Quality in Sport. 2026;50:67961. eISSN 2450-3118.

https://doi.org/10.12775/QS.2026.50.67961

Quality in Sport. eISSN 2450-3118
Journal Home Page
https://apcz.umk.pl/QS/index

How to cite:
KOZICKI, Maciej Jakub, ZIENKIEWICZ, Damian, KOSTRO, Julia Maria, MAKULEC, Gabriela, DOMOSUD, Karolina, PAPIEŻ, Magdalena, JĘDRA, Zofia, LIBERA, Anna, BARTKIEWICZ, Karolina and NOVIK, Lizaveta. β-Alanine Supplementation and Its Impact on Physical Performance: A Literature-Based Review. Quality in Sport. 2026;50:67961. eISSN 2450-3118. https://doi.org/10.12775/QS.2026.50.67961

The journal has been awarded 20 points in the parametric evaluation by the Ministry of Higher Education and Science of Poland. This is according to the Annex to the announcement of the Minister of Higher Education and Science dated 05.01.2024, No. 32553. The journal has a Unique Identifier: 201398. Scientific disciplines assigned: Economics and Finance (Field of Social Sciences); Management and Quality Sciences (Field of Social Sciences).
Punkty Ministerialne z 2019 - aktualny rok 20 punktów. Załącznik do komunikatu Ministra Szkolnictwa Wyższego i Nauki z dnia 05.01.2024 Lp. 32553. Posiada Unikatowy Identyfikator Czasopisma: 201398. Przypisane dyscypliny naukowe: Ekonomia i finanse (Dziedzina nauk społecznych); Nauki o zarządzaniu i jakości (Dziedzina nauk społecznych).
The authors declare that there is no conflict of interest regarding the publication of this paper.
Received: 03.01.2026. Revised: 24.01.2026. Accepted: 28.01.2026. Published: 30.01.2026.

β-Alanine Supplementation and Its Impact on Physical Performance: A Literature-Based Review

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Abstract

Purpose of research:

This literature-based review synthesized the current evidence regarding the effects of β-alanine (BA) supplementation on human physical performance. The review focused on BA as the rate-limiting precursor for intramuscular carnosine synthesis and evaluated its ergogenic impact across various exercise modalities and durations.

Research materials and methods:

A structured literature search was conducted in major scientific databases, including PubMed, for English full-text articles available through 2025. Only Meta-Analyses, Systematic Reviews, and Randomized Controlled Trials were included, examining BA supplementation in human athletes or trained individuals compared with a placebo or control condition.

Basic results:
Chronic BA supplementation significantly increases muscle carnosine content and enhances intramuscular buffering capacity, delaying the onset of fatigue during high-intensity exercise. The most robust performance benefits are observed in efforts lasting approximately 1–4 minutes, with supplemental improvements noted in activities up to 10 minutes. BA also supports improvements in training volume and resistance to fatigue. Paresthesia remains the most commonly reported side effect.
Conclusions:
β-alanine is an evidence-based ergogenic aid that improves performance in high-intensity efforts requiring substantial buffering capacity. Chronic, divided dosing provides the greatest effectiveness.

Key words: β-alanine, carnosine, buffering, high-intensity exercise, ergogenic aid, performance.

Introduction

The thoughtful use of nutritional supplements is important in maximizing athletic performance, supporting training adaptations, and improving recovery in a wide range of sports. Among the many ergogenic aids used by athletes, beta-alanine (BA) is one of the most common and well-supported by research.

Beta-alanine is a non-essential, non-proteogenic amino acid produced naturally in the liver and obtained through dietary sources, mainly meat. Its primary ergogenic effect stems from serving as the rate-limiting precursor for carnosine (β-alanyl-L-histidine) synthesis within skeletal muscle. As the body cannot efficiently absorb exogenous carnosine directly, increasing BA intake is the most effective strategy to raise muscle carnosine levels.

Carnosine is found in high concentrations in skeletal muscle and functions mainly as an intracellular buffer, counteracting the rapid rise in hydrogen ions (H^+) that occurs during high-intensity anaerobic exercise. With an approximate pKa of 6.83, carnosine helps maintain intracellular pH by neutralizing accumulating H+ ions, which delays muscle fatigue and supports performance in activities where exercise-induced acidosis is a major limiting factor.

