Influence of pistachios on force production, subjective ratings of pain, and oxidative stress following exercise-induced muscle damage in moderately trained athletes: A randomized, crossover trial

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A R T I C L E   I N F O

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Abstract

Although previous studies have focused on the role of pistachios on metabolic health, the ergogenic effects of the nut must be elucidated. This study evaluated the impact of ingesting raw, shelled, unsalted pistachios on subjective pain ratings, force production, vertical jump, and biochemical indices of recovery from eccentrically biased exercise. Using a crossover design, 27 moderately trained, male athletes completed 3 trials in a randomized counterbalanced fashion. Control received water only, low dose (1.5 oz/d; PL) and high dose (3.0 oz/d; PH) consumed pistachios for 2 weeks with a 3-4-week washout between trials. PH had lower pain ratings in most muscles after 72 h of recovery (p < 0.05). PH prevented a decrease in force production at 120°/s of knee flexion (p > 0.05); whereas force was diminished in the other trials. Creatine kinase, myoglobin, and C-reactive protein increased over time following exercise (p < 0.05); however, there were no advantages following pistachio consumption. No significant changes in vertical jump or superoxide dismutase were elicited during any trial. This study demonstrates that 3.0 oz/d of pistachios can reduce delayed onset of muscle soreness and maintain muscle strength, potentially promoting exercise tolerance and training adaptations.

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1. Introduction

Structured exercise training programs utilize the principles of overload and progression to yield favorable adaptations. An inevitable outcome of many regimens is an increase in perceived muscle soreness. However, pain may be problematic because of its association with muscle damage and oxidative stress [1]. Practical implications of exercise-induced muscle damage (EIMD) are impairments of sports performance [2] and activities of daily living [3].

Nutritional interventions are increasingly promoted to accelerate exercise recovery and reduce risk of muscle damage. In terms of functional foods, nuts have been gaining widespread attention due to their promising nutritive properties. The Mediterranean diet includes the consumption of nuts and is associated with benefits on cardiovascular (CV) health. Proposed mechanisms that optimize health through nut consumption are related to improvements in blood lipid profiles [4], inflammatory biomarkers [5], and flow-mediated vasodilation [6]. Despite the emerging evidence regarding the role of nut consumption on CV health, the utility of nuts as an ergogenic aid is unclear.

Although understudied, the composition of pistachios suggests a benefit to athletes by promoting recovery. Recently, pistachios were confirmed as a complete protein by providing high bioavailability of essential amino acids (Bailey & Stein, Unpublished Results). According to the United States Department of Agriculture, pistachios provide approximately 12 g of protein and 1 g of leucine in a 2 oz serving. Leucine is particularly important due to its distinct role in promoting muscle protein synthesis (MPS) through stimulating the mammalian target of rapamycin [7]. Previous studies support the efficacy of leucine supplementation in stimulating MPS after various exercise modalities regardless of sex [8,9] and age [10]. Notably, it was demonstrated that...
pistachio consumption effectively raises plasma leucine concentrations in athletes [11]. Additionally, antioxidants like those found in pistachios were shown to reduce perceived soreness [12], EIMD and an inflammatory response after exercise [13,14]. Previous investigators have confirmed an improvement in antioxidant status [15–17] and even reduced oxidative damage following pistachio consumption [18]. It is conceivable that by reducing pain and accelerating exercise recovery, athletes are less hindered from participating in subsequent training bouts that will further enhance sports performance.

A recent study observed no ergogenic effect of pistachio consumption on exercise performance, despite reporting various benefits in metabolic profile [11]. However, several considerations in terms of methodology should be highlighted. First, participants were instructed to consume pistachios both pre- and peri-exercise, which may have induced gastrointestinal (GI) upset and suboptimal performance. Indeed, the authors acknowledged a decrease in GI motility caused by exercise itself. Second, pistachios have been linked to delayed gastric emptying because of their fat and fiber content. The aim of this study was to determine the effect of different pistachio doses (1.5 oz vs. 3.0 oz) on eccentrically biased exercise recovery as measured through muscle force production, jump height, oxidative stress (i.e., creatine kinase (CK), superoxide dismutase (SOD), C-reactive protein (CRP), and myoglobin (Mb)), and subjective pain ratings. We anticipated a dose-dependent improvement on markers of exercise recovery following pistachio consumption when compared to a control.

