maltodextrin) immediately after resistance training), creatine after (CR-A: n = 12; 5 females, 7 males; 55.5 ± 3.5 years, 87.9 ± 20.1 kg, 173.4 ± 8.3 cm; placebo immediately before resistance training and creatine immediately after resistance training), or placebo (PLA: n = 12; 9 females, 3 males; 57.2 ± 6.5 years, 77.9 ± 11.8 kg, 170.5 ± 10.8 cm; placebo immediately before and immediately after resistance training) for 32 weeks. Creatine supplementation occurred only on training days, as we have previously shown that pre- and post-exercise creatine supplementation increases muscle size and decreases muscle protein catabolism compared with placebo in healthy older men (Candow et al. 2008). Contents of the creatine monohydrate powder (Creapure, AlzChem AG, Trostberg, Germany) were verified by testing in an independent laboratory (The Cary Company, Addison, Ill., USA; creatine purity >99.9%). A creatine dose of 0.1 g/kg was chosen because it increases muscle mass and strength without causing adverse effects in young and older adults (Candow et al. 2008, 2014*b*). Creatine and placebo (Globe Plus 10 DE Maltodextrin, Univar Canada) were identical in taste, texture, color, and appearance. An individual not involved in any other aspect of the study was responsible for mixing and packaging the supplements in large plastic bags and preparing individual study kits. Each study kit contained 2 individually labeled bags (Bag # 1: BEFORE resistance training, Bag # 2: AFTER resistance training), detailed supplementation instructions, and measuring spoons. Participants consumed creatine or placebo with water immediately before (i.e., 5 min) and immediately after (i.e., 5 min) each resistance training session in the presence of an exercise supervisor, as the purpose of the study was to directly compare the effects of creatine supplementation before versus after resistance training. Adherence to the supplementation and resistance training regimen was assessed using training and supplementation compliance logs.

Resistance training program

Prior to the start of the study, each participant performed 3 familiarization sessions (supervised) with the resistance training equipment in a private laboratory to reduce the amount of learning related to task acquisition, which could affect our outcome measures. Previous research has shown that 3 familiarization sessions followed by multiple testing sessions is sufficient to produce reliable strength results in older adults (Phillips et al. 2004). Participants followed the same supervised whole-body resistance training program for 32 weeks in the same private laboratory. Training sessions were supervised because previous research has demonstrated greater gains with supervised training than with unsupervised training (Mazzetti et al. 2000). Prior to training sessions, but after the supplement had been consumed, each participant performed a 5-min stationary cycling warm-up at a self-selected intensity. Participants completed 3 sets of 10 repetitions with 1–2 min rest between sets for each exercise at an intensity corresponding to their 10-repetition maximum for each exercise. Resistance exercises were performed in the following order: leg

press, chest press, lat pull-down, shoulder press, leg extension, leg curl, triceps extension, biceps curl, calf press, back extension, and abdominal curl. We used machine-based resistance training equipment because it is considered safer and easier to learn than free weights (Ratamass et al. 2009) and because the use of machine-based equipment leads to greater improvements in machine-based strength tests (Boyer 1990). Participants maintained daily training logs that included the load, number of sets, and number of repetitions. Resistance was increased by 2–10 kg once a participant could complete 3 sets of 10 repetitions to muscle fatigue for an exercise. Once the resistance had been increased, participants maintained this load until 3 sets of 10 repetitions to fatigue were completed.

Body composition

Lean tissue and fat mass was measured by dual-energy X-ray absorptiometry (Hologic Wi System, Christie Group, Winnipeg, Man., Canada) in array mode. Before scanning, participants were required to take off all removable objects containing metal (i.e., jewelry, glasses, clothing with buttons and (or) zippers). Scans were performed with participants lying in a supine position along the scanning table's centerline longitudinal axis. Feet were taped together at the toes (i.e., phalanges) to immobilize the legs, while the hands were maintained in a pronated position within the scanning region. All scans were performed by the same nuclear medicine technologist. The coefficient of variation from previous research is 0.54% for lean tissue mass (Chrusch et al. 2001).

