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Review

Efficacy of amino acids in sports nutrition- review of clinical evidences

Sreya Duttagupta, Niladri Krishna Roy, Gargi Dey *

School of Biotechnology, KIIT-Deemed to be University, Bhubaneswar 751024, India

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ABSTRACT

The efficacy of amino acids as popular sports supplements has triggered debates, with their impact on athletic performance varying across sports disciplines due to diversity and heterogeneity in clinical trials. This review evaluates the ergogenic potential of amino acids, by critical appraisal of results of clinical trials of Branched chain amino acids (BCAAs), arginine, glutamine, citrulline, β-alanine, and taurine, performed on elite sportsmen from various land and water sports. Clinical trials reviewed here confirm notable physiological benefits thereby supporting the claim that BCAA, citrulline and arginine in various doses can have positive effects on endurance and overall performance in sportsperson. Furthermore, results of clinical trials and metabolomic studies indicate that in future it would be more beneficial to design precise formulations to target the requirement of specific sports. For instance, some combinations of amino acids may be more suitable for long term endurance and some others may be suitable for short burst of excessive energy. The most important insights from this review are the identification of three key areas where research is urgently needed: a) Biomarkers that can identify the physiological end points and to distinguish the specific role of amino acid as anti-fatigue or reducing muscle soreness or enhancing energy b) In-depth sports-wise clinical trials on elite sportsperson to understand the ergogenic needs for the particular sports c) Design of precision formula for similar types of sports instead of common supplements.

1. Introduction

Modern approaches to sports nutrition aim to provide sources of ergogenic aids; which are substances that help in increasing energy production, promoting faster recovery in athletes and improving field performance. These improvements are brought about by delaying the commencement of fatigue; combined with electrolytes, stimulants, vitamins to compensate the fluid loss and hence maintain homeostasis (Raizel, Coqueiro, Bonvini, & Tirapegui, 2019).

Since, physical activity and its performance are dependent on muscle function and protein synthesis, amino acids and their derivatives are one of the most popular ergogenic aids. They have been widely studied for their applicability as sports supplements (Wolfe, 2000). Numerous clinical trials have examined their effectiveness in delaying fatigue or enhancing performance. However, a consensus has not been reached yet on this topic. A review published by (Wolfe, 2017), has drawn attention to excessive marketing by companies selling branched chain amino acid (BCAA) and has cautioned against the anabolic response which may be triggered on prolonged BCAA supplementation. Different views regarding ergogenic efficiency of amino acids have emerged from the clinical trials reported in recent years (Escribano-Ott, Calleja-González, & Mielgo-Ayuso, 2022; Marcon & Zanella, 2022; Milioni, Redkva, Barbieri, & Zagatto, 2017; Weber et al., 2021; Zanella, Cauduro, Macedo, Berti, & Master, 2021). Some of the recent reviews, mentioned above, have included non-athletes or untrained persons for the comparison, thus complicating the inference. There is still a gap in information and possible incorrect conclusions drawn based on too few studies on amino acid administration. Since it is general tendency to rely on scientific literature before considering nutritional intervention, comprehensive reviews on this topic are needed since they are critical in shaping the decision-making in sports nutrition. The current review addresses the ambiguities regarding the amino acid supplementation. It evaluates the trial results on BCAA, arginine, glutamine, citrulline, β-alanine, taurine administration to assess their efficacy in enhancing performance in

Abbreviations: ATP, Adenosine tri-phosphate; BCAA, branched chain amino acid; BFM, body fat mass; BMI, body mass index; fTrp, free tryptophan, HDL, high-density lipoprotein; LBM, lean body mass; LTL, leukocyte telomere length; NMR, nuclear magnetic resonance; RPE, rating of perceived exertion; RSAT, Repeated Sprint Ability Test; TCA, tricarboxylic acid.

* Corresponding author.
E-mail address: gargi.dey@kiitbiotech.ac.in (G. Dey).

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persons involved in land and water sports. Additionally, this review accentuates the potential use of metabolomics to elucidate the relation between sports performance and the fluctuations in athletes' metabolic profiles.

2. Amino acids in sports nutrition and their mode of action

Amino acids enhance performance through several ways: boosting anabolic hormone secretion, modifying fuel usage during exercise, improving post-performance recovery and preventing mental fatigue. Leucine, alanine and proline improve muscle recovery capacity, endurance abilities and muscle mass in combination with whey protein and carbohydrates. Tryptophan supplementation is suggested to increase serotonin level in the brain that increases tolerance to pain during high intensity exercise thereby pushing the athlete's motivation. BCAAs have been reported to delay fatigue, increase sustained exercise by serving as instant fuels and help in sports relying on endurance activity (Flockhart et al., 2021).

2.1. Branched chained amino acids (Leucine, isoleucine and Valine)

High intensity and prolonged physical activities result in increased uptake of amino acid tryptophan which is the precursor of serotonin (Blomstrand, Møller, Secher, & Nybo, 2005). A sense of fatigue is brought in when levels of serotonin increase and levels of dopamine fall within the brain cells (Cordeiro et al., 2017). In such a condition, the presence of BCAAs namely leucine, isoleucine, and valine can have a significant anti-fatigue effect. The BCAA compete with free tryptophan (fTrp) for the same carrier system in crossing the blood–brain barrier (Cheng et al., 2016.). As the muscle glycogen gets depleted due to long durations of endurance activities, BCAA is utilized as the primary source of fuel, reducing the fTrp uptake, hindering the synthesis of serotonin, and thus delaying the onset of central fatigue. Therefore, the serum levels of BCAA or the fTrp/BCAA ratio is very crucial and additional ingestion of BCAA is suggested (Hormoznejad, Zare Javid, & Mansoori, 2019; Raizel et al., 2019). Essentially oxidized in skeletal muscles, they have also been found to improve lipid oxidation and enter the tricarboxylic acid (TCA) cycle as a metabolite. The catabolism of BCAA increases as an effect of exercise, it leads to subsequent suppression of lactate production (Chang et al., 2015; Hormoznejad et al., 2019). This effect of BCAA is advantageous because lactate accumulation in a contracting muscle has been suggested as the major cause of muscle fatigue in earlier literature (Wan, Qin, Wang, Sun, & Liu, 2017).

Apart from delaying central fatigue, improving the immune system, repairing muscle damage, and boosting glucose metabolism, the use of BCAA as a sports supplement has gained a lot of recognition and has been favoured by athletes due to its established positive effects on delayed onset muscle soreness and temporary exercise-induced muscle damage (Ra et al., 2018; Walsh, Gonzalez, Ratamess, Kang, & Hoffman, 2010).

2.2. L-citrulline

L-citrulline is a non-essential amino acid formed in the body, which is not a part of any protein but is significant as it is the precursor of L-arginine, which in turn is the precursor of nitric oxide (Glenn, Gray, Jensen, Stone, & Vincenzo, 2016). In the urea cycle, citrulline is catabolized by arginase to produce ornithine and urea, buffering and clearing ammonia. This boosts the aerobic utilization of pyruvate, inhibits the formation and accumulation of lactate (Breuillard, Cynober, & Moinard, 2015; Glenn et al., 2016). The advantage of L-citrulline over L-arginine is that it does not undergo hepatic metabolism (Romero, Platt, Caldwell, & Caldwell, 2006), and hence it is directly transported to the kidneys. There it gets converted into L-arginine which acts as a substrate for nitric oxide synthase (NOS) that in turn, aids in the production of nitric oxide (NO), a potent vasodilator. NO increases the flow of blood and influence mitochondrial respiration. It restricts oxygen usage by attaching to the cytochrome *c*-oxidase present in the mitochondria thus improving oxygen distribution throughout the skeletal muscles. An increase in the level of nitric oxide brings about positive changes such as improved muscle contractibility, uptake of glucose, and blood flow and repair in muscles (Bescós, Sureda, Tur, & Pons, 2012).