2. Materials and methods

2.1. Participants

Moderately trained, male athletes (N = 40) aged 18–35 years were recruited from San Diego County. Participants were required to engage in at least 5 h of vigorous exercise per week. Exclusion criteria included smoking, medications known to impact inflammation, musculoskeletal limitations, and use of supplements known to impact antioxidant or inflammatory status within 1 month of participation. Potential participants were screened for eligibility criteria, and informed written consent was obtained prior to initiating the study. The study was approved by the San Diego State University Institutional Review Board.

Fig. 1. Schematic overview of the experimental protocol. C: Control; PL: 1.5 oz/d pistachio dose; and PH: 3.0 oz/d pistachio dose. Baseline measurements were conducted on the day of the downhill run and are categorized as time point 0 h. The recovery period was all the subsequent analyses conducted post-exercise; specifically, 24 h, 48 h, and 72 h after the downhill run.

2.2. Study design

This study utilized a randomized, crossover design with three 2-week dietary interventions separated by a 3-4-week washout period to prevent carryover effects (Fig. 1). Participants were randomized into the following groups: control (C), low dose (1.5 oz/d of shelled pistachios; PL), or high dose (3.0 oz/d of shelled pistachios; PH). Randomization was performed using a free online random number generator program by an investigator. The C was instructed to maintain usual dietary habits. All groups were directed to refrain from consuming additional nuts and seeds, as well as dietary supplements during the 2-week period.

Prior to initiating their first trial, participants were instructed to report to San Diego State University’s Clinical Nutrition and Physiological Sciences (CNaPS) laboratory for initial screening. Maximal oxygen consumption (VO2 max) was determined through a graded exercise test on a treadmill until volitional exhaustion. This measurement was utilized for descriptive data and to determine a heart rate (HR) reflective of 65–70% of VO2 max for subsequent trials. Anthropometric measurements (i.e., height, weight, and body composition) were obtained prior to randomization. Additionally, the first laboratory visit included familiarizing participants to the vertical jump and muscle force production protocols as described below.

After the 2-week feeding period, subjects reported to the CNaPS laboratory following an overnight fast and after abstaining from exercise for 2 days. Fasting blood samples, muscle soreness, vertical jump, and muscle force production were assessed prior to exercise. Participants completed a 40-min downhill run at ~10% grade while maintaining a HR reflecting 65–70% of VO2 max. Immediately after the eccentric exercise bout, a recovery serving of pistachios and 8 oz of water was provided to PL and PH, whereas C received water only. Pistachio consumption was continued after the muscle damage protocol up until 48 h of the recovery period. Participants were instructed to return to the laboratory in a fasted state at 24 h, 48 h, and 72 h after the downhill run for biochemical analyses, subjective ratings of pain, vertical jump, muscle force production, and supervised consumption of the trial feeding. Following data collection at the 72-h time point, subjects participated in a washout period lasting for 3–4 weeks. Participants returned for their next trial and repeated the protocols until all three trials were completed.
2.3. Anthropometrics

All measurements were assessed at one time point during the initial screening process prior to randomization into the participants’ first trials. Height (to the nearest 0.1 cm) was obtained with the use of a wall-mounted stadiometer (Posh Rulers, Portland, United States). Weight (to the nearest 0.1 lb) was measured using a digital scale (InBody, Seoul, Korea). Body fat percentage and lean body mass (kg) were assessed via trials. Height (to the nearest 0.1 cm) was obtained with the use of a wall-mounted stadiometer (Polar, Kempele, Finland) at the level of the 5th intercostal space and midclavicular line. Oxygen consumption, ratings of perceived exertion, and HR were continuously monitored during the exercise bout and recorded in 1-min increments. HR and oxygen consumption data were plotted to produce a regression line to estimate a HR reflective of 65–70% VO\textsubscript{2max} for the subsequent downhill runs. After the 2-week feeding period, subjects participated in a 40-min downhill run at –10% grade. Speed was adjusted until a HR reflecting 65–70% VO\textsubscript{2max} was produced. HR was continuously monitored throughout the trial and speed was adjusted to maintain HR within the predetermined ranges. The exact speeds were repeated for subsequent trials.