Muscle strength

Leg press and chest press strength were assessed using a 1-repetition maximum (1-RM) standard testing procedure. Following 5 min of cycling on a stationary cycle ergometer, participants performed 2 warm-up sets in the following order: 1 set of 10 repetitions using a weight determined by each subject to be comfortable and 1 set of 5 repetitions using increased weight. Two minutes after the warm-up sets, weight was progressively increased for each subsequent 1-RM attempt with a 2-min rest interval. The 1-RM was reached in 4–6 trials, excluding the 2 warm-up sets. The coefficients of variation from previous research are 3.0% for the leg press and 3.6% for the chest press (Chrusch et al. 2001).

Dietary assessment

Dietary intake was recorded during the first and final weeks of supplementation and resistance training to assess differences in total energy intake and macronutrient composition between groups. Participants used a 3-day food booklet to record food intake for 2 weekdays and 1 weekend day. Participants were instructed to record all food items, including portion sizes, consumed for the 3 designated days. The Interactive Healthy Eating Index (Center for Nutrition Policy and Promotion, United States Department of Agriculture) was used to analyze the 3-day food records.

Statistical analysis

A 3 × 2 ANOVA (CR-B vs. CR-A vs. PLA × pre- and post-training) with repeated measures on the second factor was used to determine differences between groups over time for lean tissue mass, relative skeletal muscle index (sum of appendicular muscle mass (kg) / m^2), fat mass, leg press strength, chest press strength, relative strength (strength / lean tissue mass), and diet. If significant interactions were detected, a one-factor ANOVA on change scores (Δ = post-training mean – pre-training mean) was conducted. If the one-factor ANOVA was significant, the smallest mean was considered different than the largest mean and therefore only 2 additional *t* tests were used to compare the smallest and largest means with the middle mean, with adjustments for multiple comparisons ($p < 0.05/2 = 0.025$). A one-factor ANOVA was also used to determine whether there were differences in baseline measurements between groups and to determine differences in training volume over time. All results are expressed as means ± standard deviation. Effect sizes are reported as partial eta squared (η^2). Statistical analyses were performed using SPSS version 21.0 for Windows XP (SPSS, Chicago, Ill., USA). Significance was set at $p < 0.05$ for omnibus tests.

Table 1. Participant characteristics at baseline for creatine before (CR-B), creatine after (CR-A), and placebo (PLA) groups.

	CR-B (n = 15)	CR-A (n = 12)	PLA (n = 12)	p value
Age (y)	53.2±2.5	55.5±3.5	57.2±6.5	0.073
Weight (kg)	77.2±15.6	87.9±20.1	77.9±11.8	0.194
Height (cm)	170.1±9.9	173.1±8.3	170.5±10.5	0.647
BMI (kg/m^2)	26.5±4.2	29.0±5.9	26.8±3.4	0.343
Lean tissue (kg)	43.6±10.5	46.6±10.8	41.7±8.7	0.491
RMSI (kg)	7.1±1.3	7.1±1.2	6.6±1.0	0.537
Fat (kg)	25.2±7.9	32.7±11.1	28.6±7.3	0.110
Leg press (kg)	137.4±55.9	144.4±53.9	134.6±53.8	0.907
Chest press (kg)	50.0±26.6	43.2±16.3	49.3±20.2	0.711

Note: Values are means ± standard deviation. BMI, body mass index; RMSI, relative skeletal muscle index.

Results

Participant characteristics, diet, adverse effects, and compliance

Of the 64 participants enrolled, 39 completed the study (22 females, 17 males; Table 1). There were no differences between groups for any of the baseline measurements. Twenty-five participants withdrew because of time constraints. Of the 39 participants, 30 (14 male, 16 female) were considered non-sarcopenic at baseline (relative skeletal muscle index >7.26 kg/m^2 for males and >5.5 kg/m^2 for females; Baumgartner et al. 1998), while 6 females (CR-B: n = 2; CR-A: n = 3; PLA: n = 1) and 3 males (CR-B: n = 1; CR-A: n = 1; PLA: n = 1) were considered sarcopenic. Following the study, only 3 women remained sarcopenic (n = 1 from each group). There was an increase in total energy intake (kilocalories) over time ($p < 0.05$), with no differences over time for protein, carbohydrate, and fat (Table 2). No adverse effects were reported from the resistance training, creatine, or placebo. For participants who completed the intervention, exercise and supplementation compliance was 70%. Changes in all measurements over time were similar between males and females (no gender × time interactions).

