

# Branched-Chain Amino Acid Ingestion Can Ameliorate Soreness from Eccentric Exercise

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## ABSTRACT

JACKMAN, S. R., O. C. WITARD, A. E. JEUKENDRUP, and K. D. TIPTON. Branched-Chain Amino Acid Ingestion Can Ameliorate Soreness from Eccentric Exercise. *Med. Sci. Sports Exerc.*, Vol. 42, No. 5, pp. 962–970, 2010. **Purpose:** The purpose of this study was to examine the role of branched-chain amino acid (BCAA) supplementation during recovery from intense eccentric exercise. **Methods:** Twenty-four non-weight-trained males were assigned to one of two groups: one group (supplementary, SUP) ingested BCAA beverages ( $n = 12$ ); the second group (placebo, PLA) ingested artificially flavored water ( $n = 12$ ). Diet was controlled throughout the testing period to match habitual intake. The eccentric exercise protocol consisted of  $12 \times 10$  repetitions of unilateral eccentric knee extension exercise at 120% concentric one repetition maximum. On the day of the exercise, supplements were consumed 30 min before exercise, 1.5 h after exercise, between lunch and dinner, and before bed. On the following 2 d, four supplements were consumed between meals. Muscle soreness, muscle function, and putative blood markers of muscle damage were assessed before and after (1, 8, 24, 48, and 72 h) exercise. **Results:** Muscle function decreased after the eccentric exercise ( $P < 0.0001$ ), but the degree of force loss was unaffected by BCAA ingestion ( $51\% \pm 3\%$  with SUP vs  $-48\% \pm 7\%$  with PLA). A decrease in flexed muscle soreness was observed in SUP compared with PLA at 48 h ( $21 \pm 3$  mm vs  $32 \pm 3$  mm,  $P = 0.02$ ) and 72 h ( $17 \pm 3$  mm vs  $27 \pm 4$  mm,  $P = 0.038$ ). Flexed muscle soreness, expressed as area under the curve, was lower in SUP than in PLA ( $P = 0.024$ ). **Conclusions:** BCAA supplementation may attenuate muscle soreness, but it does not ameliorate eccentric exercise-induced decrements in muscle function or increases in reputed blood markers of muscle damage, when consumed before exercise and for 3 d after an eccentric exercise bout. **Key Words:** NUTRITION, UNACUSTOMED EXERCISE, DELAYED ONSET MUSCLE SORENESS, MUSCLE FUNCTION

Unaccustomed eccentric exercise results in muscular dysfunction (10,19), increased muscle soreness lasting several days (17), and increased concentrations of myofiber proteins (creatine kinase (CK) and myoglobin (Mb)) in the blood (6,17). Increased muscle soreness in combination with loss of muscle force may have a detrimental effect on muscle function (14). Thus, an impaired functional capacity of the muscle may prevent repeated exercise sessions that are required for adaptations to training, that is, an improved tolerance to the stress of resistance exercise or muscle hypertrophy. Thus, nutritional strategies aimed at reducing the deleterious impact of eccentric exercise may be advantageous by allowing repeated exercise bouts of superior quality to be performed.

Recent studies have focused on nutritional interventions during exercise recovery in an attempt to alleviate muscle soreness and impairments in muscle function (17,21,23). Postexercise supplementation of protein and amino acids has been suggested to reduce the negative impact of eccentric exercise (6,17,22). However, the results of these studies are equivocal. Muscle soreness and blood concentrations of myofiber proteins were decreased with supplementation of mixed amino acids ingested in a fed state 30 min before exercise, after exercise, and during the 4-d recovery period (17). Supplementation of mixed amino acids twice a day for 10 d resulted in an attenuated loss of isometric contraction force after eccentric exercise training (23). Similarly, during the first week of a 4-wk intensified training resistance protocol, impairments in maximum strength of squat and bench press were attenuated with  $0.4 \text{ g} \cdot \text{kg}^{-1} \cdot \text{d}^{-1}$  of amino acid supplementation (11).

Conversely, mixed amino acid supplementation of shorter duration before and after exercise in a fasted state had no impact on muscle soreness or blood myofiber proteins (17). Likewise, White et al. (30) demonstrated no differences in muscle function or soreness when comparing a protein/carbohydrate supplement to a placebo administered in a fasted state before or after eccentric quadriceps exercise. Discrepancies between studies may be caused by the type or the amount of amino acids in the supplements, whether the

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Submitted for publication March 2009.

Accepted for publication September 2009.

0195-9131/10/4205-0962/0

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DOI: 10.1249/MSS.0b013e3181c1b798

supplements are coingested with other nutrients, the duration of supplementary period, the degree of dietary control, or the measurement tool used to assess the negative indices associated with an intense eccentric exercise. Therefore, the effectiveness of amino acid or protein supplementation on attenuating muscle function loss and elevation in muscle soreness and blood myofiber proteins seems somewhat equivocal at present.