Citrulline is generally combined with amino acid malate to give further enhanced performance. This is because malate is one of the intermediates in the TCA cycle that induces oxidation pathway and indirectly increases ATP production (Glenn et al., 2016). Thus, citrulline and malate have been found to impart synergistic effects that have resulted in increased skeletal muscle tissue perfusion alongside its heightened ATP production to ultimately improve exercise and sports-based performance (Gonzalez & Trexler, 2020).

Researchers have formulated a combination of BCAA, arginine, and citrulline as amino acid supplements for players of different sports (like football, handball, basketball and swimming) with the hypothesis that while BCAA will compete with free tryptophan reducing the production of serotonin, arginine, and citrulline will convert the accumulated ammonia from BCAA oxidation into nitrous oxide, serving as a vasodilator and increasing mitochondrial respiration and muscle repair. Experiments on both land (Yang, Wu, Chen, & Chang, 2017) and water sports (Hsueh, Wu, Tsai, Wu, & Chang, 2018) have supported this hypothesis and demonstrated an improvement in performance and alleviation of fatigue.

2.3. β-alanine

As we have already discussed in earlier section, with the increase in the duration of strenuous or high-intensity exercise, anaerobic glycolysis is favoured leading to the formation of lactic acid. This pathway results in accumulation of hydrogen ions (H^+) and pH drop in the muscles (Culbertson, Kreider, Greenwood, & Cooke, 2010). Supramaximal exercise leads to a sharp fall in ATP levels with rapid accrual of serum lactate and H^+ ions instead, which can eventually lead to acidosis (Caruso et al., 2012). In order to cope with such circumstances, the body employs mechanisms to remove this accumulated lactic acid and H^+ by using buffering agents. One such agent is a naturally occurring dipeptide called carnosine. It is made up of β-alanyl and L-histidine, synthesized by carnosine synthase, and is present in many tissues, but most abundantly in the skeletal muscles (Boldyrev, Aldini, & Derave, 2013). The ergogenic effect in this molecule is brought about by the pK_a of the imidazole ring of the histidine which is vital for buffering H^+ and thus maintaining the pH (Abe, Dobson, Hoeger, & Parkhouse, 1985). Although carnosine is just one among several other buffering agents, its advantage over the rest is that it does not have a capping with respect to its intramuscular concentration (Caruso et al., 2012). Additionally, carnosine also functions as a diffusible Ca^{2+}/H^+ exchanger at the sarcomere. The molecule is capable of binding to both Ca^{2+} and H^+. During periods of strenuous exercises, the increase in H^+ concentration ensures that they are bound to carnosine and consequently the Ca^{2+} is accrued in the sarcomere, facilitating a cross-bridge formation resulting in muscle force production (Swietach et al., 2013, 2014). In an attempt to increase the muscle carnosine levels, studies have indicated that although one of its constituents, L-histidine is present abundantly inside the human body, β-alanine instead is a non-proteogenic amino acid that is produced endogenously in the liver only in sufficient quantities to produce a small amount of carnosine in muscles. β-alanine has other functions in the body, most importantly as a neuromodulator or a neurotransmitter (Trexler et al., 2015). In reference to carnosine synthesis β-alanine is found to be the rate-limiting amino acid (Stellingwerff, Decombaz, Harris, & Boesch, 2012). This explains how supplementary dose of β-alanine can be beneficial in increasing carnosine synthesis from normal levels to meet an increased demand in athletes and sportspersons. Investigations were conducted using β-alanine and L-histidine separately, and a combination of β-alanine and L-histidine and it was found that both β-alanine and a combination of β-alanine and L-histidine have an impact on the increase in muscle carnosine levels. Supplementation of L-histidine singly did not give the expected result (Van-Dusseldorp et al., 2018).

2.4. Taurine

Another amino acid that has documented ergogenic aids and is popularly used in sports drinks is 2-Aminoethanesulfonic acid or taurine. It is a semi-essential sulphur containing amino acid that is abundantly present in the mammalian tissues (Huxtable, 1992). Most important functions of taurine from the athletic point of view, is its sarcoplasmic reticulum Ca^{2+} handling to regulate the contractile function of the skeletal muscles (Dutka, Lamboley, Murphy, & Lamb, 2014). Taurine is taken up by cardiac and skeletal muscles through the taurine transporter (TauT) to facilitate Ca^{2+} handling improving muscle performance (Ito et al., 2010). Having antioxidative properties (De Carvalho et al., 2017), it has also been found to exert stabilizing or buffering effects in the mitochondrial matrix, resulting in enhanced ATP production in the muscle cells (Hansen, Andersen, Cornett, Gradinaru, & Grunnet, 2010). Many other functions have been associated with taurine such as bile acid conjugation (Lourenço & Camilo, 2002), regulation of the cell fluid volume (Ae, Michotte De Welle, Verbeeck, Poortmans, Ward, Xavier, Ae, & Francaux, 2002), increase in insulin sensitivity (Vettorazzi, Ribeiro, Santos-Silva, Borck, Batista, Nardelli, & Carneiro, 2014), preventing oxidative stress in athletes (De Carvalho et al., 2017), ability to act as a neuromodulator, activating extra-synaptic gamma aminobutyric acid (GABA) receptor isoforms in the thalamus, along with the possibility of control over thermoregulation, as found in animal models (Jia et al., 2008), improving energy expenditure (Ren et al., 2015) and lipid metabolism (Kim et al., 2016) and other anti-inflammatory functions (Barua, Liu, & Quinn, 2001; Lourenço & Camilo, 2002). The effect of taurine in enhancing endurance activity performance has been confirmed by the reduction in exhaustion time in TauT knockout mice attributing to its inability to uptake taurine owing to the genetic modification (Ito, Yoshikawa, Schaffer, & Azuma, 2014). Oral supplementation induced increase in plasma taurine levels is likely to obstruct ordinary extrusion of muscle taurine from skeletal cells during periods of hypo osmolality caused during exercise, thus maintaining the bioavailability of intramuscular taurine (Ae et al., 2002; Ishikura, Ra, & Ohmori, 2013). Although taurine has great ergogenic potential, isolated taurine supplementation has been very less studied and documented.

2.5. Glutamine

Glutamine is the most abundantly available naturally formed free amino acid found in the plasma and skeletal muscles (Antonio & Street, 1999). Physiological function of glutamine includes homeostasis, acid-base balance during acidosis, especially in the immune system and the gastrointestinal tract (Ahmadi, Rayyani, Bahreini, & Mansoori, 2019). It protects the intestinal barrier against septic shock (Castell, 2003; De-Souza, 2005), augmenting intestinal damage and permeability during heat stress, and acts as an alternate source of energy, resulting from the decrease in leukocytes and macrophages occurred post strenuous physical activities (Petry, Cruzat, Heck, De Bittencourt, & Tirapegui, 2015). Additionally, glutamine aids as a vehicle in nitrogen transport for ammonia buffering, used in cell proliferation, and is an active source of fuel for ATP production (DuBourdieu, 2021). Glutamine has a significant role in gluconeogenesis, activating the glycogen synthase that will lead the glucose synthesis, and in the anaplerosis of the TCA cycle. These functions, along with its role in shuttling ammonia or attenuating muscle damage have rendered it an efficient anti-fatigue amino acid (Coqueiro, Rogero, & Tirapegui, 2019). Glutamine is already used in many sports drinks as an additional supplement; however, its ergogenic potential is still under investigation as it has not shown any great improvement in suppressing fatigue biomarkers, in clinical trials. Neither has its role in improving physical performance properly documented. Glutamine has been seen to give better results when supplemented with alanine (L-alanyl-L-glutamine) and in some cases with BCAA to give better results with more enhanced performance (Raizel et al., 2019). Glutamine supplementation has also been studied for beneficial results for physical activities performed under heat (Osborne, Stewart, Beagley, Borg, & Minett, 2019).

