MedCrave
Step into the World of Research
Journal of Nutritional Health & Food Engineering

Review Article

Open Access

Efficacy of BCAA supplementation for exercise performance and recovery: a narrative review

Abstract

The BCAAs (leucine, isoleucine, and valine) are essential amino acids able to bypass metabolism in the liver after ingestion and be oxidized directly within skeletal muscle. A consistent state of turnover between protein synthesis and protein degradation exists within skeletal muscle, and the rate of turnover can be accelerated with exercise. Because intense exercise can increase the protein turnover rate, skeletal muscle may require additional intake of BCAAs in the attempt of attenuating muscle protein breakdown following exercise. Moreover, the products of BCAA oxidation include Kreb Cycle intermediates and ketones, suggesting a potential role for protein/BCAA substrate utilization during exercise. The aim of this review was to investigate the existing evidence behind the purported ergogenic benefits of BCAA supplementation regarding muscle protein synthesis, muscular hypertrophy, various aspects of exercise recovery, muscle damage and inflammation, immune system function, and substrate utilization. BCAAs do not appear to augment improvements in muscular strength, power, or endurance with resistance training, but may be able to preserve these muscle characteristics over time during hypocaloric states. However, BCAAs appear to mitigate elevations in indices of muscle damage in response to acute endurance and resistance exercise, regardless of different damage protocols being utilized. Despite enough evidence showing the ability of BCAAs, particularly leucine, to up-regulate muscle protein synthesis, there is no provision towards additional benefit to performance or adaptations to resistance and endurance training with supplementation. In conclusion, peri-exercise BCAA supplementation appears to be most effective only in terms of recovery between exercise sessions and the preservation of both muscle mass and muscle performance under states of hypocalorism.

Keywords: protein synthesis, skeletal muscle, leucine, muscle strength, hypertrophy

Volume 9 Issue 3 - 2019

Taylor Morse, Darryn S Willoughby
Exercise and Biochemical Nutrition Laboratory Baylor University, USA

Correspondence: Darryn S. Willoughby, Ph.D., Department of Health, Human Performance, and Recreation, Baylor University, P.O. Box 97313, Waco, TX 76798, USA,
Email darryn_willoughby@baylor.edu

Received: December 22, 2019 | **Published:** December 30, 2019

Introduction

Amino acids, the building blocks of protein, are critical for various metabolic processes in the body. Out of the 20 amino acids, 9 are considered to be essential, meaning they cannot be synthesized in the body and must come from the diet. Of these essential amino acids (EAAs), 3 of them are known as branched-chain amino acids (BCAAs). The BCAAs (leucine, isoleucine, and valine) are a special group of essential amino acids due to their ability to bypass metabolism in the liver after ingestion and be oxidized directly within skeletal muscle.[1,2] While skeletal muscle is consistently in a state of turnover between protein synthesis and protein degradation, the rate of turnover can be accelerated with exercise. Increased turnover rates due to exercise require additional protein (amino acid) intake, and consequently, it has been suggested BCAAs may have a unique role in augmenting protein turnover via increases in muscle protein synthesis and/or decreases in muscle protein breakdown.[2–4] Additionally, the end products of BCAA catabolism include Kreb Cycle intermediates and ketones,[2] suggesting a potential role in shifting substrate utilization during exercise.

These properties of BCAAs in particular have led to their rising popularity among many exercisers, including bodybuilders, powerlifters, athletes, and even the typical gym-goer. A majority of well-established sport supplement brands now sell BCAAs, making various claims about their benefits, including their role in supporting muscle, faster recovery, reducing fatigue, and supporting both fat loss and lean mass maintenance during caloric restriction. On the other hand, others in the fitness industry have been claiming that supplementing with BCAAs is ineffective and unnecessary. While fitness "gurus" with differing philosophies may always be debating over the necessity of different sport supplements, the research has the potential to paint a clearer, more objective picture. In the case of BCAAs, however, the research is incredibly mixed. Differences in resistance and endurance exercise protocols, whether dietary control was utilized, the training status of the study participants, whether supplementation was acute or chronic, the dosing of BCAAs, and the specific performance variables under investigation all have an impact on the mixed findings found in the literature, making direct comparisons across individual studies difficult as well.