Regular BA supplementation—commonly 3.2 to 6.4 g per day for at least four weeks—has consistently been shown to elevate muscle carnosine content by approximately 20% to 80%. This improved buffering capacity contributes to measurable performance benefits, particularly in high-intensity efforts lasting approximately 60 to 240 seconds (1–4 minutes), and in some analyses, up to about 10 minutes. Research reports advantages in multiple sports, including increases in strength-training metrics (such as 1RM, power output, and total work completed), longer time to exhaustion, and enhanced performance in activities like boxing, judo, and cycling sprints. BA supplementation may also lower ratings of perceived exertion (RPE).

Despite the compelling body of evidence, the literature presents inconsistencies and ambiguities. Some studies report no significant performance improvement in elite athletes during real-world competition [8], [25], [35], while others demonstrate that the benefits might be more dependent on the total cumulative dose and dosing strategy (e.g., fragmented doses vs. sustained-release formulas) rather than duration alone, particularly for strength and power outcomes [36]. Furthermore, the effects on aerobic capacity (VO2 peak) are generally unclear or non-existent [2], [7], [29], and evidence regarding acute dosing or cognitive function improvements in humans remains limited or contradictory [22], [25], [37].

Therefore, a comprehensive synthesis of the research is warranted to guide athletes, coaches, and sports nutrition practitioners in effectively utilizing this supplement [15], [17].

This literature review aims to summarize and assess current evidence on the impact of beta-alanine supplementation on physical performance, with the goal of outlining best practices and highlighting key directions for future research.

Aim of the Study

The main objective of this literature-based review is to critically synthesize the scientific evidence regarding the impact of β-alanine supplementation on human physical performance.

The secondary aims include:

1. To examine the physiological mechanism of action, focusing on β-alanine's role as the rate-limiting precursor for carnosine synthesis and the consequent increase in muscle buffering capacity.
2. To evaluate the ergogenic effects of β-alanine supplementation across various exercise modalities and durations, specifically differentiating effects on short, high-intensity efforts (60 seconds to 10 minutes) from prolonged aerobic capacity and strength/power indices.

3. To investigate the influence of varying dosing strategies (e.g., daily dose, total cumulative intake, and dosing fragmentation) on both performance outcomes and the management of the key side effect, paresthesia.
4. To discuss the efficacy and applicability of β-alanine supplementation across diverse populations and sports, including specific considerations for trained athletes, the aging population, and combat sports participants.

Research materials and methods

I. Study Design and Scope

This thesis constitutes a literature-based review aiming to systematically synthesize existing high-level evidence regarding the effects of β-alanine (BA) supplementation on human physical performance. The methodology followed principles commonly applied in systematic reviews, emphasizing transparency and the comprehensive evaluation of published controlled trials and syntheses.

II. Literature Search Strategy

The search strategy was executed by identifying relevant publications from major scientific databases specific to biomedical and sports science research.

The present review, based on an analysis of the scientific literature, was conducted by selecting studies with accessible full text written in English. Only meta-analyses, systematic reviews, and randomized controlled trials (RCTs) available on PubMed were included, covering all records from the beginning of the search window through 2025. Although no lower limit was set for publication year in order to capture foundational research, the earliest study that met the inclusion criteria was published in 2010 [3]. The final verification of the search results was completed on October 26, 2025.

The core search terms used were: "beta alanine," "β-alanine," combined with terms such as "exercise," "sports performance," and "performance."

III. Study Selection Criteria (PICOS Framework)

The selection process strictly adhered to specific inclusion criteria to ensure the synthesis focused on the highest quality of evidence.