3. Clinical trial outcomes of amino acid supplementation

Although the market is booming with a range of amino acid supplement targeting the sports industry, it is still a matter of debate as to how many of those supplementations have support of scientific literature. While some of the amino acids have been a subject of rigorous human and animal trials, others have surprisingly limited number of clinical trials. For this review, we have taken into consideration human clinical trials from recent years for various kinds of sports and different amino acid supplements.

3.1. BCAA

BCAA supplementation was found to have an overall beneficial impact on athletes especially on the muscle damage and perceived soreness, which reduced significantly (Table 1). Inspection of the reported data revealed that BCAA delayed exhaustion without reaching muscular fatigue and also improved the rate of recovery in isometric strength. 0.084 gm/Kg of body mass or 18–20 g of BCAA in the ratio of 2:1:1 of leucine, isoleucine, and valine proved to be the most beneficial. These positive results were reported in the case of cycling, resistance training, and long-distance running (Abumoh'D, Matalqah, & Al-Abdulla, 2020; Dorrell & Gee, 2016; Manaf, Peiffer, Maker, & Fairchild, 2021; Waldron et al., 2017). However, (Martín-Martíez et al., 2020) reported that there was no significant difference between the placebo and BCAA supplemented groups in the case of volleyball players. In comparison to previous studies, he observed that BCAA continuous supplementation was required for it to be physiologically effective.

3.2. Citrulline

Human trials on citrulline administration considered in this review (Table 2) showed an improvement of upper and lower body performances, induce anti-fatigue effects and reduce the total time taken to finish the cycle ergometer test. This was reported by (Kiyici, Eroğlu, Kishali, & Burmaoglu, 2017; Suzuki, Morita, Kobayashi, & Kamimura, 2016), in case of handball, cycling, and running respectively. The doses administered were around 2.4——3 g per day, for 7, 8 days and four weeks respectively. In the case of weightlifting, positive results were obtained but on a higher dosage of 8 g/ day (Glenn et al., 2016) The same dosage also improved maximal and average grip strength and the peak power and explosive power for Wingate test in case of female tennis players, however, peak and average vertical power had no effect due to the supplementation (Glenn et al., 2016). 4, 8 and 12 g of citrulline were unable to improve the aerobic or anaerobic power, blood lactate, and urea levels in blood in case of soccer players (Farkhani, Javadikia, & Modaresi, 2019). Administration of 8 g citrulline malate (2:1) was unable to influence any change in specialized judo fitness test in judo players (Cezar Biccas Viana et al., 2021). Recent reports (Cezar Biccas Viana et al., 2021; Farkhani et al., 2019) also confirmed that citrulline malate did not improve aerobic and anaerobic power as expected. However, a better outcome was demonstrated in the study by Kiyici and colleagues, that aerobic power could be improved if the supplementation of citrulline was continued for a longer period of time around 7 to 14 days instead of acute supplementation (Kiyici et al., 2017).

Table 1
Clinical trials for BCAA supplementation on sportspersons.

Sl. No.	Sports / Training	N=	Experiment	Physical test	Assessments		Result	Final Effect +/-	Ref
					Mechanical tests	**Biochemical tests**			
1.	Cycling	18 athletes	BCAA or a no caloric placebo was supplemented at 0.084 gm/ kg of body weight pre-exercise and then at 0.056 gm/kg per hour during exercise	Heart rate, perceived exertion, muscle voluntary activation level, maximal voluntary contraction.	Cycling trial on an electronically braked cycle ergometer. MDC, nerve stimulation test using EMG.	–	The performance of the recreationally active cyclists improved with subsequent supplementation of acute BCAA. Along with that, a stark reduction in perceived exertion was found.	+	(Manaf et al., 2021)
2.	Long distance running	16 males	2 weeks of bcaa or placebo supplementation was done, at a dosage of 20gm, 1hr prior to exercise session.	Incremental exercise on treadmill.	–	Plasma serotonin level, Serum creatine kinase (CK), Serum free fatty acids (FFA), Serum myoglobin level	Time to exhaustion was increased while muscular fatigue was not reached.	+	(Abumoh'D et al., 2020)
3.	Resistance training	16 athletes	BCAA (in a ratio of 2:1:1 of leucine, isoleucine and valine) or placebo were given to two groups of 8 athletes each, at a dosage of 0.087 g/kg of body mass.	Countermovement jump (CMJ) height. Induction of muscle damage by 6 sets of 10 full-squats at 70 % 1RM.	Peak isometric knee extensor force.	Creatine Kinase (CK).	Oral BCAA supplementation improved the rate of recovery in isometric strength, CMJ height and perceived soreness at a dose of 0.087 g/kg body mass.	+	(Waldron et al., 2017)
4.	Resistance training	5 males	6 or 18gm of BCAA (in a ratio of 2:1:1 of leucine, isoleucine and valine) or placebo was randomly supplemented, 20 mins before and immediately after resistance session.	Strength training, counter movement jump (CMK), squat jump (SJ), Seated medicine-ball chest throw (MBT), 6 s Cycle sprint test.	Rating of perceived muscle soreness (RMS), Mean power, peak power.	–	Both dosages reduced decrease of muscle function and soreness. Higher dose had a higher impact.	+	(Dorrell & Gee, 2016)
5.	Volleyball	12 male players	21 g of BCAA (in a ratio of 2:1:1 of leucine, isoleucine and valine) or placebo (watermelon flavoured drink without sugar) was supplemented at a dose of 7gm/2days.	Polymetric training, technical and tactical drills, counter movement jump performance (CMJ test).	–	–	The given dosage did not bring any difference in the BCAA or supplement group.	–	(Martín-Martíez et al., 2020)

BCAA: Branched chain amino acids, CK: Creatine Kinase, CMJ: Counter-movement jump, EMG: Electromyography, FFA: Free fatty acids, MBT: medicine ball chest throw, RMS: Rating of perceived muscle soreness.

3.3. Arginine

From the clinical trials on human subjects after the administration of arginine as supplement (Table 3), it appears that soccer players improved the sports performance without significantly altering the body mass index (BMI), body fat mass (BFM), and lean body mass (LBM) (Pahlavani et al., 2017) and 6 gm/ day of arginine supplementation in another group of soccer players not only improved their anaerobic performance but also aided in fat removal from the body and faster muscle repair post injury (Mor, Atan, Agaoglu, & Ayyildiz, 2018). Lower dose of 0.15 g/Kg/day supplementation did not improve the heart rate, blood pressure, and Repeated Sprint Ability Test (RSAT) parameters (Birol, Kılınç, Deliceoğlu, & Keskin, 2019). However, in the case of wrestlers, administration of 0.1 gm/Kg improved the Vascular Endothelial Growth Factor (VEGF) and VEGF to Endostatin ratio (Motahari Rad & Attarzadeh Hosseini, 2016), and 5 gm/ day of arginine supplementation improved overall performance and oxidative metabolism in water polo players (Gambardella et al., 2021). Arginine supplementation has been beneficial for improving anaerobic performance and oxidative metabolism; however, it does not significantly influence parameters like heart rate, blood pressure, and RSAT performance.