Positive effects of amino acid supplementation have been claimed to be related to the branched-chain amino acids (BCAA) (17). Recent interest has focused on the effectiveness of BCAA in reducing the negative symptoms associated with an intense exercise (6,8). To our knowledge, only one preliminary study has investigated BCAA supplementation and recovery from intense eccentric exercise (22). These authors reported a reduction in muscle soreness after squat exercise with supplementation of only 5 g of BCAA in females (22). However, BCAA were ingested only once. At present, no data demonstrating the beneficial role, if any, of ingestion of multiple supplements containing BCAA after intense eccentric exercise in males exist. Therefore, despite some evidence for the efficacy of BCAA in the amelioration of adverse indices associated with an intense exercise, the effectiveness of BCAA is not clearly established.

Pilot data from our laboratory suggest that high doses of whey protein ingestion may impact muscle soreness after resistant exercise. Mixed amino acids have also been shown to impact muscle soreness (17). BCAA have been suggested to be the active ingredient (17,22). The aim of this study was to investigate the effectiveness of BCAA supplementation for the attenuation of the deleterious impact of an intense eccentric exercise bout in healthy males with no previous experience of regular resistance exercise. In accordance with the study of Nosaka et al. (17) showing an effect of amino acid supplementation, we provided supplements before and in the 4 d following the eccentric exercise bout. In contrast to many previous studies, this study implemented strict dietary control to ensure that any differences that were observed could be attributed to the additional BCAA intake. We hypothesized that BCAA supplementation would ameliorate the negative symptoms associated with unaccustomed eccentric exercise, including muscle soreness, loss of muscle function, and increased myofiber protein concentrations in the blood, when compared with a placebo.

## METHODS

**Participants.** Twenty-four non-weight-trained males were recruited for this study, which was approved by the University of Birmingham School of Sport and Exercise Sciences ethics subcommittee. Subjects were made aware of procedures, including the risks and benefits, gave written informed consent, and completed a general health questionnaire. Participants were able to withdraw from the study at any point without provision of reason. All participants refrained from physical activity and alcohol consumption

for 2 d before testing and throughout the testing period. Participants were excluded if they had a previous history of resistance training or had completed high-intensity eccentric exercise within the last 6–9 wk (5). No subject reported experiencing rhabdomyolysis, a syndrome characterized by muscle breakdown and necrosis resulting in the leakage of intracellular muscle constituents into the circulation and extracellular fluid (29).

**General design.** Subjects were assigned to either a supplementary (SUP) or placebo (PLA) group and performed one single-blind experimental trial. Groups were matched for weight and one repetition maximum (1RM). Subject characteristics are shown in Table 1. An eccentric exercise protocol was implemented to allow the comparison of putative blood markers of muscle damage, muscular dysfunction, and muscle soreness between SUP and PLA. Subjects consumed four supplements daily between meals. The composition of the supplement consumed by the participants in SUP was 3.5 g of leucine, 2.1 g of isoleucine, and 1.7 g of valine mixed in 300 mL of artificially sweetened and flavored water. The control supplement contained 300 mL of artificially sweetened and flavored water. The artificial sweetener was free of amino acids.

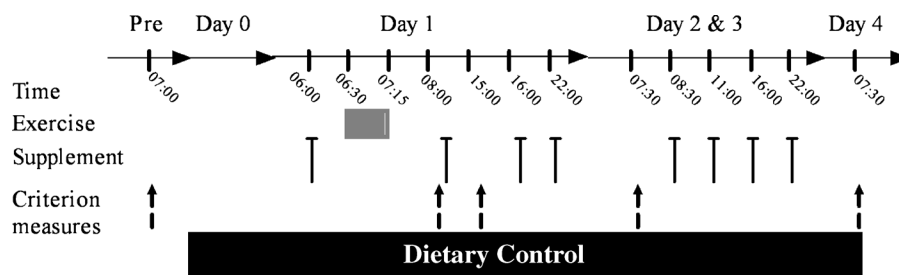
**Before testing.** Subjects visited the laboratory for preliminary measurements on two occasions. On the first leg, the volume of the nondominant leg was calculated (31). Determination of 1RM of their nondominant leg followed using a Cybex leg extension machine (Cybex International Medway, MA). The subjects lifted an initial load, which was then increased in increments of 2.5 kg. The subjects were instructed to lift the weight, hold it outstretched for 2 s, and then slowly lower it. The subjects rested for 3 min between lifts to minimize the impact of fatigue. The subjects were given a second attempt after the rest period if they failed with any given lift. This session also served as a familiarization for the eccentric exercise protocol that followed. The familiarization involved two lifts at 50% of their concentric 1RM in which the weight was lifted by the researchers for the subject to lower. The subjects were strapped into the chair to ensure that the weight was lifted using only their leg. The subjects' nondominant leg was positioned at 90° to their torso, with their knee flexed to approximately 110°. The lift started with the exercising leg positioned at approximately 15° of flexion. Two testers lifted the weight to its full extension; a “contract” command prepared the subjects for the weight to be lowered. This command was followed by the command “release,” and the weight was released onto the subjects' leg and was then lowered by the subjects, resisting the load. The weight

TABLE 1. Participants' characteristics.