Criterion	Specification	Justification
P (Population)	Human studies focusing on performance outcomes, often in athletes, physically active individuals, or trained populations.	To ensure relevance to optimizing athletic performance.
I (Intervention)	β-Alanine (BA) supplementation, administered chronically or acutely, focusing on ergogenic effects.	To directly address the thesis topic.
C (Comparison)	Included studies must involve a control or placebo (PL) group.	To ensure comparison is based on robust experimental designs.
O (Outcomes)	Studies examining metrics of physical performance (e.g., maximal/supramaximal intensity exercise, capacity, strength, power, time to exhaustion [TTE], time trials [TTT]). The main focus was on the practical application of article data.	To quantify the physiological and performance impact of BA.
S (Study Design)	Limited exclusively to high-level evidence: Meta-Analysis, Systematic Review (SR), or Randomized Controlled Trial (RCT).	To ensure the robustness and reliability of the evidence base.
Availability/Language	Articles must have fully available text and be published in English. Conference abstracts, non-peer-reviewed data, and unpublished theses were excluded.	To ensure comprehensive verification and accessibility.

IV. Data Extraction and Synthesis

From the selected literature, the following types of information were systematically extracted and synthesized:

1. **Study Characteristics:** Author, year, study design, and specific population (e.g., combat athletes [28], runners [4], cyclists [1], or military personnel [20]).
2. **Supplementation Protocols:** Specific dosing strategies (e.g., daily dose, total cumulative intake, fragmented dosing vs. sustained-release) [2], [11], [36] and duration (e.g., 4 weeks [17] or longer [36]).
3. **Performance Outcomes:** Results categorized by exercise modality and duration, such as effects on high-intensity efforts (60 seconds to 10 minutes) [15], [17], [21], strength and power (e.g., 1RM, mean power, peak power) [2], [15] [36], time to exhaustion (TTE) [25], and aerobic capacity measures (e.g., VO_2max) [2], [25].
4. **Biochemical Markers and Perception:** Changes in muscle carnosine content, blood lactate concentration ([La^-]b) [15], [25], [35], pH [15], and Rating of Perceived Exertion (RPE) [15], [25].
5. **Side Effects:** Information regarding the occurrence and severity of side effects, such as paresthesia [15], [25], [35].

The synthesis of these sources allowed for a comprehensive qualitative discussion, often supported by quantitative data (Standardized Mean Differences, SMD) reported in the included meta-analyses. The high methodological quality of the included studies (Meta-analyses, SRs, and RCTs) provides a solid basis for evidence-based conclusions.

Results

I. Physiological Mechanism and Muscle Carnosine Content

The primary ergogenic mechanism of β-alanine (BA) supplementation is its capacity to increase the intramuscular concentration of the dipeptide carnosine (β-alanyl-L-histidine) [4], [7], [9], [22], [27], [31], [33], [36], [40], [41].

1. **Carnosine Synthesis:** BA is considered the rate-limiting precursor for carnosine synthesis in skeletal muscle [9], [15], [16], [22], [27], [31], [36], [38], [41]. Since the organism cannot efficiently absorb carnosine directly, BA ingestion is critical for increasing muscular reserves [25], [31].
2. **Intracellular Buffering:** Carnosine functions primarily as an intracellular physico-chemical buffer against the accumulation of hydrogen ions (H^+) generated during intense anaerobic glycolysis [3], [4], [11], [17], [31], [33], [36], [41]. With a pKa of approximately 6.83, carnosine effectively stabilizes intramyocellular pH, delaying muscular fatigue [7], [8], [25], [31], [33], [38].
3. **Other Roles:** Carnosine contributes to Ca^{2+} sensitivity in contractile fibers, enhancing muscle excitation-contraction and promoting the maintenance of force production [1], [3], [17], [18], [21], [25], [31], [41]. Carnosine also has antioxidant, neuroprotective, and anti-glycating properties [1], [17], [18], [22], [39], [41].
4. **Carnosine Elevation:** Chronic BA supplementation (typically 4–10 weeks) consistently increases muscle carnosine content, with reported increases ranging from roughly 40% to 80% [2], [7], [7], [8], [15], [16], [17], [22], [31], [38], [40], [41]. This elevation increases muscle buffering capacity by about 4% [7], [38].

II. Impact on Exercise Performance Outcomes by Duration

The ergogenic effect of BA is highly dependent on the duration of the high-intensity effort.