As a result, this review aimed to further investigate the existing evidence behind the purported ergogenic benefits of BCAA supplementation regarding muscle protein synthesis, muscular hypertrophy, various aspects of exercise recovery, muscle damage and inflammation, immune system function, and substrate utilization. A secondary aim of this review was to explore the use of leucine itself as an alternative to BCAA supplementation on the variables mentioned. Ultimately, the primary goal of this review was to determine whether BCAA supplementation provides a performance or recovery benefit to certain groups of exercisers, or if its suggested value is nothing more than hype.

Efficacy of BCAAs to augment muscle protein synthesis and skeletal muscle mass

Branched-chain amino acids are thought to augment muscle protein synthesis by either upregulating muscle protein synthesis, inhibiting muscle protein breakdown, or through both of these mechanisms. Some researchers are giving credit to the ability of leucine to stimulate the Akt-mTOR pathway,[2] some to decreases in the release of essential amino acids from the muscle following exercise,[3] and others are citing that BCAAs have no anabolic effect on their own.[4] In agreement with [2] and [4] chronic BCAA supplementation was shown to be able to increase skeletal muscle mass index in older individuals in a rehabilitation setting; although rates of muscle protein synthesis or degradation were not measured.[5] Similarly, trained males supplementing with BCAAs were able to preserve their fat free mass during an 8 week resistance training program while on a hypocaloric "cut" diet.[6]

In contrast, [7] found peri-exercise BCAA supplementation for 8 weeks did not result in significant changes in fat-free mass in a group of trained males who were not hypocaloric. Additionally, BCAA co-ingestion with carbohydrate in the peri-exercise period was not found to provide any additional benefit to carbohydrate supplementation alone on the PI3K/Akt-mTOR pathway involved in stimulating muscle protein synthesis.[8] These results agree with the conclusions drawn by [4] in a review of branched-chain amino acids and protein synthesis. Wolfe[4] concluded based on results of various studies that BCAAs alone do not have an anabolic effect. Further, he cites empirical data indicating that rather than stimulating muscle protein synthesis, intravenous infusion of branched-chain amino acids decreases rates of muscle protein synthesis and muscle protein breakdown, decreasing overall muscle protein turnover. The most likely limiting factor for muscle protein synthesis when consuming BCAAs is the availability of the six other essential amino acids, which will end up coming from protein breakdown if not through exogenous means. While other researchers claim to find BCAAs to increase muscle protein synthesis rates, many of them do not measure actual rates, and instead report activity of signaling pathways involved, which may not always accurately correlate with the rates of protein synthesis and degradation.[4] Although the data do not provide significant amounts of support for BCAA supplementation to dramatically increase muscle size with exercise, there does appear to be some value of BCAAs in maintaining lean body mass over time.

Efficacy of BCAAs on improvements in exercise performance

Resistance exercise performance. The use of BCAA supplementation before, after, and/or during resistance exercise has been investigated both acutely and in more chronic (training) circumstances. Over the course of 8 weeks, BCAAs were found to help maintain muscular strength in the 1RM squat and 1RM bench press even while trained male participants were on a hypocaloric "cut" diet. The carbohydrate group, in comparison, over the course of training did have an increase in squat strength; although less than that of the BCAA group but exhibited a decrease in bench press strength by the end of the training program. While BCAAs showed a benefit in preserving muscular strength, there was not a benefit in muscular endurance (repetitions to fatigue) like there was in the carbohydrate group.[6] Supplementing with BCAAs pre- and post-exercise were also found to be acutely beneficial in trained males to reduce decrements in muscular power 24 hours after strength training. Compared to baseline testing, the reduction in performance of counter-movement jumps and seated shot-pot throws in the BCAA group was less than those observed in the placebo group.[9]

Not all studies using trained males found performance improvements with BCAA supplementation, however. In an acute upper body resistance exercise session, no improvements in strength (compared to baseline testing a few weeks earlier) were found in the BCAA trial or the combined BCAA and carbohydrate trial.[10] The lack of performance improvement seems likely due to insufficient time for significant training adaptations to occur. However, even in untrained males over 8 weeks of resistance training, there was no difference between the strength increases exhibited by BCAA and placebo groups.[7] In this case, performance benefits were due to the training itself, which is expected, but BCAAs were not able to augment this response.