	Weight (kg)	Height (m)	1RM (kg)	Leg Volume (mL)
SUP	72.8 ± 10.4	1.80 ± 0.1	61.2 ± 9.3	5512 ± 1353
PLA	74.9 ± 9.1	1.80 ± 0.1	62.3 ± 9.5	5725 ± 1094

Values are expressed as means ± SD.

Leg volume, volume of the upper leg that was exercised, calculated via anthropometry (28).



**FIGURE 1**—Schematic protocol depicting the duration of the study. Criterion measures include muscle soreness measures, blood draw, and muscle function tests. Exercise = 12 sets of 10 repetitions of eccentric knee extensions at 120% concentric 1RM. Supplements were consumed four times on the day of and 2 d after the exercise and were either BCAA or placebo.

was then lowered through 95° to bring the weight back to rest. The participants aimed to control the weight in the downward movement for 4 s; if the movement was shorter in duration, another repetition was completed. On the second visit to the laboratory, preliminary measurements were taken. These involved the measurements taken at each time point, that is, the visual analog scale (VAS), a blood draw, and muscle function tests.

**Experimental protocol.** On the day of the exercise protocol, subjects reported to the laboratory at ~06:00 h after an overnight fast (Fig. 1). The subjects ingested their first supplement followed by a 30-min rest. The eccentric exercise protocol was then performed, which lasted approximately 45 min. Subsequently, the subjects rested for 1 h before the first measurements were done. Pain was assessed using the VAS, followed by a blood draw. Finally, the participants' muscle function was assessed via maximal isometric strength (MIS) and low-frequency fatigue (LFF) as described below. The order of these measurements was standardized for 8, 24, 48, and 72 h after exercise to eliminate measurement order from confounding results. After completion of the 1-h testing, the participants consumed another supplement before breakfast. A third supplement was ingested between lunch and dinner, and the fourth was at bedtime. On the 3 d following the exercise bout, all measurements were taken in the morning in the fasted state with the exception of the 8-h time point. To maximize measurement reliability, all measurements were carried out by the same investigator for each subject.

**Diet and activity.** Before each trial, the subjects were instructed to record a weighed 3-d diet record, including at least one weekday and one weekend day. An average energy intake from these 3 d was calculated and used to determine the individuals' energy requirements. Food was prepared and supplied to the subjects to ensure that any differences observed could be attributed to the supplements, and diets were comparable between subjects. The diet was

composed of 55% carbohydrates and 1.5 g of protein·kg<sup>-1</sup> body mass (BM), with the remainder of the energy from fat. Prepared food was administered the day before, the day of, and 2 d after the eccentric exercise protocol. The food composition for the study is shown in Table 2.

**Eccentric exercise protocol.** Subjects were seated as described previously and completed 12 sets of 10 eccentric repetitions at 120% concentric 1RM, with 5-s rest between each repetition and 1-min rest at the end of each set. If the subject failed to control the weight for two consecutive repetitions, a rest period of 30 s was given. During each eccentric contraction, the subject was verbally encouraged to exert maximum effort.

**Muscle function.** MIS was assessed using electrical stimulation with a Tornvall chair (7). Participants were seated so the knee was at 90° with a cord fastened around the ankle. This cord was attached to a strain gauge interfaced with a computer. Two arm straps held the subject in place in the chair. Damp electrodes (13 × 8 cm) were secured to the thigh over the proximal and distal ends of the quadriceps. The participants were electrically stimulated at their maximal electrical stimulation three times before being encouraged to push out with their leg against the cord as hard as possible. Three electrical stimulations were superimposed while contraction was occurring to ensure that the contraction was maximal. This procedure occurred three times at each time point. The highest force obtained for each leg represented the subjects' MIS. Another measurement of muscle function is LFF, that is, a loss of force at low-frequency stimulation common in damaged muscle (7,10). Force frequency measurements occurred at one-third of the maximal electrical stimulation current. Electrical stimulation of the quadriceps at 20 and 100 Hz for 2 s was performed in random order. The relationship between 20 and 100 Hz was used as an assessment of LFF. This procedure with electrical stimulation has been shown to not affect the response to eccentric exercise (14).

TABLE 2. Diet composition of food provided to the subjects.