2.4. Maximal oxygen consumption (VO\textsubscript{2max}) testing and downhill run

Testing was conducted on a motor driven treadmill (ElectraMed Corporation, Flinn, United States) while participants were connected to a calibrated metabolic measurement system (Parvo Medics, Murray, United States). A 3-min warm-up was provided at a self-selected speed that was subjectively rated as a moderate intensity. Following the 3 min, the incline was increased by 1% grade every minute and thereafter until volitional exhaustion. HR was determined using a strapped monitor (Polar, Kempele, Finland) at the level of the 5th intercostal space and midclavicular line. Oxygen consumption, ratings of perceived exertion, and HR were continuously monitored during the exercise bout and recorded in 1-min increments. HR and oxygen consumption data were plotted to produce a regression line to estimate a HR reflective of 65–70% VO\textsubscript{2max} for the subsequent downhill runs.

2.5. Muscle soreness

A series of visual analog scales (VAS) measured soreness by asking questions that assessed ratings of pain on both the right and left sides of the following muscle groups: quadriceps, hamstrings, gluteus, gastrocnemius, and tibialis. Additionally, pain was rated during the vertical jump and muscle force production protocols, as well as at extended (0°) and flexed (90°) knee positions while seated. Each question was followed by a 100 mm line that was demarcated by the left-most side indicating “no pain” and the right-most side indicating “worst pain imaginable.” Subjects recorded their responses by marking a spot on the line indicating their feelings about each question. Responses were quantified by measuring the distance from the left end of the line to the designated mark.

2.6. Physical performance

Maximal isokinetic strength testing was determined using a Biodex\textsuperscript{®} dynamometer (Biodex Medical Systems, Shirley, United States). Participants were fastened on to the chair at the torso, waist, and ipsilateral thigh. Each trial consisted of 3 repetitions of unilateral knee flexion and extension at a speed of both 60° and 120° per second. A 1-min rest period was incorporated between the two different speed settings. Maximum torque (Nm) data were assessed prior to the downhill run (0 h), as well as the post-exercise recovery period (24 h, 48 h, and 72 h).

Vertical jump (VJ) height was measured using a Vertec (Sports Imports, Columbus, United States). The participant’s reach height was assessed with a wall-mounted ruler prior to conducting the jump test. Subjects stood against a marked wall and reached as high as possible with their dominant hand without lifting their heels from the floor; height was recorded based on the middle finger. For VJ assessment, participants were instructed to perform a rapid countermovement by quickly descending into a squat while swinging their arms down and back; no lead-up steps were allowed. The rapid descent was immediately followed by an explosive jump in which the dominant hand reached to touch the highest possible Vertec vane. Three attempts were allowed with the highest number of vanes altered to determine VJ height. Performance was calculated as the difference between standing reach and the highest jump recorded (cm). VJ height assessment took place prior to the downhill run (0 h), as well as the post-exercise recovery periods (24 h, 48 h, and 72 h).

2.7. Biochemical analyses

Fasted blood samples were collected via venipuncture prior to the downhill run and each morning during the recovery period. Vacutainers were centrifuged to enable the extraction of plasma samples and stored at –80 °C until analysis. Plasma was assayed for CRP, CK, Mgb, SOD using commercially available ELISA kits.

CRP was measured using an ultrasensitive enzyme-linked immunoassay kit (ALPCO, Salem, United States). Plasma samples were first diluted 1:100 and then placed in microplate wells coated with polyclonal antibodies to CRP. Sensitivity of the kits was 0.124 ng/mL with an assay range of 1.9–150 ng/mL. For SOD determination, the intra-assay coefficient of variation (CV) was 3.2%, the inter-assay CV was 3.7%, and the assay range was 0.005–0.050 units/mL.

2.8. Compliance

Participants received a reminder regarding adherence during the feeding period on the first day of the 2-week intervention. A 24-h notification containing information on refraining from medications, supplements, and exercise, as well as fasting instructions were sent prior to the downhill run. A 24-h dietary recall was completed before beginning the eccentric exercise bout and every day during the recovery period to assess compliance to dietary restrictions. The record received during baseline was returned to participants and they were asked to follow a similar diet for each downhill run and follow-up day.