Endurance exercise performance. One of the mechanisms in which BCAAs may be able to improve endurance exercise performance, in theory, is through a reduction in central fatigue. Central fatigue is associated with the ability of the central nervous system to effectively interact with the musculoskeletal system. It is believed to be caused by rising levels of serotonin in the brain as exercise duration increases, leading to fatigue and decrements in performance as a result. BCAAs may have a role in decreasing serotonin concentrations in the brain through their potential impact on free tryptophan (fTRP), a precursor to serotonin, in the blood. Increased BCAA concentrations can decrease the fTRP: BCAA ratio because BCAAs and fTRP competitively bind at the same transport sites along the blood-brain barrier.[3,11,12] Theoretically, this should lead to decreased serotonin synthesis in the brain with prolonged exercise and a reduction or delay in the onset of central fatigue. However, there is a lack of sufficient evidence in the literature to suggest that BCAAs improve endurance performance through this mechanism.

[11]mentions that some researchers have found small improvements in physical and mental performance in different endurance activities when supplementing with BCAAs before and during exercise, but that most of these studies using more "real-world" scenarios have failed to control for numerous confounding factors between treatment groups. Highly controlled lab experiments involving BCAA supplementation during these types of activities have not found any benefit for reducing central fatigue and subsequently improving performance.[3,11] More recently, serotonin levels 10 minutes prior to exercise and 30 minutes after exercise have been found to be significantly lower in college-aged males supplementing with BCAAs 50 minutes before cycling at 70% VO_2 max to exhaustion compared to placebo.[13] These results suggest reductions in fatigue itself and improvements in aerobic performance, but these variables were not directly measured. Similarly, BCAA supplementation in combination with ornithine aspartate was shown to decrease fTRP:BCAA more than placebo, and also improve multiple-choice reaction time, a measure of psychomotor performance, in trained males.[12]

While psychomotor performance could be improved with BCAA supplementation, measures of aerobic performance were not improved,[12] and the co-ingestion of BCAAs with ornithine aspartate (used to delay fatigue through the reductions in ammonia) interferes with the interpretation of the effects of BCAAs alone on these outcomes. A different study, however, using BCAAs alone, found an significant increase in VO_2 max and the VO_2 at the lactate threshold (thus displaying a higher lactate threshold) compared to placebo following one week of supplementation in trained males.[14] Similarly, "volunteer subjects" supplementing with BCAAs for three days displayed greater resistance to fatigue, demonstrated by a greater time to exhaustion one day following exercise-induced muscle glycogen depletion.[15] On the contrary, BCAAs consumed before and 60 minutes into cycling did not provide a performance benefit compared to placebo in untrained males. In fact, carbohydrate supplementation was more effective in improving distance traveled in the time trial compared to BCAAs and placebo.[16]

In addition to direct measures of aerobic performance, differences in rating of perceived exertion (RPE) and respiratory exchange ratio (RER) in response to BCAAs were also found in the literature. Both [17] and [15] demonstrated decreases in RER in their BCAA trial subjects compared to placebo, suggesting a higher reliance on fat oxidation, which was found along with improvements in aerobic performance in both scenarios. [16] on the other hand, did not find an effect of BCAAs on RER, or performance either. However, an effect was observed for RPE, with significant reductions in RPE compared to placebo and carbohydrate at both 75 and 90 minutes into exercise. This effect on RPE for untrained males was not repeated in the [12] study with trained males.

Efficacy of BCAAs on recovery from exercise

Recovery from Resistance Exercise. While the influence of BCAAs on resistance exercise performance directly does not appear very promising, it is theorized that supplementation has more potential to impact the recovery of muscle performance variables between exercise bouts. For example, BCAAs were found to have a beneficial impact on the recovery of power output following muscle-damaging exercise as measured by counter-movement jump height,[9,18] seated shot-put throw,[9] and leg press exercise.[19]

[9] and [18] both found that the decrement in BCAA groups' power production was not as great as that found in the placebo group 24 hours after the exercise bout, but it did not return to baseline within their 48-hour observation period. [19], however, saw mean average and mean peak power output return to baseline 48 hours after the exercise bout in those taking BCAAs alone. This difference may be due to the length of the supplementation period in which [19] had participants supplementing for 11 days prior to the muscle damage protocol, while the other studies only had participants supplement peri-exercise. Additional differences could also be coming from the muscle damage protocol used. While all studies demonstrated that the exercise induced muscle damage, using creatine kinase (CK) as one of the markers, [9] and [18] utilized traditional multi-joint resistance exercises, and [19] utilized a multitude of drop jumps. In contrast, [20] also utilized a drop jump protocol to evoke muscle damage and did not find BCAAs to have any benefit on the recovery of counter-movement vertical jump height compared to placebo. Similarly, BCAAs were not found to attenuate reductions in counter-movement jump height following an eccentric-exercise focused damage protocol either.[21] The degree of muscle damage participants are undergoing is likely a factor in these mixed outcomes.