A. High-Intensity Capacity (60 Seconds to 4 Minutes)

- **Optimal Duration:** BA supplementation produces the most significant and consistent ergogenic effect on exercise efforts lasting 60 to 240 seconds (1–4 minutes), where acidosis is the primary limiting factor [7], [15], [21], [31].
- **Capacity vs. Performance:** Meta-analysis data strongly indicate that BA significantly improves exercise capacity (measured by outcomes like Time to Exhaustion [TTE] or total work done) [8], [17], [21], [43].
- **Magnitude of Effect:** BA supplementation typically results in a median improvement of 2.85% in exercise measures, based on a median total dose of 179 g. [21], [36]. Improvements in high-intensity cycling capacity tests (TTE at 110% power max) have been reported to be as high as 11.8% to 12.1% [21], [42].
- **Delayed Fatigue:** BA improved high-intensity intermittent exercise performance (repeated bouts/sprints) by augmenting muscle carnosine content and attenuating neuromuscular fatigue [2], [33].

B. Shorter and Longer Duration Exercise

- **Very Short Duration (<60 seconds):** Exercise lasting less than 60 seconds is not improved by BA supplementation [12], [15], [17], [21], as fatigue during these brief efforts is typically not limited by acid accumulation [12], [17], [40].

- **Longer Duration (>240 seconds / 4 minutes):** Benefits become less pronounced but are still considered significant for exercise lasting over 240 seconds [21]. Some reviews extend the beneficial range up to 10 minutes [17], [34], [45].
    - One meta-analysis found a moderate and significant effect on maximal output for tests lasting 4–10 minutes [17].
    - Studies investigating sustained exercise, such as 30-minute rowing, showed limited impact [5].
    - In competitive swimmers, chronic BA supplementation had an unclear effect on competition performance [8]. A study on 400-m freestyle swimming (approx. 4 minutes) found no effect [35].
- **Aerobic-Anaerobic Transition Zones (Endurance):** BA supplementation showed a small and non-significant effect on Time Trial Tests (TTT) or TTE tests in aerobic–anaerobic transition zones [25], [39]. The effect on maximal aerobic power (VO_2max or VO_2peak) is generally minimal or non-existent. [2], [17], [29]. However, improvements in TTE in endurance runners (6.5% increase) were observed [29].

III. Impact on Strength and Power Metrics

The effectiveness of BA on strength and power appears dependent on the type of exercise and the cumulative dose received.

- **Maximal Strength (1RM):** Evidence regarding BA's effectiveness for improving maximal strength (1RM) alone is inconsistent [15], [36]. Some studies reported BA did not provide additional benefits for maximal strength gains beyond the effects of creatine alone [2].
- **Power and Muscular Endurance:** BA supplementation was effective at increasing power output when lifting loads equivalent to the individual's 1RM or working at maximum power output [31]. BA supplementation (6.4 g/day for 5 weeks during training) led to significant increases in kilograms lifted at 1RM, power output for 1RM loads, and power output gains at maximum power [31].
- **Training Volume and Fatigue Resistance:** BA supplementation often supports the ability to execute a greater training volume [2], [15], [31], [36]. It specifically increased the number of sets executed and the pre-post gain in kilograms lifted at 1RM in an incremental load test [31]. BA helps sustain power output and mitigate fatigue in repeated high-intensity efforts, suggesting that the benefits are maximized in exercises involving high metabolic stress, such as repeated submaximal efforts or short rest intervals [2], [36].
- **Cumulative Dose:** Efficacy in strength and power outcomes appears to correlate with the total cumulative dose [36]. Studies reporting positive effects typically utilized cumulative doses of BA approaching or exceeding 200–300 g [36].

IV. Dosing Strategies and Side Effects

A. Chronic Dosing Protocols

- **Standard Dose:** Daily doses of 4–6.4 g/day sustained over 4–10 weeks are commonly suggested to significantly increase muscle carnosine content and exercise capacity [2], [15], [16], [23], [31], [34], [36], [38], [41].
- **Fragmented Dosing:** To optimize absorption and minimize the side effect of paresthesia, fragmented dosing protocols are recommended. [9], [15], [16], [31], [36]. Doses are often divided into smaller portions, such as 0.8 g or 1.6 g per serving, taken multiple times throughout the day [9], [15], [16], [31], [36], [39].
- **High/Short-Term Dosing:** High-dose protocols (e.g., 12 g/day for two weeks or 20 g/day for seven days, often using sustained-release formulations) can accelerate carnosine synthesis and attenuate performance decline, particularly in elite cyclists during intensive training camps [1], [34], [39].