Subjects were instructed to return any uneaten food products at their downhill run visit to assess adherence to the intervention. Prior to distribution, pistachios were pre-packaged, and vacuum sealed in their respective serving size for convenience and palatability. Compliance to the dietary intervention was assessed by researchers counting the number of uneaten bags left over from the 2-week feeding period.

2.9. Statistical analyses

All data are expressed in means ± standard deviation (SD). The assumption of normality was assessed before performing statistical analyses. If non-normal distribution was suspected, a log transformation was conducted to obtain normal distribution of data. Values of zero were scaled by the following formula: x = 1 + 0 to prevent any loss of data during the log transformation [19]. Outliers were identified and analyses were run with and without inclusion to determine any changes of statistical significance. A 3 (trial) x 4 (time) repeated-measures analysis of variance was applied to detect changes over time and within the trials. Mauchley’s test of sphericity was evaluated, and violations of the assumption were adjusted with the Greenhouse-Geisser correction if estimated epsilon was less than 0.75 and the Huynh-Feldt correction if greater than 0.75. Paired T-tests were performed to further examine significant main effects as needed. A P-value < 0.05 was considered statistically significant. All data was analyzed using IBM SPSS Statistics Version 28.

3. Results

3.1. Descriptives and adherence

Of the 40 participants enrolled, a total of 27 individuals completed
all aspects of the study. The observed 33% attrition rate was largely a result of the COVID-19 pandemic and its lockdown procedures declared by the state of California. During the C trial all subjects had a compliance rate of 100%. Approximately 63% and 67% of PL and PH had a compliance rate of 100%, respectively. Remaining dietary compliance rates of PL were the following: 93% (n = 5), 88% (n = 3), and 79% (n = 2). Additionally, dietary compliance rates for PH were the following: 93% (n = 3), 88% (n = 4), 79% (n = 1), and 64% (n = 1). Characteristics of the study population are provided in Table 1.

3.2. Vertical jump

Results revealed no significant interaction (F(1,85, 46.24) = 2.031, p < 0.147, η² = 0.08) and no trial effect (F(2, 50) = 1.208, p < 0.308, η² = 0.05) on vertical jump performance. No time effect was detected (F(1,55, 38.73) = 0.450, p < 0.592, η² = 0.02) despite mean values for jump height appearing to improve at 72 h in PL and at 48 h for PH (Fig. 2).

3.3. Muscle force production

Maximal torque (TRQ) was impaired over time across various intensity settings on the isokinetic dynamometer (Table 2). Max TRQ at 60° per second of extension produced a significant time effect (F(3,78) = 7.738, p < 0.001, η² = 0.23). Follow-up t-tests revealed that force production was significantly reduced after 24 h of the recovery period. Force production returned to baseline after 48 h in PH compared with 72 h in PL. No time effect was observed for muscle force production at 60° per second of flexion (F(2,53, 65.70) = 1.893, p < 0.149, η² = 0.07). Max TRQ at 120° per second of extension indicated a significant time effect (F(3, 78) = 5.810, p < 0.002, η² = 0.18). Further examination displayed significant changes in PL only, decreasing at the 24 h time point; however, strength failed to return to baseline even after 72 h. Additionally, there was a significant time effect for max TRQ at 120° per second of flexion (F(2,63, 68.31) = 2.918, p < 0.048, η² = 0.10). Follow-up analyses revealed a significant reduction in force production in PL at the 48-h time point, but returned to baseline at 72 h. Interestingly, force production in PH appeared like baseline levels throughout the entire recovery period and even showed a significant increase at 72 h when compared to 24 h and 48 h.