Lean tissue mass

There was a time main effect ($p < 0.05$; $\eta^2 = 0.4$) and a group × time interaction for whole-body lean tissue mass ($p < 0.05$; $\eta^2 = 0.2$). Post hoc analyses of the change score showed that the CR-A group experienced greater gains in lean tissue mass (pre, 46.6 ± 10.8 kg; post, 49.6 ± 11.8 kg) than the PLA group (pre, 41.7 ± 8.7 kg; post, 42.2 ± 9.1 kg; $p < 0.025$; Fig. 1).

There was a time main effect ($p < 0.05$; $\eta^2 = 0.4$) and a group × time interaction for relative skeletal muscle index ($p < 0.05$; $\eta^2 = 0.2$). Appendicular muscle mass improved more in the CR-A group (pre, 7.1 ± 1.2 kg; post, 7.7 ± 1.7 kg) than in the PLA group (pre, 6.6 ± 1.0 kg; post, 6.7 ± 1.0 kg; $p < 0.025$). There was no difference between the CR-B group (pre, 7.1 ± 1.3 kg; post, 7.4 ± 1.6 kg) and either the CR-A or the PLA group.

All groups experienced a decrease in fat mass over time ($p < 0.05$; $\eta^2 = 0.2$), with no differences between groups (CR-B: pre, 25.2 ± 7.9 kg; post, 24.4 ± 7.1 kg; CR-A: pre, 32.7 ± 11.1 kg; post, 29.2 ± 9.1 kg; PLA: pre, 28.6 ± 7.3 kg; post, 27.4 ± 8.1 kg).

Muscle strength and training volume

There was a time main effect ($p < 0.05$; $\eta^2 = 0.4$) and a group × time interaction for muscle strength ($p < 0.05$; $\eta^2 = 0.2$). Compared with the placebo group, both creatine groups experienced greater gains in leg press strength (CR-B: pre, 137.4 ± 55.9 kg; post, 174.1 ± 70.4 kg; CR-A: pre, 144.4 ± 53.9 kg; post, 185.2 ± 58.3 kg; PLA: pre,

Table 2. Total calories (kcal/day) and macronutrient content (grams/day) of creatine before (CR-B), creatine after (CR-A), and placebo (PLA) groups for 3 days during the first and final weeks of nutritional supplementation and training.

	CR-B		CR-A		PLA	
	Week 1	Week 32	Week 1	Week 32	Week 1	Week 32
Total calories (kcal/day)	1912.6±360.2	2629.7±1423.1*	1919.6±390.1	2567.3±998.0*	1937.2±576.7	2213.0±599.2*
Carbohydrates (g/day)	233.6±72.3	304.4±167.7	231.1±54.8	301.2±94.6	231.8±87.5	273.2±118.7
Fat (g/day)	70.1±18.9	101.3±56.8	79.6±14.5	91.3±32.8	68.3±23.9	79.7±18.7
Protein (g/day)	82.6±17.6	112.0±46.6	78.1±14.7	90.0±28.5	98.4±45.7	105.8±26.6

Note: Values are means ± standard deviation. Data are based on the average for 1 day from 3-day food records.
*Significantly greater after training ($p < 0.05$).

Fig. 1. Change (post-training mean – pre-training mean) in lean tissue mass for creatine before (CR-B), creatine after (CR-A), and placebo (PLA) groups. Values are means ± standard deviation. All groups significantly increased lean tissue mass over time ($p < 0.05$). *, Significantly greater than PLA ($p < 0.025$).