	Energy	Protein		Carbohydrate		Fat	
	kJ	g·kg <sup>-1</sup> BM·d <sup>-1</sup>	% En	g·kg <sup>-1</sup> BM·d <sup>-1</sup>	% En	g·kg <sup>-1</sup> BM·d <sup>-1</sup>	% En
SUP	12,305 ± 1677	1.5 ± <1	15 ± 3	5.7 ± 1.1	55 ± <1	1.4 ± 0.4	30 ± 3
PLA	12,026 ± 2074	1.5 ± <1	16 ± 3	5.3 ± 0.8	55 ± 4	1.3 ± 0.4	29 ± 6

Values are expressed as means ± SD. % En, percentage of total energy intake.

**Muscle soreness.** The subjects rated general muscle soreness and soreness with the knee flexed and extended using VAS. The VAS consisted of a 50-mm line with anchor points of “no soreness” on the left and “extremely sore” on the right. Subjects marked a point along the line, which represented the perceived soreness felt in the quadriceps muscle group. Pain was given a value by measuring the distance from the left anchor point. It has been shown that 90% of pain ratings can be repeated within 9 mm using the VAS (2).

**Blood analysis.** Plasma concentrations of CK and Mb were used to assess commonly measured putative markers of muscle damage. Serum was collected and analyzed for interleukin-6 (IL-6) as an indirect marker of inflammation. Blood was drawn from the forearm vein of each subject at each testing point. Plasma samples were placed on ice, and serum samples were left at room temperature for 30 min to allow clotting. Samples were centrifuged at 3000 rpm for 10 min at 4°C. Plasma and serum were extracted and stored in the freezer at -20°C until further analysis. Enzymatic analyses for plasma concentrations of CK (CK NAC CP; ABX Diagnostics, Northampton, UK) and Mb (myoglobin CP; ABX Diagnostics) were performed in duplicate at each time point using a semiautomated analyzer (COBAS MIRA S-plus; ABX Diagnostics). Serum concentrations of IL-6 were analyzed using commercially available sandwich enzyme-linked immunosorbent assay (ELISA; High sensitivity Human IL6 Assay; R&D Systems, Abingdon, UK). Plates were read in duplicate on a Labsystems Original Multiskan MS at selected wavelengths (490 nm, with correction at 630 nm). The reported sensitivity of the ELISA was 0.039 pg·mL<sup>-1</sup>.

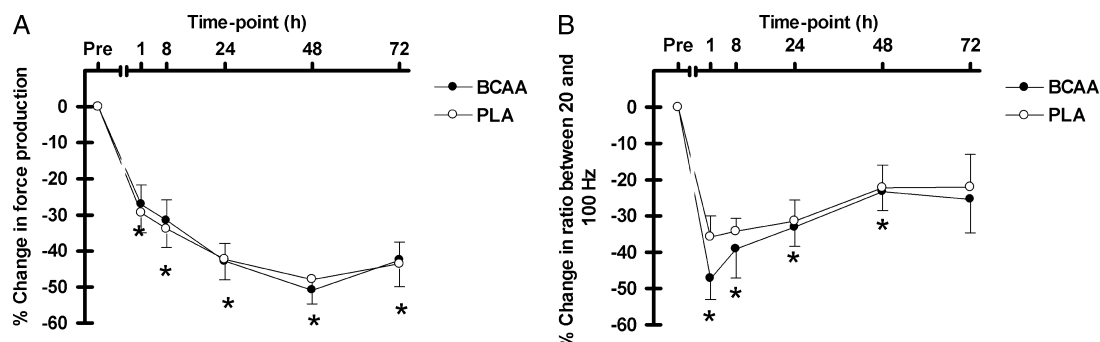
**Data presentation and statistical analysis.** Data were analyzed using the Statistical Package for Social Sciences (SPSS) 15.0 for Windows (SPSS, Inc., Chicago, IL). Differences across time for blood concentrations, force loss, and VAS scores were analyzed by a mixed-design, two-way ANOVA with two between-subjects (SUP and PLA) and six or four (depending on variable analyzed) within-subject (time points) variables. Significance was set at the 0.05 level of confidence. Where significance was found, least significant difference *post hoc* tests were run to

distinguish differences between supplementary groups. Missing data points were averaged from the other data sets for that time point and group. This manipulation allowed a higher number of subjects to be included in the analysis to improve statistical power. VAS scores are shown as raw values and area under the curve (AUC) to give an indication of soreness during the 72-h experimental period. AUC baseline values were taken as a mean of preliminary values. Force frequency data were obtained by averaging the values during a 1-s period (0.8–1.8 s). Force frequency is calculated as the ratio between force values at 20 and 100 Hz and shown as a percentage of baseline values. Because of technical difficulties in this measure, data are shown for only  $n = 10$  in each group. MIS data were taken from the best value of three attempts and converted into newtons from the volts value obtained. MIS values are shown as a percentage of the preexercise value to show the force that was lost, and using the preexercise value as a baseline. It was not possible to collect blood from one subject in PLA. Plasma CK and Mb are depicted as a percentage of the individual participants' maximum. Serum IL-6 concentrations are shown as mean.