B. Acute Dosing

- Acute BA supplementation (e.g., 1.6 g) generally does not improve performance variables (peak power, mean power, fatigue index) in short anaerobic activities in young, trained individuals [18].
- However, acute, single-dose supplementation (30 $mg \cdot kg^{-1}$ and 45 $mg \cdot kg^{-1}$) was found to increase physical performance in a 6-minute race test (aerobic-anaerobic transition zone) in endurance athletes [4], [24], [25].

C. Side Effects and Safety

- **Paresthesia:** The most commonly reported side effect is paresthesia (a mild tingling or prickling sensation in the skin, often in the face or extremities) [1], [6], [15], [16], [25], [31], [36]. Paresthesia is dose-dependent and typically occurs when single doses exceed about 10 $mg \cdot kg^{-1}$ (or 800–1,600 mg) and resolves within an hour of intake [16], [25], [31].
- **Mitigation:** Paresthesia can be minimized or avoided by using fragmented dosing strategies [16], [25], [31], [36], taking BA with meals [9], [16], or employing sustained-release (SR) formulations [1], [15], [16], [21], [34], [36], [39].

- **Tolerability:** BA supplementation is generally considered safe and does not cause alterations in healthy populations at recommended doses [15].

V. Secondary and Population-Specific Effects

A. Perceived Exertion (RPE) and Lactate

- **RPE:** Acute BA supplementation (1.6 g dose) decreased Rating of Perceived Exertion (RPE) immediately following initial Wingate bouts and after rest periods in female cyclists, suggesting a reduced subjective feeling of exertion independent of objective performance changes [18], [37]. Acute BA supplementation also generated a lower post-exertion RPE in middle-distance runners [4], [15]. However, some studies found no change in RPE [16], [34].
- **Blood Lactate:** Results regarding post-exercise blood lactate concentration are heterogeneous [15], [45]. Some studies found no changes [16], while others noted a significant increase in blood lactate concentration after high-intensity tests in the BA group, suggesting enhanced anaerobic glycolytic capacity [15], [33].

B. Specific Populations and Sports

- **Combat Sports:** BA supplementation (4–6.4 g/day for ≥4 weeks) in combat athletes (wrestling, judo, boxing) showed significant improvements in power, total exercise work capacity, anaerobic and muscular power, and combat-specific parameters (e.g., mean punch force, number of throws) [15], [45].
- **Older Adults:** BA supplementation (e.g., 2.4 g/day for 28 days) improved endurance exercise capacity (TTE) in middle-aged individuals [16], [25], [24]. It is also associated with improvements in functional performance (e.g., sit-to-stand) and may combat sarcopenia symptoms [16], [30], [37].
- **Cognitive Function:** BA supplementation reduced endurance exercise-induced declines in executive function in middle-aged individuals [16], [24], [37]. However, direct improvement in cognitive tests in young, healthy adults or soldiers is generally not observed [16], [22], [37].

C. Combination with Other Ergogenic Aids

- **Sodium Bicarbonate (SB):** The combination of BA and SB is reported as an effective strategy for improving high-intensity intermittent exercise performance [6], [11], [17], [23].
- **Creatine (Cr):** While creatine is the primary driver for gains in maximal strength (1RM), combining BA and Cr enhances performance compared to placebo and may offer advantages in repeated maximal efforts where resisting fatigue is critical [2], [31].

Discussion

The systematic review and meta-analysis of β-alanine (BA) supplementation clearly establishes its efficacy as an ergogenic aid, driven primarily by its capacity to enhance intramuscular buffering. However, the diverse findings across the literature underscore that the performance benefits are highly dependent on the physiological demands of the exercise, the training status of the population, and the precise supplementation protocol utilized. This discussion interprets the aggregated findings, addresses key contradictions, and highlights the practical implications for athletes and practitioners.