3.4. β-alanine

Out of all the trials mentioned in this review (Table 4), β-alanine was the most extensively studied amino acid. It has been mostly tested on field and water sportspersons with diverse outcome. In the case of rowing, it improved lactate accumulation, although it was unable to positively affect the high-intensity performance (Gharaat, Kashef, Eidi Abarghani, & Sheykhlouvand, 2020; Suszter, Ihász, Szakály, Nagy, Alföldi, Bálint, & Mák, 2020). However, it did not bring about any additional benefits in comparison to the placebo used. Nevertheless, the swimming performance was boosted up in the case of water polo players, and the ventilatory threshold was also found to increase in swimmers (Arjmandpanah Eilaki, Afzalpour, Bagheri, & Mosaferi Ziaaldini, 2018; Claus et al., 2017). β-alanine gave positive results for the trials on field sports such as handball and football (Rosas et al., 2017, Shbib, Rashidlamir, & Hakak Dokht, 2021. Power was successfully enhanced although the supplementation failed to reduce the fatigue index for the former, and endurance, repeated sprinting and jumping performances were improved significantly in case of the latter due to supplementation for 6 weeks. Although, in another study comprising of female football players being supplemented for 3 weeks, no significant distinguishable factor could be observed in Repeated anaerobic spring test (RAST), Yo-Yo, and spring tests (Ribeiro et al., 2020). No beneficial

Table 2
Clinical trials for citrulline malate supplementation on sportspersons.

Sl. No,	Sports / Training	N=	Experiment	Physical test	Assessments		Result	Final Effect +/-	Ref
					Mechanical tests	Biochemical tests			
1.	Soccer	40 young player	Divided in 4 groups of 10 players each according to their VO_{2max} value. The groups were supplemented with dosage of 4, 8 and 12gm and sugar solution control respectively.	RSA test	–	Blood lactate test, Blood urea test.	Did not affect aerobic or anaerobic power, blood lactate or urea level.	–	(Cezar Biccas Viana et al., 2021)
2.	Handball	22 athletes	1 gm of CM or placebo was supplemented three times a day, 4 days a week, for 4 weeks along with intense training.	Rest (R), end effort (EE), recuperation 5 min (R5 m), and recuperation 20 min (R20 m)	–	Blood lactate levels pre and post training.	Improved performance in athletes and postponed fatigue after prolonged physical activities.	+	(Kiyici et al., 2017)
3.	Cycling	22 athletes	2.4 g/day of L-citrulline or placebo was supplemented for a period of 8 days, on the last day it being administered 1hr before the physical test.	4 km cycling time trial,	Time taken, power output / VO_2 ratio (PO/ VO_2) and visual analog scale (VAS) scores	Plasma nitrite and nitrate (NOx) and amino acid levels	Supplementation decreased the time taken to finish a cycle ergometer time trial.	+	(Suzuki et al., 2016)
4.	Running	9 male athletes	3gm/day of citrulline or placebo were given for 7 days.	–	Wingate test on Day 0 and Day 7	Ammonia, creatine kinase (CK), serum glucose and NO	Inhibited exercise performance deterioration and induced anti fatigue effects.	+	(Terasawa et al., 2019)
5.	Weightlifting	15 females	CM (8 g dextrose + 8 g CM) or placebo (PLA) (8 g dextrose) was supplemented.	6 sets of bench press and leg press	Heart rate, rating of perceived exertion (RPE)	–	Acute supplementation improved upper and lower-body performance and reduced RPE.	+	(Bech et al., 2018)
6.	Tennis	17 female players	CM (12 g dextrose + 8 g CM) or placebo (PLA) (12 g dextrose) was supplemented.	Vertical power, grip strength, Wingate anaerobic cycling assessment,	Maximal and average grip strength, peak and average vertical power, anaerobic capacity, peak power, explosive power, and ability to sustain anaerobic power.	–	Supplementation improved maximal and average grip strength and the peak power and explosive power for wingate. Peak and average vertical power had no effect due to supplementation.	+ & -	(Glenn et al., 2016)
7.	Judo	10 athletes	8gm of CM (2:1) was supplemented 60 mins prior to the onset of training.	Special judo fitness test (SJFT)	No. of throws (SJFT index), rating of perceived exertion	Blood lactate concentration	Did not improve the performance in SJFT.	–	(Pahlavani et al., 2017)

CK: Creatine Kinase, CM: citrulline malate, RPE: rating of perceived exertion, RSA: Radiostereometric analysis, SJFST: Special judo fitness test, VAS: visual analogue scale.

results were noted due to the supplementation in basketball (Milioni et al., 2017) and rugby players (Smith, Harty, Stecker, & Kerksick, 2019). On the other hand, sport persons engaged in combat sport performances like Judo (de Andrade Kratz et al., 2017) and boxing (Kim et al., 2018) had benefitted from the supplementation.

3.5. *Taurine*

According to clinical trials a dose of 15–40 mg / Kg/day or 1–5 gm/ day of taurine was administered for an average time span of 4——8 weeks to players participating in different water and land sports. Amongst them, only administration of 5gm of Taurine to professional squash players was found to reduce neuromuscular fatigue and blood lactate accumulation (Kowsari, Alsadat Moosavi, Rahimi, Faramarzi, Mehdizadeh Haghighi, & Mehdizadeh, 2018). A dose of 3gm of taurine mixed with 400 gm of chocolate milk, supplemented for 4 weeks, helped in the reduction of oxidative stress but could not bring about much of a difference in the anaerobic performance of triathletes (De Carvalho et al., 2017). However, the same amount of taurine, when supplemented to triathletes for 8 weeks, could not repair muscle damage (Galan et al., 2018). Unsatisfactory results were also obtained in case of cycling (Ward, Bridge, McNaughton, & Sparks, 2016), swimming (Batitucci et al., 2018), and taekwondo (Samandari, Sanjideh, Faramarzi, Banitalebi, & Ghahfarrokhi, 2021). All the clinical trials on taurine, reported and appraised in this review have been summarized in (Table 5).

4. Discussion

In order to evaluate the importance of amino acid administration in sportsperson, clinical trials performed on athletes and persons engaged

Table 3
Clinical trials for Arginine supplementation on sportspersons.

Sl. No,	Sports / Training	N=	Experiment	Physical test	Assessments		Result	Final Effect +/-	Ref
					Mechanical tests	Biochemical tests			
1.	Football	56 male athletes	L-arginine or placebo was supplemented at a dose of 2gm/day for 45 days	–	Sport performance (VO_{2max}), body mass index (BMI), body fat mass (BFM) and lean body mass (LBM)	–	Increased sports performance but no significant impact on BMI, BFM and LBM.	+	(Mor et al., 2018)
2.	Football	20 male players	L-arginine or placebo was supplemented at a dosage of 0.15 g/kg/day with 500 ml of water, an hour before repeated sprint ability test (RSAT).	Warm up followed by repeated sprint ability test (RSAT), and the % performance decrement due to RSAT	Running time, blood pressure, heart rate	–	Had no significant effect on HR, blood pressure and RSAT total sprint time and sprint decrement score	–	(Motahari Rad et al., 2018)
3.	Football	28 male players	14 gm of arginine and 6 g of wheat bran (placebo) were supplemented to athletes for 14 days.	Anaerobic capacity levels (RAST)	Height, weight, body mass index (BMI) levels, heart rate	Lactic acid, urea, creatinine, cholesterol, triglyceride, High Density Lipoprotein (HDL), Low Density Lipoprotein (LDL), Gamma Glutamyl Transferase (GGT) Aspartate Aminotransferase (AST), Alanine Aminotransferase (ALT) and Lactate Dehydrogenase (LDH)	Has a positive impact on anaerobic performance by accelerating the lactic acid excretion and fat removal from body. Also aids in faster muscle injury repairs.	+	(Birol et al., 2019)
4.	Wrestling	20 elite wrestlers	Divided into 2 groups of 10 each, one group was supplemented with 0.1 gm/kg of L-arginine and the other with placebo, for a period of 14 days.	–	–	Serum levels of VEGF and endostatin levels, and VEGF to endostatin ratio	VEGF and VEGF to endostatin ratio improved as compared to the placebo but not the endostatin level. Hence specific wrestling training with consumption of L-arginine can be effective in stimulating angiotensin.	+	(Gambardella et al., 2021)
5.	Water Polo	17 male players	5 g per day of L-Arginine (9 players) or placebo (8 players) was supplemented for 4 weeks.	Maximal speed swimming test	Mitochondrial respiration and gene expression in human fibroblasts	Serum lactate, NO production	Effective in increasing the oxidative metabolism in water polo players.	+	(Gharaat et al., 2020)