3.4. Ratings of pain

Subjective ratings of pain for right-sided muscle groups increased over time for the following: quadriceps (F(1,69, 43.82) = 45.477, p < 0.001, η² = 0.64), hamstrings (F(1,61, 41.87) = 17.442, p < 0.001, η² = 0.40), gastrocnemius (F(1,82, 47.21) = 36.970, p < 0.001, η² = 0.59), tibialis (F(1,53, 39.86) = 36.534, p < 0.001, η² = 0.58), and gastrocnemius (F(1,56, 40.58) = 33.420, p < 0.001, η² = 0.56) (Table 3). Follow-up tests indicated that participants experienced the most pain on the right-sided muscles 24 h after the eccentric exercise bout. Also, pain in the right quadriceps, hamstrings, glutaeus, and gastrocnemius were significantly reduced to baseline levels at 72 h in PH only. Notably, there was an observed interaction for the right gluteus measurement in PL and PH (F(4,90, 127.50) = 2.478, p < 0.037, η² = 0.09). T-tests revealed a similar trend of pain being the highest at 24 h and significantly reduced at 72 h; however, only PH demonstrated ratings of pain returning to baseline.

Additionally, left-sided muscle groups also exhibited a significant time effect for the following: quadriceps (F(1,67, 43.42) = 42.808, p < 0.001, η² = 0.62), hamstrings (F(1,69, 41.56) = 17.422, p < 0.001, η² = 0.40), gastrocnemius (F(1,76, 45.80) = 42.377, p < 0.001, η² = 0.62), tibialis (F(1,75, 45.45) = 34.625, p < 0.001, η² = 0.60), and gluteus (F(1,63, 42.23) = 37.068, p < 0.001, η² = 0.59) (Table 4). Participants experienced the most pain on their left-sided muscles 24 h after the eccentric exercise bout. Pain in the left quadriceps, hamstrings, and glutaeus returned to baseline levels after 72 h in PH only. A significant interaction was also demonstrated for the left glutaeus (F(6, 156) = 2.368, p < 0.033, η² = 0.08). Interestingly, t-tests demonstrated a return of subjective pain ratings back to baseline in PH only.

Ratings of pain measured following eccentric exercise demonstrated a significant time effect for the following assessments: vertical jump (F(1,95, 42.80) = 13.387, p < 0.001, η² = 0.39), maximal contraction performed on the isokinetic dynamometer (F(2,207, 53.72) = 18.434, p < 0.001, η² = 0.42), extension (F(1,86, 44.56) = 22.267, p < 0.001, η² = 0.48), and flexion (F(2,06, 49.38) = 18.474, p < 0.001, η² = 0.44) (Table 5). Participants experienced the most pain at 24 h, but values returned to baseline after 72 h of recovery for most measurements. Notably, PH, but not C and PL, consistently achieved ratings of pain returning to baseline for all performance parameters.

3.5. Biochemical indices

Analyses revealed a significant time effect for the following biochemical markers of muscle damage: Mgb (F(1,89, 47.19) = 6.978, p < 0.004, η² = 0.22, CK (F(1,74, 45.34) = 44.838, p < 0.001, η² = 0.63, CRP (F(3, 78) = 7.923, p < 0.001, η² = 0.23). Further examination indicated that Mgb levels were the highest at 24 h but returned to baseline values at 48 h in C and PH; PL values were elevated throughout the recovery period (Fig. 3A). Similarly, CK levels were the highest 24 h after the eccentric exercise bout but returned to baseline values in C and PH only; PL values appeared elevated throughout the recovery period (Fig. 3B). However, CK values returned to baseline at 48 h in PH instead of 72 h when compared to C. The highest concentration of CRP was at 24 h of the recovery period but returned to baseline following 48 h in C and PH (Fig. 3C). Follow-up tests revealed that CRP was not significantly elevated beyond baseline levels throughout the entire trial of PL. As an indicator of antioxidant potential, SOD appeared to be consistently elevated throughout the recovery period only in PL and PH when compared to C, but statistical analyses did not reveal any significant interaction (F(5,06, 126.56) = 1.128, p < 0.350, η² = 0.04), trial effect (F(1,69, 42.19) = 1.244, p < 0.295, η² = 0.05), or time effect (F(3,75) = 1.604, p < 0.197, η² = 0.06) (Fig. 3D).

4. Discussion

As a natural source of essential amino acids and bioactive phytochemicals, pistachios may be a beneficial snack option to promote sports performance. In the present study we investigated the influence of daily 2-week supplementation of 1.5 oz and 3.0 oz of pistachios on post-exercise recovery in moderately trained, male athletes. Vertical jump, muscle force production, subjective ratings of pain, as well as biochemical markers of muscle damage and antioxidant status were compared throughout a 72-h recovery period following a 40-min downhill run.