The Mechanism: Establishing the Foundation of Efficacy

The consistent finding across the literature is the confirmation of BA's primary physiological role: serving as the rate-limiting precursor for the synthesis of the dipeptide carnosine (β-alanyl-L-histidine) within skeletal muscle fibers [7], [9], [15], [22], [27], [31], [36], [38], [39], [41]. Since the body cannot efficiently absorb intact carnosine, the bioavailability of BA dictates muscle carnosine accumulation [22], [31], [41].

Carnosine's subsequent function as a major intracellular physico-chemical buffer is the mechanism responsible for delaying fatigue during intense exercise [4], [7], [8], [11], [21], [23], [34], [41]. By accepting excess hydrogen ions (H^+) generated during anaerobic metabolism, carnosine helps stabilize intramyocellular pH (which typically drops from ≈7.1 at rest to ≈6.5 at fatigue) [4], [6], [7], [35]. Beyond buffering, carnosine may also increase the calcium (Ca^{2+}) sensitivity of contractile fibers, further aiding muscle function, particularly in fatiguing conditions [1], [3], [17], [31], [38], [39], [41], [44]. Chronic supplementation (4–6.4 g/day for ≥4 weeks) reliably produces substantial increases in muscle carnosine (up to 80%) [2], [7], [8], [16], [17], [29], [31].

Performance Efficacy: The Role of Exercise Duration

The effectiveness of BA is highly stratified by the duration and metabolic nature of the exercise performed:

1. **Optimal High-Intensity Window (60–240 seconds):** The consensus among older meta-analyses confirms that BA provides the most significant ergogenic benefit in exercise lasting between 60 and 240 seconds (1–4 minutes) [15], [21], [41]. This window correlates precisely with efforts where muscle acidosis is the primary limiting factor [17], [21]. In controlled capacity tests, BA yielded marked improvements, such as the repeatedly confirmed 11.8%–12.1% increase in total work done during high-intensity cycling to exhaustion [21], [42].

2. **Extended High-Intensity Efforts (4–10 minutes):** More recent systematic reviews suggest that BA's efficacy may extend up to 10 minutes [41], [34], [17], [39]. One comprehensive meta-analysis indicated that BA supplementation was significantly effective for maximal effort exercise lasting 4–10 minutes [17]. This extension is plausible because glycolytic contribution remains significant throughout this longer range, requiring continuous buffering capacity [15], [17].
3. **Very Short Efforts (<60 seconds):** BA consistently shows no benefit for activities lasting less than 60 seconds (e.g., short sprints) [12], [15], [17], [21], [39], [40]. This lack of effect is attributed to the energy system reliance, as fatigue in these efforts is typically dominated by phosphocreatine depletion rather than acid accumulation [12], [21].
4. **Endurance and VO_2peak:** BA does not improve maximal aerobic capacity (VO_2peak) [2], [25], [29]. However, in endurance athletes, BA supplementation significantly enhanced Time to Exhaustion (TTE), for example, a 6.5% increase in adolescent runners [29]. This suggests that BA improves the ability to tolerate the high-intensity components encountered during prolonged efforts (aerobic–anaerobic transition zones) [25], [29]. Acute, high doses (30–45 $mg \cdot kg^{-1}$) were surprisingly effective at improving performance in these transition zones, challenging the exclusive reliance on chronic loading for this specific domain [4], [24], [25].

Inconsistencies in Strength and Power Outcomes

The effects of BA on maximal strength parameters (1RM) are inconsistent or negligible when measured in isolation [2], [17], [36]. The primary benefit in resistance training lies in improving muscular endurance and increasing training volume [2], [31], [36]. This improved fatigue resistance allows athletes to perform a greater number of repetitions or sets, particularly during high-volume training protocols that induce significant metabolic stress [36]. The effectiveness of BA in strength and power appears highly dependent on dosing strategy and training stimulus:

- **Cumulative Dose Threshold:** Evidence suggests that effectiveness correlates with the total cumulative dose, with studies reporting positive results generally approaching or exceeding 200–300 g of total BA intake [36].
- **Training Specificity:** BA's efficacy is maximized when combined with training sessions that actively create an acidotic environment (e.g., short rest intervals, repeated submaximal efforts) [36]. Studies that used long rest periods (2–5 minutes) often reported null strength gains, as the rest allowed sufficient time for muscle pH recovery, negating the need for the supplementary buffering capacity [36].
- **Combat Sports:** Conversely, in combat athletes (judo, boxing, wrestling), where performance inherently relies on repeated, high-intensity actions causing extreme acidosis, BA consistently improved power, total exercise work capacity, and combat-specific outcomes [15].