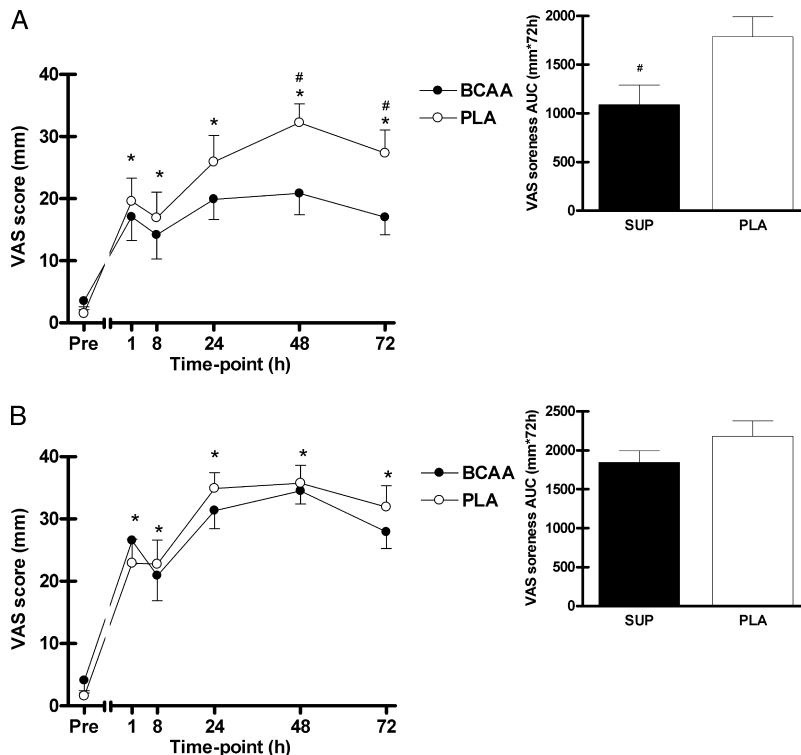
Data were also analyzed using inferential statistics with 90% confidence limits (CL) to produce magnitude-based values about the probabilities of the outcome (1). For overall flexed soreness, an effect was assumed to be a change of 143 mm × 72 h, and for extended soreness, this value was 137 mm × 72 h. These values were derived from the smallest standardized (Cohen) difference in mean (0.2) multiplied by the SD of PLA. The likelihood of the outcome being of beneficial or detrimental nature was also determined using a published spreadsheet (9). When the value is determined to be <1% detrimental or beneficial, it is almost certainly not; 1%–5% very unlikely, 5%–25% unlikely, 25%–75% possible, 75%–95% likely, 95%–99% very likely, and >99% almost certain.

## RESULTS

**Muscle function.** A decrease in MIS (Fig. 2A) and in the force–frequency ratio (Fig. 2B) was apparent in all



**FIGURE 2**—Percentage change in leg muscle function before and after an intense eccentric exercise bout. Depicted as (A) electrically stimulated MIS or (B) 20:100 Hz force–frequency relationship. SUP = closed circles (A,  $n = 12$ ; B,  $n = 10$ ) and PLA = open circles (A,  $n = 12$ ; B,  $n = 10$ ). Data are expressed as means  $\pm$  SE. \*Significant difference from baseline in both groups.



**FIGURE 3**—Muscle soreness before and after an intense eccentric exercise bout measured using a 50-mm VAS. *A*, Knee in a flexed position; insert italicize shows AUC. *B*, Knee in an extended position; insert shows area under the curve. SUP = black bar/closed circles ( $n = 12$ ); PLA = white bar/open circles ( $n = 12$ ). \*Significant difference from baseline. #Significant difference of SUP from PLA.

subjects after exercise without difference between groups. The maximal percentage of force loss assessed using MIS was observed 48 h after exercise in both groups (SUP =  $-51\% \pm 3\%$ , PLA =  $-48\% \pm 7\%$ ). The lowest force–frequency ratio was observed at 1 h after the eccentric exercise (SUP =  $-42\% \pm 6\%$ , PLA =  $-47\% \pm 5\%$ ).

**Muscle soreness and inflammatory responses.**

The response of muscle soreness to eccentric exercise is illustrated in Figure 3. The eccentric exercise protocol resulted in increased overall soreness in both groups. However, no statistical differences were detected between SUP and PLA. Muscle soreness was also increased both with the knee flexed and extended. Soreness ratings tended to be lower at 8 h compared with that at 1 h. Soreness then continued to significantly increase to peak soreness observed at 48 h. A main effect of SUP was observed ( $P < 0.05$ ). SUP resulted in a decrease in quadriceps muscle soreness with the knee flexed compared with PLA at both 48 h ( $21 \pm 3$  mm vs  $32 \pm 3$  mm,  $P = 0.02$ ) and 72 h ( $17 \pm 3$  mm vs  $27 \pm 4$  mm,  $P = 0.038$ ) after exercise (Fig. 3A). There were no significant differences between SUP and PLA with the knee in an extended position. During the total 72-h experimental period when data are expressed as AUC, muscle soreness with the knee flexed was 64% less for SUP compared with PLA ( $P = 0.024$ ; Fig. 3A). There were no statistical differences between SUP and PLA AUC with the knee in an extended position.