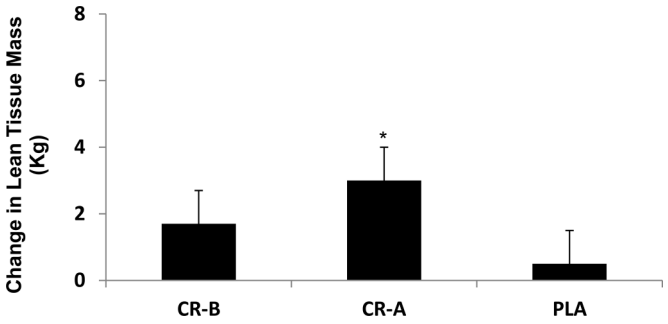
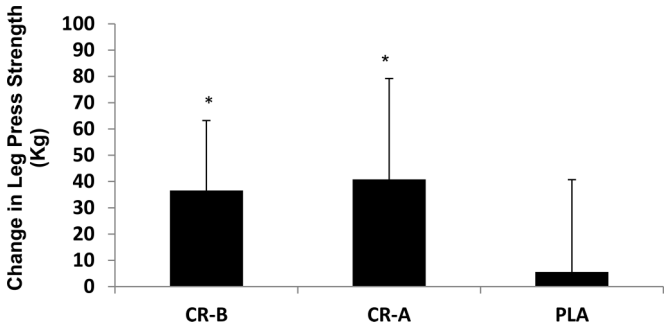


Fig. 2. Change (post-training mean – pre-training mean) in leg press strength for creatine before (CR-B), creatine after (CR-A), and placebo (PLA) groups. Values are means ± standard deviation. All groups significantly increased leg press strength over time ($p < 0.05$). *, Significantly greater than PLA ($p < 0.025$).

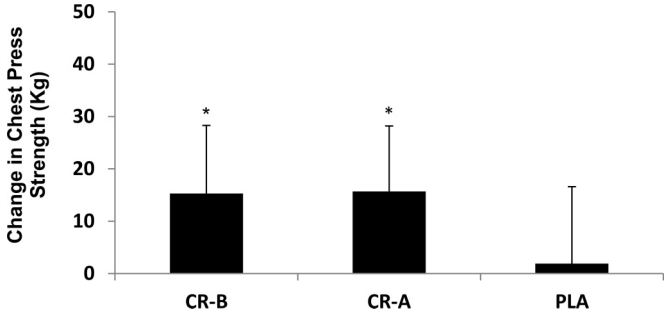


134.6 ± 53.8 kg; post, 140.1 ± 35.2 kg; $p < 0.025$; Fig. 2) and chest press strength (CR-B: pre, 50.0 ± 26.2 kg; post, 65.2 ± 33.6 kg; CR-A: pre, 43.2 ± 16.3 kg; post, 58.9 ± 29.8 kg; PLA: pre, 49.3 ± 20.2 kg; post, 51.2 ± 16.4 kg; $p < 0.025$; Fig. 3).

All groups experienced a significant increase in relative strength (strength (kg)/lean tissue mass (kg)) for the leg press (CR-B: pre, 3.2 ± 1.0 kg; post, 3.8 ± 0.9 kg; CR-A: pre, 3.1 ± 0.9 kg; post, 3.8 ± 0.7 kg; PLA: pre, 3.2 ± 1.0 kg; post, 3.4 ± 0.6 kg; $p < 0.05$; $\eta^2 = 0.4$) and the chest press (CR-B: pre, 1.1 ± 0.4 kg; post, 1.4 ± 0.4 kg; CR-A: pre, 1.0 ± 0.3 kg; post, 1.2 ± 0.3 kg; PLA: pre, 1.1 ± 0.4 kg; post, 1.2 ± 0.3 kg; $p < 0.05$; $\eta^2 = 0.4$), with no differences between groups.

The amount of resistance exercise performed over the study was similar between groups (CR-B: 151 384.6 ± 64 428.1 kg; CR-A: 174 643.1 ± 54 092.7 kg; PLA: 132 546.2 ± 68 829.1 kg).

Fig. 3. Change (post-training mean – pre-training mean) in chest press strength for creatine before (CR-B), creatine after (CR-A), and placebo (PLA) groups. Values are means ± standard deviation. All groups significantly increased chest press strength over time ($p < 0.05$). *, Significantly greater than PLA ($p < 0.025$).