BFM: body fat mass, BMI: body mass index, HR: Heart Rate, LBM: lean body mass, RAST: running anaerobic spring test RSAT: repeated sprint ability test.

in different sports have been collected and considered for this review. The PubMed, Scopus, Cochrane Library, scholar google were mainly searched. For this review, the sports that have been considered are a) Ball over net (Tennis, Squash, Volleyball), b) On water sports (Kayaking, Rowin) c) In water sports (Water polo, Swimming) d) Combat sports (Taekwando, Wrestling, Boxing), e) Athletics (Running, Cycling, Tri-atheletics f) Field sports (Football, Handball, Basketball, Rugb).

From the results of clinical trials (Fig. 1), it can be inferred that among the different amino acids studied as potential ergogenic aid, BCAA and Arginine have been found to be most effective in improving the motor skills of athletes. The ratio of trials reporting positive performance is to negative performance is 80:20 in case of both BCAA and Arginine. This establishes the importance of BCAA, citrulline and arginine as ergogenic aids. This also explains why most of the commercially available amino acids, sold as sports supplements are either a complete amino acid complex or mainly containing BCAA. Some examples of commercially available amino acid supplements are summarized in (Table 6). Most of the products are soy free, dairy free, gluten free and vegan. They do not contain any substances banned by WADA (World Anti-Doping Agency) or any government sports agency, and are available in capsules and powders, snack bars and gels. On the other hand, trial results of β-alanine show only 50 % trials with positive, 43 % with negative and 7 % of contradictory or mixed results.

Another striking observation from the review of data was that taurine has mostly given negative result (57 %), amongst the studies that have been conducted. There was only one report where Taurine showed best results in optimum conditions of 1-3gm/day administered 2hrs before exercise in a chronic dosage of more than 7 days (Kurtz, Van-Dusseldorp, Doyle, & Otis, 2021). In spite of the poor performance indicated in the clinical trials, Taurine supplements are widely available and marketed for use in the sports industry. Like, Zenith Sports Taurine Capsules by Zenith Nutrition Sports, L-Taurine by My Fit Fuel, Taurine Pure Powder by Now Foods, etc. Industry conflict of interest seems to outweigh the real benefits taurine consumption. In our opinion, the lack

Table 4
Clinical trials for β-alanine supplementation on sportspersons.

Sl. No,	Sports	N=	Experiment	Physical test	Assessments		Result	Final Effect +/-	Ref
					Mechanical tests	**Biochemical tests**			
1.	Football	24 females	6.4gm per day of sustained release of β-alanine was supplemented to 12 and an equivalent amount of maltodextrin was supplemented to another 12 participants for 3 weeks.	Yo-Yo intermittent recovery test Level 1, running anaerobic spring test (RAST), 20 m maximal sprint test.	–	–	No significant difference in the Yo-Yo test, RAST, or the spring test was observed post-β-alanine supplementation.	–	(Smith et al., 2019)
2.	Football	25 female footballers.	2 groups of 8 players each were supplemented with either 4.8 gm/day (divided into 6 equal doses of 0.8gm) of β-alanine or placebo while undergoing polymetric training for a duration of 6 weeks. Another control group received a placebo without undergoing any training for the same duration.	Body height, mass, running anaerobic sprint test [RAST], 20 m sprint test, explosive jumping, sprinting, repeated sprinting, 60 s repeated jumping, endurance, and change-of-direction speed performance.	–	–	β-alanine supplementation contributed to the improvement of endurance, repeated sprinting and repeated jumping performances. However, the improvement was not significantly greater than that of the control.	+	(Shbib et al., 2021)
3.	Handball	18 male players	9 male were supplemented with β-alanine and the other 9 were given placebo.	–	Anaerobic power.	Serum level of carnosine and blood lactate were evaluated	β-alanine increased power but failed to decrease the fatigue index significantly. There was an enhancement in the serum carnosine level post β-alanine supplementation.	+	(Ribeiro et al., 2020)
4.	Rugby	15 male players	6.4 gm per day of β-alanine or maltodextrin was supplemented for 6 weeks.	Intermittent sprint tests of 6 sets with 30 s rest between sets. Bench press 1 repetition maximum (RM), backspot 1hr.	Body composition, upper and lower body maximal strength and muscular endurance, heart rate performance and rating of perceived exertion.	Post exercise lactate level.	No significant effect on body composition, dietary analysis, endurance or sprint performance. Except for improvement in upper body force production, β-alanine did not have any other significant difference from the placebo group.	–	(de Andrade Kratz et al., 2017)
5.	Basketball	27 young male	6.4 gm per day of β-alanine or placebo were supplemented to two groups for 6 weeks.	RSA test, Yo-Yo intermittent recovery test. Free throws and jumping ability.	–	Blood lactate level was evaluated.	The peak of blood lactate level lowered. No other positive impact was found post β-alanine supplementation exclusively.	–	(Milioni et al., 2017)
6.	Judo	23 people	6.4gm per day of β-alanine or dextrose (placebo) was given to highly trained judo athletes for 4 weeks.	5 min simulated fight followed by 3 bouts of special judo fitness test.	–	Blood pH, PCO_2, bicarbonate (HCO_3^-), plasma lactate levels were determined pre and post-match.	Throw and serological levels improved in β-alanine with no significant change in case of placebo. Lactate response increased in β-alanine group in comparison to placebo.	+	(Kim et al., 2018)
7.	Boxing	19 male boxers.	9 athletes were supplemented with 4.9–5.4 gm of β-alanine and 10 others were supplemented with	Bench press and back squat and other exercises.	Standing height, body mass and body fat percentage. Wingate anaerobic testing, arm ergometer.	Lactate response to sparring.	β-alanine supplementation moderately improved lower body peak power and upper body power draw. A	+	(Kowasari et al., 2018)

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Table 4 (*continued*)