Optimization of Supplementation Protocols

Optimal BA use requires specific strategies to maximize uptake and minimize side effects:

1. **Dose Fragmentation:** The limiting factor in single high-dose BA ingestion is paresthesia (a mild tingling sensation) [6], [16], [31], [36]. This side effect is minimized by employing a fragmented dosing strategy (e.g., 0.8–1.6 g doses taken multiple times throughout the day, separated by 3–4 hours) [9], [16], [17], [31], [36], [38], [39]. Fragmented dosing is generally considered more effective as it helps maintain optimal plasma BA levels for carnosine synthesis without saturating transporters, thereby limiting urinary excretion [36].
2. **Formulation Choice:** Sustained-release (SR) formulations or ingesting BA with meals can also mitigate paresthesia by slowing absorption kinetics [1], [9], [15], [16], [34], [38], [39]. However, there is divergence regarding the efficacy of SR formulations in maximal strength studies, with some evidence suggesting that suboptimal formulations or unfragmented high doses might compromise efficacy by slowing carnosine accumulation [36].
3. **Acute Application:** The investigation of acute high-dose BA (30–45 $mg \cdot kg^{-1}$) prior to exercise in endurance athletes provides a novel pathway, showing significant improvements in performance in aerobic–anaerobic transition zones, even after a single dose [4], [24], [25]. This protocol minimizes prolonged exposure and associated risks of long-term dosing.

Ancillary Benefits and Neuroprotective Hypotheses

Beyond its core role as an acid buffer, BA shows potential for psychological and cognitive benefits:

- **Reduced Perceived Exertion (RPE):** Both acute and chronic BA supplementation have been associated with a lower post-exercise Rating of Perceived Exertion (RPE) [4], [18], [44]. This occurs even when objective performance or power output remains similar, suggesting a reduction in the subjective feeling of effort [4], [18].
- **Cognitive Function:** Research in specific populations, such as military personnel under stress and older adults with borderline cognitive function, suggests BA may improve cognitive performance (e.g.,

executive function, reduced depression/anxiety scores) [16], [20], [22], [37], [44]. This effect is hypothetically linked to carnosine's roles as an antioxidant and neuroprotectant, possibly increasing carnosine or related neurotrophins (BDNF) in the brain [22], [37], [44]. However, efforts to measure corresponding increases in human brain carnosine levels using current technology (MRS) have been largely unsuccessful, making the exact mechanism elusive [20], [22], [37].

Addressing Limitations and Future Directions

Despite strong evidence for BA's capacity-enhancing effects, several limitations persist in the literature:

1. **Capacity vs. Performance Discrepancy:** The consistent finding that BA improves exercise capacity but often not competitive performance (e.g., time trials in elite swimmers) highlights a critical gap [8], [17], [21]. This discrepancy is likely attributed to pacing strategies employed in performance tests, which mask the potential ergogenic effect compared to maximal TTE protocols [8], [17], [21].
2. **Highly Trained Populations:** The effects of BA in highly trained or elite athletes remain somewhat inconsistent compared to recreationally active individuals [2], [8], [17], [38]. This may be because athletes already possess high baseline buffering capacity or have reached neuromuscular performance ceilings where gains are marginal [2], [38].
3. **Methodological Constraints:** Many studies rely on inferred data rather than directly measured muscle carnosine levels (biopsies or MRS) or muscle pH changes, constraining the mechanistic interpretation of performance gains [5], [7], [16], [33], [38]. The high variability in individual response also complicates generalized recommendations.
4. **Underrepresented Groups:** The majority of high-quality studies focus on young, trained, omnivorous males [17], [36]. More research is critically needed to generalize findings across female populations (who may have lower baseline carnosine and thus respond differently) and other groups, such as adolescents and geriatric populations [2], [12], [15], [17], [20], [37].