In regards to the recovery of muscular strength following exercise induced muscle damage (EIMD), static strength measured as maximal isometric voluntary contraction force or peak isometric force of the knee extensors has been positively influenced through BCAA supplementation before and after exercise in trained males,[18,20,21] but it does not seem to accelerate recovery of dynamic strength measured as an individual's 1RM back squat.[22] In this study measuring dynamic strength, however, this was the conclusion comparing co-ingestion of BCAA supplementation with carbohydrate to carbohydrates alone rather than just to a placebo. This same study did not find BCAAs to have any added benefit in addition to carbohydrate to mitigate decreases in isometric knee extensor strength either.

The mechanisms most likely responsible for accelerating the recovery of exercise performance variables following EIMD are theorized to involve attenuations in delayed-onset muscle soreness (DOMS), inflammatory markers, and immune responses to exercise.[1,3] Most of the literature is in agreement in regards to peri-exercise BCAA supplementation reducing trained males' perceived soreness following muscle damaging resistance exercise.[18–21,23] Many researchers finding reductions in perceived soreness also found BCAAs to decrease the elevation in serum CK levels[19–21,23] but [18] actually found increases in serum CK 24 and 48 hours post exercise in the BCAA group compared to the placebo group. The reason behind this finding is largely unknown but the researchers speculate that it could be related to the limits of CK as an indicator of muscle damage.[18]

Conversely, [9] and [22] did not find any differences in levels of perceived soreness following exercise between BCAA and non-BCAA groups. The latter study, however, did find that the group taking BCAAs with carbohydrate exhibited a prevention in increases in monocyte percentages compared to the group taking carbohydrate alone. Although the monocyte counts were not different between groups, this may suggest a possible role of BCAAs in attenuating the immune system response in the post-exercise recovery period,[22] which [1] has suggested may be related to the relationship between BCAA catabolism and the L-glutamine pathway. Additionally, acute supplementation of BCAAs throughout a resistance exercise session can decrease elevations in cortisol 60 minutes after exercise.[10] While consuming BCAAs with carbohydrate demonstrated the lowest levels of cortisol, BCAAs alone still resulted in lower cortisol than carbohydrate alone and placebo, which [10] suggest demonstrates the added value of BCAAs in promoting a "less-catabolic" environment post-exercise.

Recovery from Endurance Exercise. Prolonged exercise also has the potential to cause muscle damage and impact the immune system based on the intensity and duration of activity. While moderate intensity aerobic activity is known to increase the secretion of anti-inflammatory cytokines and to have a positive influence on the immune system, when the activity is extremely prolonged the balance of anti-inflammatory to pro-inflammatory cytokines may be impaired and actually make individuals more susceptible to infection.[1] Branched-chain amino acids have been suggested to impact the immune response to exercise via L-glutamine, an amino acid reported to be used as "fuel" for immune cells.[24] Thus, BCAAs may be able to improve recovery following endurance exercise bouts as well.

Similar to the results of studies investigating recovery from resistance exercise, college-aged males supplementing with BCAAs are found to have lower elevations in serum CK compared to placebo following cycling at 70% VO_2 max to exhaustion[13] as well as long-distance runners in the BCAA trial following a 3-day intensive training program.[14] Both of these studies found those with the BCAA treatment to have lower CK at all time points (during and after exercise) compared to placebo groups or trials. Additionally, they both found lactate dehydrogenase (LDH) elevations, another marker of muscle injury or damage, to be reduced in BCAA groups or trials compared to placebo following the experimental protocol. Attenuated CK and LDH responses suggests that BCAAs may be beneficial in reducing muscle damage after prolonged exercise[13,14] Also measured both muscle soreness and feelings of fatigue in participants, finding the BCAA users also exhibited reductions in soreness and fatigue sensation during the intensive training period. These results provide additional support for the role of BCAAs in mitigating muscle damage after endurance activity because of the link between DOMS and EIMD.[3]