Sl. No,	Sports	N=	Experiment	Physical test	Assessments		Result	Final Effect +/-	Ref
					Mechanical tests	**Biochemical tests**			
			placebo in the same manner along with training for 10 weeks.				significant effect was observed for isokinetic knee extension strength and Seargent jump height. No significant difference between β-alanine and placebo with regard to blood lactate level.		
8.	Kayaking	17 (10 men and 7 women)	80 mg per kg body mass per day of β-alanine or placebo was supplemented to kayak rowers and the effects were investigated.	Muscular fatigue development: 2 min elbow flexor MVC. Performance evaluation based on 1000 m and 5*250 m kayak ergometer rowing.	EMG: 30, 60, 90, 115 s into the 2 min MVC.	–	β-alanine supplementation did not have any direct effect against muscle fatigue development. Similar results were found in case of both placebo and β-alanine indicating no additional protection.	–	(Beasley et al., 2018)
9.	Rowing	27 men	2.4 g per d, 4.8 g per day on alternate days of β-alanine and 2.4 g per day of cornflour placebo as control were supplemented to the rowers for 4 weeks.	30 mins rowing time trial followed by 3*30 s. Maximal sprint efforts at days 0, 14 and 28.	Total distance, average power (w), relative average power (w/kg), cardiorespiratory measures and perceived exertion.	Blood lactate pre and post trials.	Individual beneficial results have been obtained, however, in comparison to placebo, β-alanine is unable to enhance performance or high intensity efforts remarkably.	+&_	(Silva Norberto et al., 2020)
10.	Rowing	24 men	40 mg per kg of β-alanine, placebo and no supplements were given to three groups of 8 people each for a period of 21 days.	6 mins rowing ergometer.	Volume of O_2 max (VO_2 max), velocity in VO_2 max (vVO_2 max), mean power output, mean velocity in 6 mins, rowing maximum (vR max), time at vR max. Heart rate.	Blood lactate pre and post trials.	β-alanine supplementation delayed lactate storage thus leading to enhanced aerobic capacity and an increased time to exhaustion.	+	(Suszter et al., 2020)
11.	Rowing	23 people	50 mg per kg per day for 5 weeks was supplemented to one group (12 people) with the other group being control (11people) and being without any supplementation.	–	Body composition was measured using a bioelectrical impedance analyser. Cardiorespiratory system using treadmills.	Serum lactate pre and post trials.	Only decreased the blood lactate value but ergogenic potential was not found to be increased in this dosage.	–	(Clause et al., 2017)
12.	Water Polo	15 young players	6.4 g per day of β-alanine or placebo were given for 6 weeks.	200 m swimming performance, repeated sprint ability test (RSA), with free throw (shooting), 30sec maximal tethered eggbeater kicks.	Mean and total RSA time and ball velocity after sprint.	–	β-alanine showed improvement in swimming performance, RSA and 30sec test.	+	(Arjmandpanah Eilaki et al., 2018)
13.	Swimming	14 male swimmers.	2–3 gm per day of β-alanine in the first week followed by 4–6 gm per day of the same were supplemented to one group. The control group was supplemented with dextrose for two weeks in the same manner.	Treadmill test.	Cardiopulmonary exercise testing. VO_2, VCO_2 and VC were recorded.		Ventilatory threshold increased significantly due to the β-alanine supplementation. Competitive ability improved with respect to the given dosage.	+	(Rosas et al., 2017)
14.	Swimming	13 swimmers	4.8 gm per day of β-alanine or placebo was incorporated	Baseline oxygen consumption			The changes in the result were due to the training period and	–	(Xiang Lim et al., 2018)

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Table 4 (*continued*)

Sl. No,	Sports	N=	Experiment	Physical test	Assessments		Result	Final Effect +/-	Ref
					Mechanical tests	**Biochemical tests**			
			into the diets of the swimmers for 6 weeks.				β-alanine was found not to contribute to any enhancement of performance.		

EMG: Electromyography, RAST: running anaerobic spring test, RSA: Radiostereometric analysis.

of abundant scientific evidence leading to the inability of having a conclusive data suggests taurine should undergo more extensive clinical trials in different field of sports before such a large-scale marketability takes place.

The ergogenic effects of amino acids have been reviewed by several authors in past. For example, Fouré and Bendahan (2017) specifically reviewed the clinical data in administration of BCAA. However, the studies included in their review were on healthy volunteers who were subjected to different exercise regime. Similarly, Master & Macedo, 2021 reviewed on the same topic of BCAA supplementation; where the clinical trials included were very diverse. The authors had compared trials on healthy volunteers subjected to exercise regimes along with trials on sportspersons. Furthermore, in same review (Master & Macedo, 2021) the clinical trials which are performed on athletes (for instance Howatson et al., 2012) clearly demonstrate a reduction in muscle soreness and increased recovery after BCAA administration. Another report by Yang et al. (2017) cited in the same review (Master & Macedo, 2021) evaluated the effect of BCAA supplementation on tennis players and reported an enhancement in performance biomarkers. These studies further confirm the inference drawn in our review. Hence, the clinical trials performed on actual sportspersons does seem to merit further investigations on amino acid consumption. Another review by Plotkin et al., 2021, scrutinized the effects of BCAA and leucine supplementation. The studies included in this particular review (Plotkin et al., 2021) were very diverse groups, ranging from resistance trained men to sedentary untrained post-menopausal women to women above 75 yrs. Therefore, several well written reviews on this topic seem to fall short because of the widely diverse trials that have been considered in them. Comparison based on such obviously diverse subjects (including healthy untrained volunteers, sports persons, aged women post-menopausal woman, can lead to biased, if not erroneous inference.

Current review differs from other past reviews, in that, it does not investigate the effects on amino acid supplementation on non-athletes or geriatric population. This review lays out the wide scope of application of amino acids as ergogenic aids in a large pool of sportspersons. The common denominator in the current review is that all clinical trials included here were performed on sportsperson and the comparison was based on overall performance indicator like delay of fatigue or enhancement of performance. The data reviewed confirms the functionality of some of the amino acids and their usefulness in sports nutrition. The taurine consumption stimulating muscle recovery or performance enhancement is unwarranted based on the results of clinical trials reported so far.

It is important to understand that clinical studies considered here are performed on human subjects involved in different sports, which involves several variables such as physical fitness, diet, strength, and tenacity of the exercises could have impacted the final results. The gender, age, diet, type of sports, demographics of the players, all would have influenced the ultimate result of these clinical studies. Thus, detailed comparison of the effects on individual biomarkers was not possible from the given data. An important gap that has emerged from the review of the existing literature is the absence of specific biomarkers for evaluating the different efficiencies of ergogenic aids for instance, some aids could be efficient as anti-fatigue, others could be more efficient in delaying muscle soreness, others could be involved in performance enhancers. The are several different roles of ergogenic aids and unambiguous biomarkers must be used in clinical trials to understand the exact role that a specific amino acid can play in sports physiology. As of now the clinical trials are a collection of very heterogenous biomarkers. In future, evaluation of amino acid efficiency on specific sports would help in more objective comparison of results since different sports vary in their need for energy and hence the requirement of precision ergogenic aids.

In past this topic has inspired several authors to evaluate the physiological effects of food interactions and combination of these amino acids. For instance, BCAA was combined with citrulline in a study involving college soccer players to find both perception of tiredness and cycling performance to be benefitted as a result of the supplementation (Suzuki et al., 2019). BCAA in addition to arginine was successful in alleviating fatigue and improving performance on the second part of day 2 of a two-day trial in case of basketball players (Chang & Chiu, 2017). BCAA, Citrulline, and Arginine together, significantly impacted on decreasing the plasma free tryptophan/BCAA ratio and increased the NO_x and NH_3 concentrations in elite taekwondo players (Chen, Wu, Chen, Chou, & Chang, 2016). They also enhanced the motor performance, heart rate, and NO_x levels, decreased the tryptophan to BCAA ratio, thereby decreasing fatigue in male tennis players (Yang et al., 2017). This combination also positively impacted young swimmers, aiding in lower tryptophan/BCAA ratio and faster swimming performance (Hsueh et al., 2018). A few studies have also evaluated amino acids with other conventional sports supplements such as carbohydrates and caffeine. Ermolao and colleagues, combined arginine with BCAA and caffeine and supplemented it to young soccer players (Ermolao et al., 2017). A commercially available supplement consisting of BCAA, alanine and carbohydrates was also tested on untrained adults who gave positive results with respect to reduction in training time, capacity to endure strenuous training and ultimately improve performance (Gervasi et al., 2020). Kackley et al. (2020) formulated a Pre-Workout Supplement of Ketone Salts, caffeine, and amino Acids in order to improve high-intensity exercise performance.

It is pertinent to clarify that our review discusses at length only those clinical trials where individual amino acids have been used so as to correctly identify the physiological effects on specific biomarkers of performance enhancers, muscle repair and anti-fatigue. Studies mentioned earlier have included trials on supplementation containing multiple ergogenic aids. Through such studies it is not possible to identify the mechanism of action individual ergogenic aids Hence, the current review has excluded those trials.