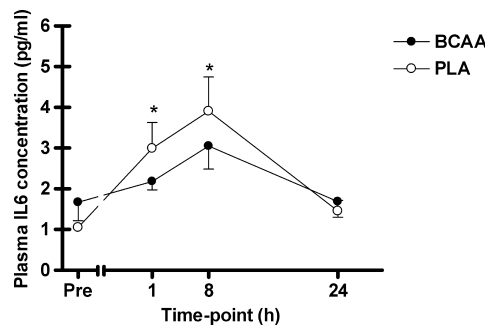
Evaluation using inferential statistics showed that SUP was 96.7% very likely beneficial ( $700 \pm 490$  mm, 90% CL)

for the amelioration of muscle soreness with the knee flexed. Furthermore, the positive effect of BCAA in the extended position was 78.5% likely beneficial ( $300 \pm 420$  mm, 90% CL; Fig. 3B).

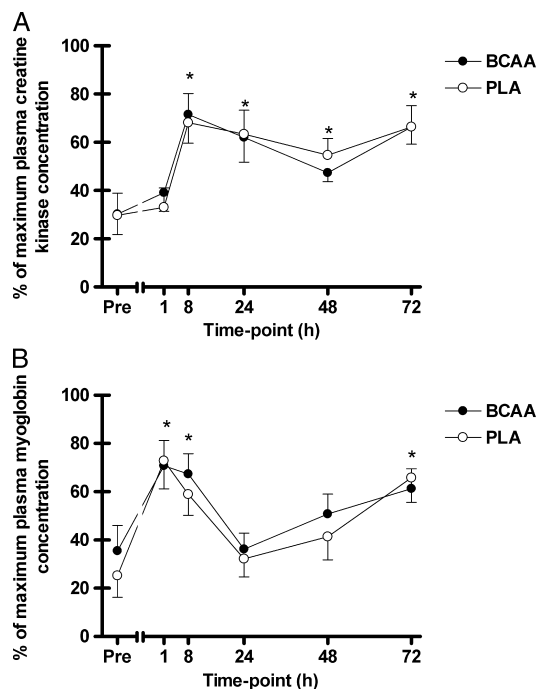
**Blood parameters.**

Serum IL-6 data are depicted in Figure 4. IL-6 concentrations significantly increased after the eccentric exercise protocol in both groups ( $P = 0.02$ ). At 24 h after exercise, IL-6 concentration had returned to normal. There were no differences in IL-6 concentrations observed between SUP and PLA.

Plasma CK ( $P < 0.001$ ) and Mb ( $P < 0.001$ ) concentrations increased after exercise and remained elevated throughout the testing period (Fig. 5, A and B, respectively). Peak



**FIGURE 4**—Serum IL-6 concentration measured before and at 1, 8, and 24 h after exercise. SUP = closed circles ( $n = 12$ ); PLA = open circles ( $n = 11$ ). Data are means  $\pm$  SE. \*Significant difference from baseline in both groups.



**FIGURE 5**—Myofiber concentrations in the plasma before and after an intense eccentric exercise bout expressed as a percentage of maximum: CK (A) and Mb (B) concentrations. SUP = closed circles ( $n = 12$ ); PLA = open circles ( $n = 11$ ). Data are means  $\pm$  SE. \*Significant difference from baseline.

CK concentrations were observed between 8 and 24 h after exercise. Peak Mb concentrations were observed between 1 and 8 h after exercise. There were no significant differences observed between groups for plasma concentration of CK or Mb. In both blood metabolite concentrations, a large inter-subject variability was observed.

## DISCUSSION

In the present study, we investigated the effects of BCAA supplementation on recovery from intense eccentric exercise under conditions of strict dietary control. Our findings are the first to suggest a beneficial role for BCAA supplementation after intense eccentric exercise in males. We observed a reduction of overall soreness in the quadriceps muscle with the knee in the flexed position. In addition, we calculated that there was a likely beneficial effect of BCAA supplementation with the knee in an extended position. No differences in plasma myofiber concentrations, indirect measurement of inflammation, or muscle function were detected between BCAA and placebo supplementary conditions when supplements were provided before and for 3 d following an intense eccentric exercise bout.