Branched-chain amino acids have also been found to have a benefit on the immune system's inflammatory responses to EMID following prolonged exercise. For example, granulocyte elastase (GEL) was an inflammatory marker shown to be reduced after the BCAA trial in addition to the reductions observed in CK, LDH, muscle soreness, and fatigue sensation after three days of intensive endurance training.[14] Similarly, during two to four weeks of BCAA supplementation in elite distance runners and tri-athletes, respectively, BCAAs prevented decreases in plasma glutamine post-competition (30K Run or Olympic Triathlon), recovered the proliferation abilities of monocytes and lymphocytes, and led to differences in cytokine production in the cultured cells characteristic of a shift to a Th1 immune response.[24] While the benefit of the changes among cultured cell cytokine production and proliferation is not entirely clear, it shows an evident effect on the immune system that requires further investigation. Additionally, the ability of BCAAs to mitigate plasma glutamine decreases following prolonged endurance competition in this study supports more recent research regarding the ability of BCAAs to improve or quicken recovery between training bouts from an immune system perspective.

Efficacy of leucine alone as an alternative to BCAAs

Leucine by itself has been suggested by many researchers to be the primary BCAA responsible for the observed effects on muscle protein synthesis and metabolic changes. While leucine has the potential to exert an anabolic effect on skeletal muscle through its activation of the mTOR signaling pathway directly, and possibly due to its ability to increase pancreatic insulin secretion,[25] there is no data to support that isoleucine and valine are able to do the same.[4] Further, all of the BCAAs compete for transport into the muscle, so by taking leucine alone it's suggested that the effectiveness of the anabolic response would be improved.[4] Leucine also can stimulate AMPK and SIRT1 pathways involved in fat oxidation and mitochondrial biogenesis.[25] Activation of both AMPK and mTOR may be involved in the ability of leucine to be associated with an upregulation of gene expression PGC-1 alpha, which further supports its potential to influence the production of new mitochondria. [25] also report that isoleucine and valine are not found to exhibit these same effects related to oxidative metabolism. Increases in gene expression of PGC-1 alpha by leucine have been supported through in vitro studies, as well as the ability of leucine to cause a shift in metabolic preference in myotubes from glycolytic to oxidative.[26]

Altogether this would suggest that leucine itself might be just as effective or even more effective than all three BCAAs together on aspects of muscle protein synthesis, exercise performance, and exercise recovery. However, the literature does not support this notion. One study in particular divided recreationally active individuals (primarily males) into a leucine only group, a BCAA group (2:1:1 leucine: isoleucine: valine), and a BCAA group with extra leucine (4:1:1). Participants were subjected to an eccentric muscle damage protocol on day 8 out of 11 of their supplementation period and various measurements were taken up to 48 hours following the protocol. Overall there was no added benefit of the extra leucine added to the standard BCAA mix in terms of muscle soreness, recovery of average and peak power output, and CK levels. Additionally, leucine alone was found to be ineffective for recovery of muscle damage and performance measures, exhibiting higher CK levels, increases in muscle soreness at rest and under tension, and an impaired power production at 24 and 48 hours post-exercise compared to the other two treatment groups.[19] [4] mentions that one of the reasons leucine may actually be ineffective is that increasing concentrations of leucine will activate pathways for oxidizing all of the BCAAs, which can make concentrations of isoleucine and valine limiting factors for protein synthesis. Thus, just as all essential amino acids are needed for protein synthesis, the literature seems to support that if BCAAs are going to be effective, they should all be taken together.

Discussion

The literature overall provides important take-aways for the value of BCAA supplementation on each exercise-related topic discussed in this review. In terms of muscle protein synthesis and subsequent muscular hypertrophy the literature does not support the claims many supplement manufacturers make about their BCAA products. It does not appear that BCAAs offer a significant benefit to increase muscle mass or size in college-aged, trained males when taken before, during, or after exercise. Whether hypocaloric [6] or consuming sufficient calories,[7] BCAAs do not increase muscle mass in conjunction with 8 weeks of resistance training. The value of BCAA supplementation in this population, however, is more likely to be its potential to preserve muscle mass over time in states of hypocalorism. This may be of importance for those in weight-class oriented sports trying to maintain muscle while, trying to cut down to meet weight requirements, as well as in those with conditions related to muscle wasting, such as cancer cachexia or sarcopenia. While BCAA supplementation has been found to help an elderly population undergoing gait rehabilitation treatment increase skeletal muscle mass and prevent decreases in body weight, more research is necessary to be able to draw conclusions about the use of BCAAs in the prevention of sarcopenia and other muscle wasting conditions.