Meanwhile, different facets of sport performance and their link to energy biochemistry has been studied using metabolomic tools. Several of these metabolomic studies have identified critical biomarkers which have provided distinction between different athletic abilities, ranging from elite athletes to those engaged in regular sports, and even individuals with a sedentary lifestyle (Al-Khelaifi et al., 2019; Parstorfer, Poschet, Kronsteiner, Brüning, & Friedmann-Bette, 2023). Furthermore, metabolomics has facilitated the development of predictive models that not only assess the current status of athletes but also predict their potential to achieve elite performance (Cai et al., 2022). This molecular-level information has helped in proposing nutritional strategies for augmentation of specific metabolic pathways to improve recovery. For

Table 5
Clinical trials for taurine supplementation on sportspersons.

Sl. No,	Sports / Training	N=	Experiment	Physical test	Assessments		Result	Final Effect +/-	Ref
					Mechanical tests	Biochemical tests			
1.	Triathletes	9 male long-distance triathletes	3 g of taurine (TAU) or placebo (PLA) was supplemented to the athletes for an 8 week period.	Exhaust test on a treadmill,	Heart rate, speed, Anaerobic intensity threshold, Maximum workload attained (Wmax), rating of perceived exertion at anaerobic threshold (RPEAT) and heart rate at anaerobic threshold (HRAT).	Lactate dehydrogenase (LDH) and creatine kinase (CK), and inflammatory markers tumor necrosis factor-α (TNF-α) and interleukin-6 (IL-6). Plasma taurine determined by liquid chromatography	Taurine supplementation did not benefit on the performance or muscle damage of triathletes.	–	(Galan et al., 2017)
2.	Triathletes	10 male athletes	3gm of taurine and 400gm of chocolate milk or only 400gm of chocolate milk was supplemented for four weeks.	Maximal incremental running test on a treadmill	Vmax, heart rate (HR) and rate of perceived exertion (RPE)	Oxidative stress marker levels, and 24 h urinary nitrogen, creatinine, and urea excretion	Did not improve anaerobic parameters but resuction in oxidative stress marker levels indication of taurine preventing oxidative stress.	+&-	(De Carvalho et al., 2017)
3.	Running	14 male athletes	Divided into caffeine and non-caffeine groups, each group was then supplemented with 40 mg/kg of taurine or placebo to study the effect of caffeine withdrawal on performance.	Four isokinetic knee extensions and three maximal isometric knee extensions	BMI, peak torque, power output	–	Taurine supplementation is detrimental to non-caffeine consuming athletes, in case of caffeine deprived athletes, it only improve the maximal voluntary muscle power.	–	(Lim et al., 2018)
4.	Cycling	11 male trained cyclists	1000 mg of taurine or placebo was supplemented 2hrs before a simulated 4 km cycling trial at the 5th and 7th day from the familiarisation trial.	3 simulated 4 km cycling trial (1st trial was for familiarisation).	Respiratory gases, heart rate, Breath-by-breath respiratory responses	Blood lactate, pO2, pCO2, pH and HCO3 – levels	Provides no advantage to players with taurine supplementation as compared to ones with placebo in respect to performance or blood buffering capacities.	+	(Ward et al., 2016)
5.	Squash	20 professional male squash players	Supplemented with 5 capsules a day with 1gm of taurine in each capsule, or placebo.	–	EMG, treadmill	Plasma lactate level	Short term supplementation has been found to be effective in reducing neuromuscular fatigue and blood lactate accumulation.	+	(Galan et al., 2018)
6.	Taekwondo	10 elite male players	Three servings of 15 mg/body weight per day for 10 days, following a 10-day washout period.	Simulated taekwondo competition including five stages of competition, including three 45-sec stations with different movements as 15-sec counter-movement jump training, 15-sec skpping, and15-sec turning kick.	–	Serum cytokine concentrations, hs-CRP, TNF-α, and blood lactate concentrations	Did not improve performance or enhance HR responses, inammatory biomarkers and blood lactate levels.	–	(Samandari et al., 2021)
7.	Swimming	14 male swimmers	3gm per day of taurine or placebo was supplemented for a period of 8 weeks.	Maximum time and velocity for 400 m swimming performance, energy expenditure,	BMI	Peak blood lactate concenteration, plasma taurine (using HPLC),	Only serum lactate level increased, suggesting a positive effect of taurine supplementation on	–	(Batitucci et al., 2018)

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Table 5 (*continued*)

Sl. No,	Sports / Training	N=	Experiment	Physical test	Assessments		Result	Final Effect +/-	Ref
					Mechanical tests	Biochemical tests			
				mean speed performed, the anaerobic threshold resting energy expenditure (REE), oxygen uptake (VO_2) and carbon dioxide elimination (VCO_2)			anaerobic lactate metabolism. However, no significant changes in performance was observed.		

BMI: body mass index, CK: creatine kinase, EMG: Electromyography, HPLC: High-performance liquid chromatography, HR: heart rate, hs-CRP: High-sensitivity C-reactive protein, IL-6: interleukin-6, LDH: Lactate dehydrogenase, REE: resting energy expenditure, RPE: rate of perceived exertion, TNF-α: tumor necrosis factor-α.