The eccentric exercise bout successfully elicited a moderate amount of muscle damage in the study cohort of moderately trained males. Biochemical analysis indicated a peak in CK, Mgb, and CRP concentrations at 24 h after the downhill run and that pistachios modestly attenuated these effects during the remainder of the 72-h recovery period. Simultaneously, the lowest muscle force production and highest ratings of pain were observed at the 24-h time point; pain tended to be further lowered during the recovery period by pistachio intake. Peak

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Table 1

| Subject characteristics (N = 27) |   |
|----------------------------------|---|
| Height (cm)                      | 174.8 (6.5) |
| Weight (kg)                      | 75.6 (11.2) |
| Age (y)                          | 24.0 (4.0)  |
| Body Fat (%)                     | 20.6 (9.4)  |
| Lean Body Mass (kg)              | 57.3 (6.3)  |
| Maximal Oxygen Consumption (mL/kg/min) | 51.1 (8.4) |
pain scores pain ranged between 20 and 30 on a 0–100 scale, suggesting that EIMD elicited relatively minor amounts. Based on our data, most pain scores ranged between 20 and 30 on a 0–100 scale, suggesting significant differences (p < 0.05) across respective timepoints were observed.

Table 2
Changes in maximum torque over time across different dosages of pistachios.

| Variable | 0-H | 24-H | 48-H | 72-H |
|----------|-----|------|------|------|
| Max TRQ 60’ EXT (Nm) | | | | |
| 0 oz | 179.2 (48.1) | 171.1 (39.4) | 176.5 (40.1) | 172.0 (41.1) |
| 1.5 oz | 181.9 (47.2)a | 166.9 (49.7)b | 163.1 (44.5)b | 176.2 (48.2)a |
| 3.0 oz | 182.8 (46.6)a | 170.9 (41.8)b | 175.5 (45.0)b,c | 173.2 (46.1)b,c |
| Max TRQ 60’ FLX (Nm) | | | | |
| 0 oz | 110.9 (37.4) | 113.0 (28.9) | 117.0 (30.4) | 116.7 (29.4) |
| 1.5 oz | 110.8 (34.0) | 111.5 (34.1) | 106.7 (37.1) | 113.4 (36.0) |
| 3.0 oz | 111.1 (35.8) | 111.5 (33.0) | 113.8 (32.3) | 115.3 (32.5) |
| Max TRQ 120’ EXT (Nm) | | | | |
| 0 oz | 138.2 (43.6) | 137.0 (36.0) | 135.6 (37.7) | 137.7 (40.2) |
| 1.5 oz | 146.6 (41.2)a | 134.1 (40.1)b | 129.8 (39.7)b,c | 137.5 (45.5)b,c,d |
| 3.0 oz | 142.5 (43.0) | 135.1 (42.4) | 137.1 (38.5) | 136.4 (44.3) |
| Max TRQ 120’ FLX (Nm) | | | | |
| 0 oz | 94.2 (30.9) | 94.7 (27.5) | 96.1 (28.3) | 96.4 (26.3) |
| 1.5 oz | 94.7 (31.6)a | 92.8 (34.1)b | 88.8 (30.4)b | 95.3 (32.9)b,c |
| 3.0 oz | 93.0 (33.8)a | 92.3 (32.9)b,c | 93.7 (32.5)b,c | 99.2 (29.3)b,c |

Note: Values are presented as means (standard deviations). Different letters indicate significant differences (p < 0.05) within a trial. EXT, extension; FLX, flexion; H, hour; Nm, Newton meters; oz, ounces.