Similarly, BCAAs do not appear to augment improvements in muscular strength, power, or endurance with resistance training, but may be able to preserve these muscle characteristics over time during hypocaloric states in trained, college-aged males. Many of the differences found in studies are likely due to differences in training protocols and supplement dosage. For example, [7] had participants supplement with 9 grams of BCAAs per day on exercise days only across 8 weeks of resistance training 4 days per week. The dose was split in half for pre and post-exercise and no improvements in muscular performance were found to be attributed to the BCAA supplement. [6], however had participants supplementing with 14g of BCAAs per day split across two pre-exercise and one post-exercise time points and BCAAs were found to improve both upper and lower body strength more than the placebo group. Other studies looked at performance in the acute setting and did not find a benefit of BCAAs, which suggests that chronic supplementation is really where BCAAs may have the most value. There is ultimately a need for more chronic training studies to investigate whether or not BCAAs may improve performance directly in other age groups, females, or in untrained populations. Resistance exercise performance may have the potential

Citation: Morse T, Willoughby DS. Efficacy of BCAA supplementation for exercise performance and recovery: a narrative review. *J Nutr Health Food Eng.* 2019;9(3):128–133. DOI: 10.15406/jnhfe.2019.09.00337

to be improved indirectly through BCAA supplementation; however, due to its potential ability to improve recovery between exercise bouts.

On the other hand, direct improvements in endurance exercise performance with BCAA supplementation are not well supported by the literature either. Findings are mixed, with about half of the studies in this review showing a positive benefit and about half exhibiting no benefit of BCAA supplementation on various aspects of aerobic performance. Small improvements were found overall in psychomotor performance related to reductions in central fatigue, measured by the attenuation of rises in serotonin after exercise. Flaws in some of the studies, however, make accurate interpretation of the data difficult. One of the studies only investigated BCAA supplementation with ornithine aspartate so the effect of BCAAs alone cannot be inferred.[12] Additionally, [13] found a benefit on levels of serotonin with BCAAs but did not measure aerobic performance directly to see if the suggested reduction in central fatigue correlated with performance. Only one study in this review measured VO_2max directly and concluded BCAAs improved VO_2max as well as lactate threshold in trained males, but its crossover design and small sample size (n=8) limits the applicability of the results.[14] Similarly, crossover studies with similar sample sizes to the previous study mentioned display conflicting results in regards to time to exhaustion/fatigue resistance in untrained males, with one showing a benefit of BCAAs after glycogen depletion[15] and the other showing no benefit compared to carbohydrate supplementation.[16] Altogether, the data on aerobic endurance performance improvements with BCAA supplementation remains incredibly unclear, with many different variables changing the outcome. More research is needed in demographics other than young males, for longer supplementation periods, and with larger sample sizes to support the use of BCAAs as a valuable performance supplement. Similar to resistance training though, BCAAs may be able to indirectly improve endurance performance through improvements in the body's ability to recovery between training sessions.

Results regarding the recovery of performance parameters with BCAA supplementation following muscle damaging exercise is incredibly mixed. When the muscle damage protocol involves traditional resistance training, BCAA supplementation overall seems to benefit the recovery of muscular power and isometric strength within 48 hours post-exercise. However, with eccentric-based exercise data is conflicting. [19] used the same damage protocol consisting of 5 sets of 100 drop jumps and a similar supplementation period (11 days vs. 12 days) as [20], but only [19] found BCAAs to benefit the recovery of muscular power. One likely reason for this is that [19] used participants that were recreationally active, while [19] used participants that were competitive athletes, suggesting more of an influence of supplementation on individuals with lower training status. The measurement of muscular power between the two studies also differed, however, because [19] used a tendo system with the leg press exercise to calculate average and peak power, and [19] used vertical jump height as a measure of muscular power. [21] also failed to find a benefit of BCAAs for both muscular power and isometric strength over a similar time frame as the other two studies, which may be due to the use of participants with years of resistance training experience, rather than recreationally active participants with only a minimum of 6 months of resistance training experience.