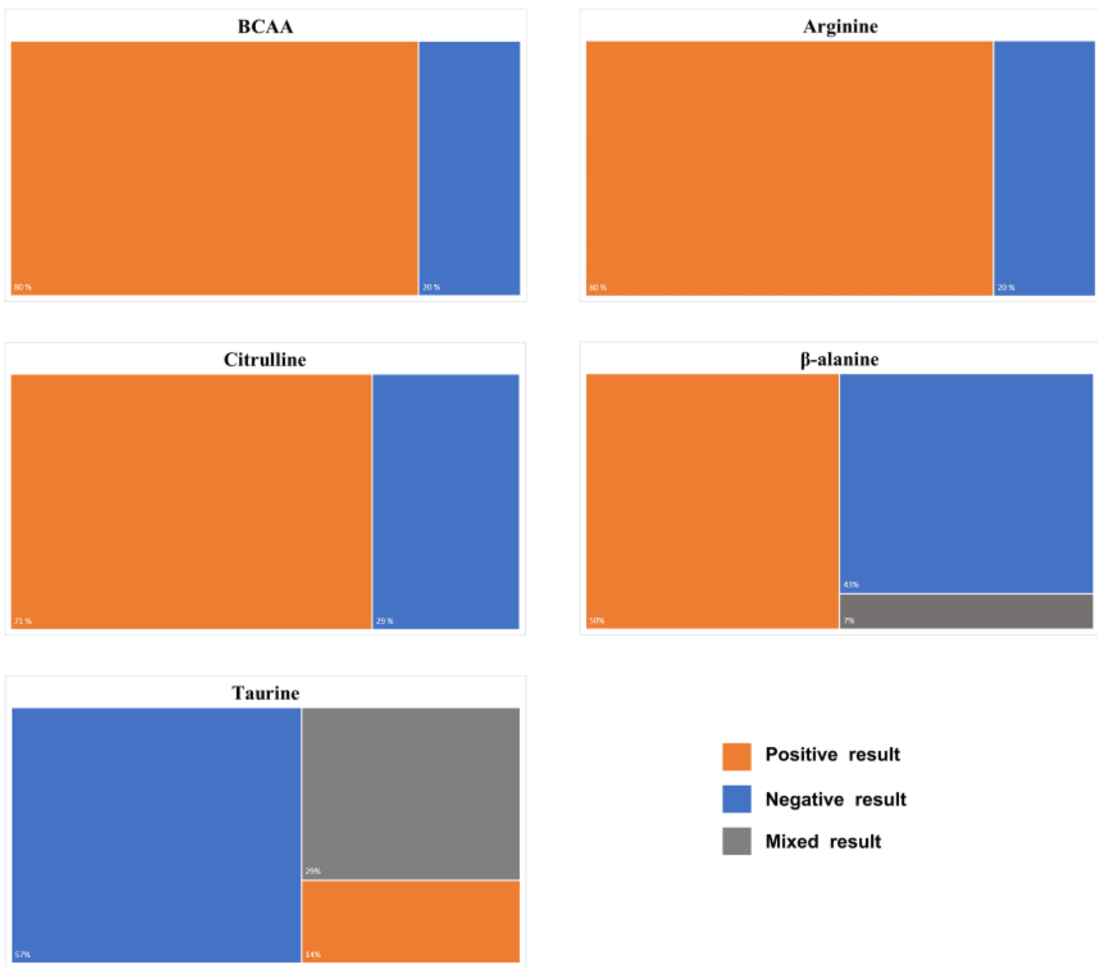

Fig. 1. Analysis of clinical trial results investigating amino acids as potential ergogenic aids underscores the effectiveness of BCAA, arginine, and citrulline. Specifically, 80% of trials report positive performance outcomes for BCAA and arginine, while citrulline demonstrates a positive performance rate of 71%. Conversely, β-alanine shows 50% of trials reporting positive results, 43% yielding negative outcomes, and 7% in mixed findings. Negative performance was reported from the taurine trials, with 57% of studies reporting unfavourable results.

instance, in collision-based sports like rugby, a focus on enhancing gluconeogenesis while preventing amino acid oxidation has emerged as a crucial dietary strategy for athletes (Hudson et al., 2021). In future, more such in depth metabolomic studies addressing the molecular basis of amino acid consumption and their consequences on field performance will felicitate in development of precision ergogenic aids.

Nutritional supplements as ergogenic aids are an ever evolving and profitable market. As the sports nutrition landscape evolves, the need for replacing generic supplement with precision-based amino acid formulations is rising. Emerging evidences from metabolomic studies has also contributed to the intricate connection between an athlete's unique metabolic profile and their sports performance. Given the recent breakthrough, ergogenic aids are bound to be in research focus in the coming years. Next-gen ergogenic aids should be based on results obtained from clinical data and should address key biomarkers of energy production, reduction in fatigue susceptibility with speedy muscle repair mechanisms among athlete population. Integration of new formulations in elite athlete population will be required, with close collaboration between researchers, practitioners, coaches and athletes in order to harness the benefits of these aids.

Table 6
Commercially available amino acid supplements.

Sl. No	Company name	Country of origin	Product name	Amino acid fortified	Purpose
1.	Thorne	United States of America	Thorne amino complex	Tyrosine, Histidine, Threonine, Phenylalanine, Lysine, Valine, Methionine, Tryptophan, Leucine, Isoleucine, Cystine	Supports muscles, mostly for training and weightlifting
			SYNAQUELL +	Leucine, isoleucine, valine	Enhances the cellular energy production, provides post impact brain support for contact sport
			Catalyte (Dietary supplement)	Taurine	Supports endurance and recovery
2.	Designs for health	United States of America	BCAA Powder with L-Glutamine	Leucine, isoleucine, valine, glutamine	Builds muscle tissues and improves the immune system
			Amino Acid Synergy	Leucine, isoleucine, valine, threonine, lysine, phenylalanine, histidine, arginine, methionine, alpha ketoglutarate	Helps in maintenance of lean body mass
3.	Klean Athlete	United States of America	KLEAN BCAA + PEAK ATP	Leucine, isoleucine, valine	Increases strength, power and promotes muscle gain
			KLEAN ISOLATE	Alanine, Arginine, Asparagine, Cystine, Glycine, Proline, Serine, Tyrosine, Leucine, Lysine, Threonine, Isoleucine, Valine, Phenylalanine, Methionine, Histidine, Tryptophan, Glutamine	Builds and repairs muscle
4.	Pure encapsulations	United States of America	Arginine & Ornithine	Arginine, Ornithine alpha ketoglutarate	Increases muscle formation and helps in growth of joints and bones. Intended for use after intense exercise
			Anti-Stress	Tyrosine, Taurine	Improves stress resistance, endurance, cognitive abilities and mental performance
5.	Now foods	United States of America	Amino Complete™ Veg Capsules	Histidine, Isoleucine, Leucine, Lysine, Methionine, Phenylalanine, Threonine, Tryptophan, Valine, Alanine, Arginine, Cysteine, Glutamine, Glycine, Ornithine, Proline, Serine, Tyrosine	Maintains, repairs and develops growing muscle tissues
			B-12 Energy Boost Tart Berry Sticks	Taurine	Increases energy production
6.	My protein	United Kingdom	Impact EAA Stick Pack	Leucine, Lysine, Isoleucine, Valine, Threonine, Phenylalanine, Tryptophan, Methionine, Histidine	Builds and repairs muscles, improves performance in successive bursts of short-term and high-intensity exercise
			Pre-Workout Blend	L-Citrulline Malate, L-Arginine alpha-ketoglutarate, L-Tyrosine, Taurine, Beta Alanine, Betaine	Increases concentration and alertness during performance and enhances endurance performance and capacity by reducing tiredness and fatigue
			Pre-Workout Gel	Beta Alanine, Citrulline Malate, Taurine, Acetyl L Carnitine, Arginine Alpha Ketoglutarate, N Acetyl L Tyrosine	Improves workout performance for different sports ranging from weightlifting to long distance running.
7.	FAST&UP	India	FAST&UP PRE-WORKOUT	Beta Alanine, Creatine Monohydrate, Taurine, N-Acetyl-L-Tyrosine	Delays fatigue and promotes muscle gain. Also improves mental focus, alertness and attention.
			FAST&UP ISOLATE WHEY	Leucine, isoleucine, valine, glutamine	Heightens muscle strength, endurance and performance
8.	Nutraworks	Hungary	BCAA 2:1:1 + B6 500	Leucine, isoleucine, valine	Improves muscle strength and performance

The details provided in table have been collected from company websites.

5. Conclusion

Studies reported and critically appraised in this review highlights the potential of amino acids as efficient anti-fatigue and performance enhancers, for sport persons. Considering the present data, it appears that BCAA, citrulline and arginine definitely show anti-fatigue and performance enhancers in sportspersons. More recent and specific metabolomic studies have aided in identifying distinct metabolite markers associated with athletes at different performance levels. However, there seems to be several research gaps that need to be bridged in the area of role ergogenic aids in sports nutrition. It is important to note that both land and water sports have different energy demands, some needing short bursts of energy and others needing higher endurance. The significant insights derived from these studies included in this review underscore firstly, well defined biomarkers are required to understand the molecular underpinnings of the ergogenic aids since these aids especially amino acids can play different roles as performance enhancers, in fatigue reduction, in reduction of muscle soreness. Secondly, the need to design sport-specific investigations to obtain conclusive data on the effectiveness of different amino acid combinations. In situ or field experiment are needed. Thirdly, it may be more useful to design precise formulations to target the requirement of specific sports. For instance, some combinations of amino acids may be more suitable for long term endurance and some others may be suitable for short burst of excessive energy.

Future research should be directed towards development of tailored ergogenic aids that precisely target the fatigue mechanisms and energy demands unique to each sport. Rather than relying on generic supplements, athletes stand to benefit significantly from “precision” amino acid combinations that align with their specific metabolic and performance requirements.

CRediT authorship contribution statement

Sreya Duttagupta: Writing – original draft, Validation, Methodology, Data curation. **Niladri Krishna Roy:** Writing – review & editing, Visualization, Formal analysis, Data curation. **Gargi Dey:** Formal analysis, Conceptualization, Investigation, Project administration, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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