Table 3
Visual analog scores for pain on right-sided muscles.

| Variable | 0-H | 24-H | 48-H | 72-H |
|----------|-----|------|------|------|
| Right Quadriceps (mm) | | | | |
| 0 oz | 5.2 (8.0)a | 30.8 (22.5)b | 23.7 (18.7)b | 14.9 (14.6)b |
| 1.5 oz | 4.5 (10.6)a | 29.7 (17.2)b | 25.8 (16.6)b | 14.1 (12.4)b |
| 3.0 oz | 6.4 (13.5)a | 24.2 (14.9)b | 20.4 (16.5)b | 11.5 (10.4)b |
| Right Hamstrings (mm) | | | | |
| 0 oz | 3.9 (5.2)a | 21.1 (22.5)b | 18.9 (19.7)b | 13.3 (17.5)b |
| 1.5 oz | 5.0 (12.3)a | 21.3 (19.7)b | 15.8 (16.9)b | 9.5 (12.4)b |
| 3.0 oz | 6.1 (11.4)a | 19.0 (18.1)b | 14.3 (15.9)b | 8.4 (10.8)b |
| Right Gastrocnemius (mm) | | | | |
| 0 oz | 4.4 (8.0)a | 24.9 (23.5)b | 23.0 (21.7)b | 13.2 (16.0)b |
| 1.5 oz | 3.8 (6.3)a | 23.9 (19.5)b | 19.0 (16.9)b | 8.4 (9.0)b,c |
| 3.0 oz | 6.3 (10.9)a | 20.0 (15.1)b | 13.6 (12.5)b,c | 8.2 (8.7)b,c |

Note: Values are presented as means (standard deviations). Different letters indicate significant differences (p < 0.05) within a trial.:

*: significant difference compared to the control (p < 0.05). H, hour; mm, millimeters; oz, ounces.
Table 4
Visual analog scores for pain on left-sided muscles.

| Variable                        | 0-H                      | 24-H                      | 48-H                      | 72-H                      |
|---------------------------------|--------------------------|---------------------------|---------------------------|---------------------------|
| Left Quadriceps (mm)            |                          |                           |                           |                           |
| 0 oz                            | 4.7 (8.6)b               | 30.2 (23.0)b              | 23.1 (20.3)c              | 14.0 (12.6)d              |
| 1.5 oz                          | 4.4 (9.9)b               | 29.6 (18.5)b              | 26.0 (18.1)b              | 14.5 (12.8)c              |
| 3.0 oz                          | 6.6 (14.0)c              | 24.2 (16.0)b              | 20.7 (16.6)b              | 13.2 (11.5)c              |
| Left Hamstring (mm)              |                          |                           |                           |                           |
| 0 oz                            | 4.2 (5.8)b               | 21.4 (22.9)b              | 18.8 (20.4)b              | 12.5 (15.0)c              |
| 1.5 oz                          | 5.2 (12.4)d              | 21.8 (18.2)b              | 14.9 (17.4)e              | 9.8 (13.3)f               |
| 3.0 oz                          | 6.6 (11.5)b              | 19.1 (17.2)b              | 13.8 (15.6)d              | 10.7 (12.3)e              |
| Left Glutus (mm)                 |                          |                           |                           |                           |
| 0 oz                            | 3.4 (4.7)c               | 27.2 (25.3)c              | 22.6 (20.7)f              | 13.8 (16.8)d              |
| 1.5 oz                          | 4.2 (8.3)c               | 25.3 (21.6)c              | 18.5 (17.0)c              | 9.9 (11.2)d               |
| 3.0 oz                          | 6.3 (14.0)c              | 20.5 (16.2)c              | 13.6 (11.3)c              | 8.6 (8.6)c                |
| Left Gastrocnemius (mm)         |                          |                           |                           |                           |
| 0 oz                            | 7.3 (11.8)c              | 31.9 (27.9)b              | 32.0 (26.9)b              | 22.3 (24.9)c              |
| 1.5 oz                          | 4.5 (7.1)c               | 27.5 (21.9)b              | 21.9 (18.9)c              | 15.7 (17.2)c              |
| 3.0 oz                          | 5.0 (7.1)c               | 26.3 (21.5)b              | 27.3 (24.3)b              | 14.8 (14.8)c              |
| Left Tibialis (mm)              |                          |                           |                           |                           |
| 0 oz                            | 3.9 (8.8)c               | 22.1 (23.3)c              | 20.4 (19.1)               | 12.6 (15.9)c              |
| 1.5 oz                          | 4.0 (7.0)c               | 28.2 (26.5)c              | 21.8 (20.2)d              | 13.5 (13.7)c              |
| 3.0 oz                          | 4.2 (6.3)c               | 22.7 (19.0)               | 20.0 (20.4)               | 13.7 (15.3)c              |

Note: Values are presented as means (standard deviations). Different letters indicate significant differences (p < 0.05) within a trial. *: significant difference compared to the control (p < 0.05). H, hour; mm, millimeters; oz, ounces.