The value of BCAAs in attenuating muscle damage and inflammatory responses to both resistance and endurance exercise is much clearer in the literature. Most studies found BCAAs to mitigate elevations in serum CK and perceived muscle soreness in response to acute endurance and resistance exercise, regardless of different damage protocols being utilized in young, trained males. Two studies did not find reductions in perceived soreness with BCAAs, but this may be due to the subjective nature of this measure, small sample sizes[9] or comparing BCAAs to carbohydrate supplementation instead of a placebo without controlling for the caloric intake of the supplement given.[22] The literature would benefit from measuring additional markers of muscle damage other than CK and LDH, as observed in the studies in this review for more substantiated claims about BCAAs attenuating muscle damage. In addition, a small amount of data suggests BCAAs as beneficial to the immune system during recovery from resistance and prolonged endurance exercise via alterations in monocytes, inflammatory cytokines, and attenuating decreases in plasma glutamine, although this may be more valuable in response to prolonged endurance exercise than traditional weight training. More research is needed across all demographics both in acute and chronic circumstances to be able to conclude if BCAAs are worthwhile to use for this purpose.

Despite enough evidence showing the ability of leucine to stimulate pathways involved in muscle protein synthesis, it does not provide any additional benefit to performance or adaptations to resistance and endurance training when added to standard BCAA mixes (2:1:1) and is ultimately found to be ineffective for these parameters when consumed by itself. This is likely due to competition for transport into the muscle with essential amino acids and the other branched-chain amino acids.[4] It is also important to remember that just because signaling pathways are activated, does not mean it will always be indicative of a direct performance benefit or adaptation due to the multi-faceted nature of exercise adaptations and all the other factors that can come into play to affect this process.

Conclusion

In conclusion, peri-exercise BCAA supplementation is shown to be most valuable for young, trained males in terms of recovery between exercise sessions and the preservation of both muscle mass and muscle performance under states of hypocalorism for up to 8 weeks. Improvements in the ability to recover between exercise sessions due to BCAA supplementation has the potential to positively influence subsequent exercise performance. However, future research should investigate longer periods of supplementation, include females and individuals over the age of 30, and consist of larger sample sizes so there is more power behind the evidence presented. More studies moving forward should also make sure to control for dietary intake of calories and macronutrients to determine differences in BCAA supplementation efficacy based on total protein intake. Lastly, given the importance of all EAAs being present for muscle protein synthesis and its subsequent adaptations to occur, research should investigate the effectiveness of BCAA supplementation in comparison to EAAs and complete protein supplements regarding muscle protein synthesis, exercise performance, and exercise recovery.

References

1. Cruzat VF, Krause M, Newsholme P. Amino acid supplementation and impact on immune function in the context of exercise. *J Int Soc Sports Nutr.* 2014;11(1):61.
2. Zhang S, Zeng X, Ren M, et al. Novel metabolic and physiological functions of branched–chain amino acids: a review. *J Anim Sci Biotechnol.* 2017;8:10.

3. Negro M, Giardina S, Marzani B, et al. Branched–chain amino acid supplementation does not enhance athletic performance but affects muscle recovery and the immune system. *J Sports Med Phys Fitness.* 2008;48(3):347–351.

4. Wolfe RR. Branched–chain amino acids and muscle protein synthesis in humans: myth or reality? Journal of the International Society of Sports Nutrition, 2017;14(30).

5. Moriwaki M, Wakabayashi H, Sakata K, et al. The effect of branched–chain amino acids–enriched nutritional supplements on activities of daily living and muscle mass in inpatients with gait impairments: a randomized controlled trial. *J Nutr Health Aging.* 2009;23(4):348–353.

6. Dudgeon WD, Kelley EP, Scheett TP. In a single–blind, matched–group design: branched–chain amino acid supplementation and resiatnce training maintains lean body mass during a caloric restricted diet. *J Int Soc Sports Nutr.* 2016;13:1.

7. Spillane M, Emerson C, Willoughby DS. The effects of 8 weeks of heavy resistance training and branched–chain amino acid supplementation on body composition and muscle performance. *Nutr Health.* 2012;21(4):263–273.

8. Ferreira MP, Li R, Cooke M, et al. Periexercise coingestion of branched–chain amino acids and carbohydrate in men does not preferentially augment resistance exercise–induced increases in phosphatidylinositol 3 kinase/protein kinase B– mammalian target of rapamycin pathway markers indicative of muscle protein synthesis. *Nutr Res.* 2014;34(3):191–198.