Discussion

This is the first study to directly compare creatine supplementation before and after resistance training with a placebo (control) in healthy older adults. Results showed that post-exercise creatine supplementation increased lean tissue mass more than placebo. Furthermore, creatine supplementation during resistance training increased upper and lower body strength compared with resistance training alone (placebo). There were no differences between pre- and post-exercise creatine supplementation. Results of the present study support the growing body of evidence showing a beneficial effect of creatine supplementation on aging muscle biology (for reviews see Candow et al. 2014*a*; Devries and Phillips 2014). From a healthy aging perspective, these positive effects of creatine are important because the age-related reduction in muscle strength decreases the ability to perform activities of daily living (Manini and Clark 2013), and muscle accretion may lead to greater functionality in older adults (Chalé et al. 2013). Therefore, improving aging muscle health is of clinical significance (Clark and Manini 2012). In addition, these results may have application for the design of effective creatine supplementation strategies for aging adults. Creatine ingestion only on training days (before or after exercise) improves muscle mass and (or) strength. This is important, as supplementation compliance may be higher and financial costs lower when less frequent doses of creatine are consumed, compared with supplementing with creatine on non-training days during a resistance training program.

Participants who consumed creatine immediately following resistance training sessions experienced a greater increase in lean tissue mass than participants who engaged in resistance training alone (placebo). The greater muscle benefits from post-exercise creatine supplementation may be due to an increase in skeletal muscle blood flow during resistance training, which would result in greater creatine transport and accumulation in exercising muscles. With repeated training sessions, elevated intramuscular creatine stores may effectively influence gene expression, signaling pathways (Safdar et al. 2008), transcription factors (Willoughby and Rosene 2003), satellite cells (Olsen et al. 2006), and anabolic hormones (i.e., insulin-like growth factor 1; Burke et al. 2008; Deldicque et al. 2005) involved in skeletal muscle hypertrophy.

Pre-exercise creatine supplementation had no significant effect on lean tissue mass compared with placebo. The lack of an effect

of pre-exercise creatine supplementation may be related to creatine absorption kinetics (Preen et al. 2002), though this idea is speculative. Plasma creatine concentration peaks at ≤ 2 h after creatine supplementation (≤10 g) (Harris et al. 1992; Schedel et al. 1999). We administered a creatine dose of approximately 8 g immediately before each training session, which lasted 1 h. Plasma creatine concentrations may not have peaked until 1 h after the resistance training session ended and therefore, the pre-exercise creatine group may not have benefited from exercise-induced blood flow and greater delivery and uptake of creatine into skeletal muscle. For example, an acute bout of lower-body resistance training increased muscle blood flow for 1 h post-exercise, with no further increase at 2 h post-exercise compared with baseline levels (Tipton et al. 2001). Unfortunately, no measurements of blood flow kinetics or plasma or intramuscular creatine levels were made, which limits our understanding of how pre-exercise creatine supplementation may have influenced muscle biology.

Creatine supplementation increased muscle strength compared with placebo. While the mechanisms underlying the greater increase in maximal muscle strength with creatine supplementation remain to be elucidated, high-energy phosphate metabolism and actin-myosin cross-bridge cycling may be involved. Creatine is a component of phosphocreatine (PCr), which rapidly rephosphorylates adenosine diphosphate to help maintain adenosine triphosphate during resistance training. There is evidence that high-energy phosphate metabolism may be jeopardized with aging (Forsberg et al. 1991; Möller et al. 1980). Theoretically, increasing PCr resynthesis through exogenous creatine supplementation could increase high-energy phosphate metabolism in aging adults. A few studies have reported that creatine supplementation increases intramuscular PCr and muscle performance in older adults (Brose et al. 2003; Smith et al. 1998). Regarding actin-myosin cross-bridge cycling, creatine may increase calcium reuptake into the sarcoplasmic reticulum, which would result in faster detachment of the actin-myosin cross-bridge and potentially augment force-generating capacity (Bazzucchi et al. 2009). Since no measurement of high-energy phosphate metabolism or muscle morphology was made in the present study, we can only speculate that creatine increased intramuscular PCr and cellular signaling, leading to greater muscle strength.

In conclusion, creatine supplementation increased lean tissue mass and muscle strength in aging adults. Consuming creatine before and after resistance training sessions produces similar results; however, ingesting creatine immediately following resistance training augments muscle accretion compared with resistance training alone. Future research should investigate the mechanistic actions of creatine on aging muscle to develop optimal creatine dosing and timing strategies for aging adults.

Conflict of interest statement

The authors do not declare any conflicts of interest.

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