Table 5
Visual analog scores for pain after sports performance measures.

| Variable           | 0-H                      | 24-H                      | 48-H                      | 72-H                      |
|--------------------|--------------------------|---------------------------|---------------------------|---------------------------|
| Vertical Jump (mm) |                          |                           |                           |                           |
| 0 oz               | 7.2 (11.1)c              | 20.5 (17.2)b              | 19.5 (19.1)b              | 10.6 (12.7)c              |
| 1.5 oz             | 10.7 (13.0)c             | 22.8 (19.9)b              | 19.3 (17.9)b              | 13.4 (14.0)c              |
| 3.0 oz             | 9.2 (10.3)c              | 20.9 (19.7)c              | 14.5 (11.8)c              | 10.0 (9.7)c               |
| Maximal Contraction (mm) |                    |                           |                           |                           |
| 0 oz               | 8.4 (10.0)c              | 22.8 (17.5)b              | 21.4 (17.9)c              | 11.6 (12.2)c              |
| 1.5 oz             | 10.0 (10.0)c             | 19.4 (16.5)b              | 21.1 (18.6)c              | 14.5 (12.6)c              |
| 3.0 oz             | 11.5 (12.4)c             | 21.8 (15.2)c              | 18.2 (15.7)c              | 12.6 (9.7)c               |
| Flexion (mm)       |                          |                           |                           |                           |
| 0 oz               | 6.3 (11.7)c              | 20.2 (18.1)               | 20.0 (22.3)c              | 12.8 (17.1)c              |
| 1.5 oz             | 6.8 (10.4)c              | 20.6 (16.9)               | 18.0 (17.7)               | 9.9 (11.7)c               |
| 3.0 oz             | 6.8 (15.2)c              | 20.4 (17.6)c              | 15.4 (12.5)               | 8.3 (9.5)c                |
| Extension (mm)     |                          |                           |                           |                           |
| 0 oz               | 5.8 (9.0)c               | 17.9 (16.5)c              | 21.0 (20.6)e              | 11.5 (11.9)d              |
| 1.5 oz             | 5.0 (7.3)c               | 20.6 (20.2)d              | 21.2 (18.2)d              | 9.2 (9.0)c                |
| 3.0 oz             | 6.1 (7.5)c               | 17.9 (15.9)c              | 13.9 (10.4)c              | 8.4 (7.8)c                |

Note: Values are presented as means (standard deviations). Different letters indicate significant differences (p < 0.05) within a trial. H, hour; mm, millimeters; oz, ounces.
knee extension and 120° per second of knee flexion when compared to 1.5 oz/d of pistachios and a control. Markers of muscle damage were attenuated similarly between PH and C. PL demonstrated consistent elevations in CK and Mgb. There were no significant changes in SOD concentrations; however, they tended to be elevated in PL. These results suggest that raw, shelled, unsalted pistachios may help reduce pain and maintain muscle force production after eccentric exercise, potentially leading to greater exercise tolerance and training adaptations.

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**Data availability**

Data generated or analyzed during this study are available from the corresponding author upon reasonable request.

**CRediT authorship contribution statement**

**Vernon Uganiza Rayo:** Data curation, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Imogene Thayer:** Data curation, Investigation. **Stuart D.R. Galloway:** Writing – review & editing. **Mee Young Hong:** Funding acquisition. **Shirin Hooshmand:** Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Changqi Liu:** Data curation, Investigation. **Elise North:** Data curation, Investigation. **Lauren Okamoto:** Data curation, Investigation. **Timothy O’Neal:** Data curation, Investigation. **Jordan Philpott:** Methodology, Writing – review & editing. **Oliver C. Ward:** Conceptualization, Funding acquisition, Methodology, Writing – review & editing. **Mark Kern:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Visualization, Writing – original draft, Writing – review & editing.

**Declaration of competing interest**

The authors declare there are no competing interests.

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**Appendix A. Supplementary data**

Supplementary data to this article can be found online at https://doi.org/10.1016/j.metop.2022.100215.

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