9. Gee TI, Deniel S. Branched–chain amino acid supplementation attenuates a decrease in power–producing ability following acute strength training. *J Sports Med Phys Fitness.* 2016;56(12):1511–1517.

10. Smith JW, Krings BM, Shepherd BD, et al. Effects of carbohydrate and branched–chain amino acid beverage ingestion during acute upper body resistance exercise on performance and postexercise hormone response. *Appl Physiol Nutr Metab.* 2018;43:504–509.

11. Davis JM, Alderson NL, Welsh RS. Serotonin and central nervous system fatigue: nutritional considerations. *Am J Clin Nutr.* 2000;72(2 Suppl):573S–58S.

12. Mikulski T, Dabrowski J, Hilgier W, et al. Effects of supplementation with branched–chain amino acids and ornithine aspartate on plasma ammonia and central fatigue during exercise in healthy men. *Folia Neuropathol.* 2015;53(4):377–386.

13. Kim DH, Kim SH, Jeong WS, et al. Effect of BCAA intake during endurance exercises on fatigue substances, muscle damage substances, and energy metabolism substances. *J Exerc Nutrition Biochem.* 2013;17(4):169–180.

14. Matsumoto K, Koba T, Hamada K, et al. Branched–chain amino acid supplementation increases the lactate threshold durig an incremental exercise test in trained individuals. *J Nutr Sci Vitaminol (Tokyo).* 2009;55(1):52–58.

15. Gualano AB, Bozza T, Lopes De Campos P, et al. Branched–chain amino acid supplementation enhances exercise capacity and lipid oxidation during endurance exercise after muscle glycogen depletion. *J Sports Med Phys Fitness.* 2011;51(1):82–88.

16. Greer BK, White JP, Arguello EM, et al. Branched–chain amino acid supplementation lowers perceived exertion but does not affect performance in untrained males. *J Strength Cond Res.* 2011;25(2):539–544.

17. Matsumoto K, Koba T, Hamada K, et al. Branched–chain amino acid supplementation attenuates muscle soreness, muscle damage and inflammation during an intensive training program. *J Sports Med Phys Fitness.* 2009;49(4):424–431.

18. Waldron M, Whelan K, Jeffries O, et al. The effects of acute branched–chain amino acid supplementation on recovery from a single bout of hypertrophy exercise in resistance–trained athletes. *Appl Physiol Nutr Metab.* 2017;42(6):630–636.

19. Osmond AD, Directo DJ, Elam ML, et al. The effects of leucine–enriched branched–chain amino acid supplementation on recovery after high–intensity resistance exercise. *Int J Sports Physiol Perform.* 2019;14(8):1081–1088.

20. Howatson G, Hoad M, Goodall S, et al. Exercise–induced muscle damage is reduced in resistance–trained males by branched–chain amino acids: a randomized, double–blind, placebo controlled study. *J Int Soc Sports Nutr.* 2012;9:20.

21. VanDusseldorp TA, Escobar KA, Johnson KE, et al. Effect of branched–chain amino acid supplementation on recovery following acute eccentric exercise. *Nutrients.* 2018;10(10).

22. Kephart WC, Mumford PW, McCloskey AE et al. Post–exercise branched–chain amino acid supplementation does not affect recovery markers following three consecutive high intensity resistance training bouts compared to carbohydrate supplementation. *J Int Soc Sports Nutr.* 2016;13:30.

23. Ra SG, Miyazaki T, Kojima R, et al. Effect of BCAA supplement timing on exercise–induced muscle soreness and damage: a pilot placebo–controlled double–blind study. *J Sports Med Phys Fitness.* 2019;58(11):1582–1591.

24. Bassit RA, Sawada LA, Bacurau RF, et al. Branched–chain amino acid supplementation and the immune response of long–distance athletes. *Nutrition.* 2002;18(5):376–379.

25. Duan Y, Li F, Li Y, et al. The role of leucine and its metabolites in protein and energy metabolism. *Amino Acids.* 2016;48(1):41–51.

26. Johnson MA, Gannon NP, Schnuck JK et al. Leucine, palmitate, or leucine/palmitate cotreatment enhances myotube lipid content and oxidative preference. *Lipids.* 2018;53(11-12):1043–1057.