Amino acids intake may affect muscle soreness. Supplementation with mixed amino acids (nine essential and three nonessential) has previously been reported to decrease muscle soreness (17). In the present study, nontrained subjects ingested only three amino acids (leucine, valine, and isoleucine) at multiple time points after exercise. Our results

demonstrated that muscle soreness after eccentric exercise was attenuated in the SUP group, suggesting that BCAA are the active ingredient in protein for reducing muscle soreness. Interestingly, no effect of nutritional supplements containing BCAA in combination with other amino acids on muscle soreness has been observed in other studies (17,30). Reasons for this discrepancy may be related to the length of the supplementary period and the total quantity of BCAA ingested.

The amount of BCAA ingested may be a particularly important factor for amelioration of muscle soreness. Conflicting findings between present and previous studies may be explained by the length of supplementary period and, consequently, total intake of amino acids. Our subjects consumed supplements before exercise and throughout the 3-d recovery period, resulting in reductions in muscle soreness. Conversely, previous studies (17,30), which used supplements on only one or two occasions, observed no differences in muscle soreness between experimental and control conditions. Interestingly, data in a review paper (22) demonstrated reduced muscle soreness after squat exercise with only a single bolus (5 g) of BCAA. However, this effect was observed in females but not in males. The authors (22) attributed the difference to the fact that the females consumed a larger amount of BCAA relative to their muscle mass compared with the males, rather than a sex effect *per se*. Despite not having female subjects, our findings may lend some support to this assertion. In our male subjects, the total amount of BCAA intake per kilogram BM was even greater than that in the females in the aforementioned study (22), resulting in decreased soreness. Thus, it seems feasible to suggest that a relatively large BCAA intake may be necessary for any reductions in muscle soreness.

Taken together, the results of our study and those reported by Shimomura et al. (22) may suggest a threshold amount of BCAA relative to individuals muscle mass, and to observe a decrease in muscle soreness, this threshold must be reached. Therefore, future studies should investigate BCAA intake relative to muscle mass.

The exact mechanism by which BCAA supplementation decreases muscle soreness cannot be deduced by our study design. Intense eccentric exercise is known to lead to an inflammatory response increasing the release of the cytokine IL-6 (3). The exact cause of muscle pain is unknown; however, it has been suggested that inflammation of the perimysium or epimysium may be causing the pain (12). The inflammatory response results in a sensitization of the muscle nociceptors leading to the common feeling of soreness (19). In the present study, we measured IL-6 as an indirect marker of inflammation. In accordance with previous studies that implemented carbohydrate feeding, no differences in IL-6 concentration were observed at any time point with BCAA supplementation when compared with the placebo condition (13). Our results suggest that BCAA supplementation did not alter this inflammatory response, and

therefore, the BCAA are unlikely to mediate soreness via the inflammatory pathway. Alternatively, soreness was reduced in both groups at 8 h after exercise when subjects were in an early postprandial state. It may therefore be suggested that the extra energy intake from the supplements of  $\sim 117 \text{ kcal}\cdot\text{d}^{-1}$  in SUP may have led to the decrease in soreness observed; however, no mechanism is clearly indicated.

Soreness may be modulated by feeding. Lower muscle soreness scores were recorded at 8 h compared with 1 h after exercise in 19 of the 24 subjects. Measurements collected 8 h after the eccentric exercise were typically performed at  $\sim 15:00$  h when participants were in a postprandial state, having eaten lunch within the previous 3 h. We therefore propose that feeding may be responsible for this temporary reduction in perceived feelings of soreness. The present study is the first to record criterion measurements within 3 h of a meal. Recently, a novel experimental design was implemented (17), whereby eccentric exercise was performed in a fed and supplemented state. Analogous to our findings, mixed amino acid supplementation provided before and for 4 d after exercise attenuated muscle soreness compared with a placebo group (17). Taken together, these data suggest that amino acid supplementation combined with food intake may attenuate muscle soreness, possibly due to a larger availability of all amino acids. The association between soreness and feeding is an interesting concept; future studies should investigate whether there is a synergistic relationship. Other nutrients including carbohydrate and fat particularly in association with protein or amino acids should be investigated with regard to the impact on muscle soreness after intense eccentric exercise. Alternatively, the delivery pattern of the amino acids may be modulated when combined with other nutrients, thus resulting in the reduced soreness observed in this study after a meal.

Intense bouts of eccentric-based exercise induce decrements in muscle function in untrained individuals (17,23,30). In the present study, BCAA supplementation failed to ameliorate impairments in MIS. However, previously, Sugita et al. (23) exercised the elbow extensor muscles and provided a mixture of 12 amino acids for 10 d after eccentric exercise. These authors (23) reported attenuations in reductions of strength on days 2 and 3 after exercise. Some additional amino acids were ingested in the aforementioned study compared with the present study. It may be suggested that all essential amino acids, not only BCAA, may be necessary for the successful amelioration of loss of muscle function. However, more recent studies (17,30), which supplemented a mixture of amino acids or protein, showed no effect on muscle function compared with placebo. Thus, future studies are required to fully elucidate how muscle function can be improved via nutritional interventions after an intense eccentric exercise.

The shift in force–frequency relationship we observed mirrors those associated with LFF and is synonymous with damaged muscle. Consistent with previous studies (14,15,20), the data in the present study demonstrated a greater reduction in

force at low frequencies compared with high frequencies after intense eccentric exercise (10). The present study was the first to investigate the effect of amino acid supplementation on LFF. However, BCAA ingestion did not affect the observed effect. Thus, in the present study, we observed no effect of BCAA on either measure of muscle function. Therefore, our data demonstrating that BCAA ingestion decreased soreness but had no effect on decrements in muscle function support previous research (28) that suggests that the relationship between muscle function and soreness is unclear.

Muscle function after intense exercise may be, at least partially, decreased owing to increased muscle soreness. Twist and Eston (26) demonstrated that exercise-induced muscle damage increases perceived exertion and decreases performance during intense exercise. Although our study was not designed to investigate a relationship between muscle soreness and function, our result may offer some insights into this relationship. In the present study, soreness increased and muscle function decreased after eccentric exercise as expected. However, although BCAA supplementation decreased muscle soreness, it had no impact on impaired muscle function. The most likely explanation for the apparent disconnect between the alleviation of muscle soreness with impaired muscle function is methodological. We used electrically stimulated maximal voluntary contraction to test the function of the muscle independent of motivation—or lack thereof—thus minimizing, if not eliminating, any unwillingness to exert maximal force because of muscle soreness. Therefore, even if soreness was greater, the muscle function would not be affected. Alternatively, or in addition, the decrease in muscle soreness with BCAA supplementation might not have been sufficient to influence muscle function. More investigations specifically designed to investigate the relationship between soreness and function should be conducted.

Previous authors attributed the attenuation of deleterious indices of eccentric exercise with amino acid supplementation to a modulated protein turnover (22). It is clear that essential amino acids stimulate muscle protein synthesis after exercise (24,25) and that resistance exercise with an eccentric component stimulates muscle protein synthesis (18). Muscle protein turnover rates are low compared with other tissues (27); thus, increases in the rate of muscle protein remodeling are likely to be insufficient to remodel enough proteins to explain these results in the short recovery period implemented in the present and previous studies. No study to date has measured protein synthesis and breakdown in an experimental model of eccentric exercise and nutrition supplementation. It is difficult to comprehend that increased protein synthesis would account for improvements observed during only 2–3 d of recovery. Furthermore, it is difficult to imagine how increased net muscle protein balance could alleviate soreness even if turnover rates were very high.

Intense eccentric exercise is known to elicit the release of CK and Mb into the blood. In the present study, we observed increased plasma concentrations of both CK and

Mb after exercise; however, BCAA did not alter the response. When comparing the magnitude of the CK response to endurance exercise in previous studies (6) with that observed in the present study, eccentric-based exercise induces a higher CK response than endurance exercise. A reduction in CK activity with BCAA supplementation has previously been observed after eccentric exercise (6). We suggest that after intense eccentric exercise, when a greater CK response is observed, more amino acids are required to reduce the release of myofiber proteins into the blood from muscle sarcolemma.

CK and Mb levels are often erroneously considered as markers of muscle damage; in fact, they are actually indicative of membrane disruption. We measured myofiber concentrations to allow comparisons between other studies; however, results showed a large variation in CK values between individuals. We demonstrate the peak response to be at 8 h after the exercise protocol, which is earlier than previously demonstrated (28). However, within our results, some subjects showed very high levels of CK compared with other individuals who showed very little increase in CK. Large interindividual variability often observed in CK concentrations (4) may have accounted for the discrepancies in peak between this and previous studies (28). There were no correlations between the increase in CK and loss of muscle force, which is a more practical measure of the ability of the muscle to perform. These data add to existing

data, which suggest that myofiber protein responses are individualized and therefore may be considered weak predictors of muscle damage (28).

It is important to consider the practical implications of these results. Any attempt to extrapolate data generated in the present study to a trained population may be nonsensical because untrained subjects were recruited. Athletes may respond differently because of the repeated bout effect (5,14, 16) and the associated adaptations. However, these data may be applied to individuals starting an exercise regimen, or athletes returning to training after injury or off-season may benefit from supplementing their diet with BCAA.

In summary, supplementing a controlled diet with 29.2 g·d<sup>-1</sup> of BCAA directly before and during short-term recovery resulted in a decrease in soreness with the knee flexed and extended. However, BCAA supplementation failed to ameliorate impairments in muscle function typically associated with an intense eccentric exercise. No alterations in levels of myofiber proteins were observed in the plasma with BCAA supplementation. In conclusion, BCAA may be an effective aid in reducing soreness after intense eccentric exercise in healthy untrained males.

No funding was received for this study. There are no conflicts of interests for any of the authors.

The results of the present study do not constitute endorsement by the American College of Sports Medicine.

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