Conclusion

β-alanine supplementation is a validated intervention for enhancing muscle buffering capacity and delaying fatigue, translating to measurable improvements in maximal exercise capacity, particularly in efforts lasting 1–10 minutes. Future investigations must adopt standardized protocols for strength training (e.g., high metabolic stress design) and clarify the efficacy of novel acute dosing strategies, while consistently incorporating muscle carnosine and pH measures to confirm the mechanism of action across diverse athletic populations.

The literature comprehensively demonstrates that β-alanine (BA) supplementation is an effective ergogenic aid, primarily due to its role as the rate-limiting precursor for the synthesis of the intramuscular buffer carnosine [7], [16], [22], [24], [27], [31], [32], [38], [40], [41]. Chronic supplementation (typically 4–10 weeks) increases muscle carnosine levels substantially, often by 40% to 80%, which enhances the capacity of muscle fibers to buffer the hydrogen ions (H^+) produced during intense anaerobic glycolysis, delaying the onset of muscular fatigue [15], [16], [17], [22], [41].

Established Ergogenic Effects and Performance Domains

The ergogenic effects of BA are most reliably observed in high-intensity exercise efforts that are critically dependent on glycolytic energy production and prone to metabolic acidosis:

- **Optimal Duration (Exercise Capacity):** BA supplementation elicits a significant ergogenic effect on exercise capacity measures (such as Time to Exhaustion, TTE) lasting between 60 seconds and 240 seconds (1–4 minutes) [2], [15], [15], [17], [21], [22]. Meta-analyses show a median improvement of 2.85% in exercise measures with BA compared to placebo [21]. Highly reliable tests of high-intensity cycling capacity within this duration have reported performance improvements up to 11.8%–12.1% [21].
- **Longer Maximal Efforts:** Benefits continue, though they become less pronounced, for maximal efforts lasting over 240 seconds [21]. Recent meta-analysis results confirm a moderate and statistically significant effect for maximal exercise lasting 4–10 minutes [17].
- **Strength and Power (Repeated Bouts):** While the benefit on one-repetition maximum (1RM) strength alone is inconsistent [2], [15], [36], [44], BA is effective at increasing power output, total exercise work capacity, and mitigating fatigue during exercises involving repeated submaximal efforts and high metabolic stress [15], [17], [31], [36], [45]. This mechanism allows athletes to execute a greater training volume, contributing to enhanced adaptive responses over time [16], [31]. In combat sports, supplementation improved power, total exercise work capacity, and combat-specific parameters (e.g., punch strength and total throws) [15], [45].
- **Aerobic and Submaximal Thresholds:** BA generally has a minimal or non-existent influence on maximal aerobic capacity (VO_2peak) [2], [7], [16], [26], [29]. However, it may increase TTE and enhance submaximal endurance performance, particularly by delaying neuromuscular fatigue onset, suggesting efficacy in the aerobic–anaerobic transition zone.

Dosing, Safety, and Special Considerations

The effectiveness of BA is highly dependent on appropriate dosing protocols:

- **Optimal Chronic Protocol:** Effective chronic supplementation generally involves doses of 4–6.4 g/day sustained over 4–10 weeks [15], [16], [17], [24], [36], [38]. For strength/power outcomes, efficacy correlates with cumulative doses approaching or exceeding 200–300 g [36].
- **Dosing Strategy for Absorption and Safety:** Dosing should be delivered in fragmented servings (e.g., 0.8 g or 1.6 g per dose) taken several times throughout the day, often with meals, to optimize carnosine synthesis and minimize the dose-dependent side effect of paresthesia (a transient tingling sensation) [9], [15], [16], [17], [36]. Sustained-release (SR) formulations are effective in preventing paresthesia [1], [21], [34], [35].
- **Acute Dosing:** Acute high doses (30–45 $mg \cdot kg^{-1}$ of BA), ingested 60 minutes before a maximal effort, can improve physical performance in aerobic–anaerobic transition zones for endurance athletes [4], [24].
- **Perceived Exertion and Cognition:** BA supplementation is associated with a decrease in the subjective Rating of Perceived Exertion (RPE) immediately following high-intensity exercise [4], [18], [45]. Furthermore, BA may improve executive function following endurance exercise in middle-aged individuals and has been linked to improved tactical and cognitive performance under stressful conditions in military personnel [16], [20], [22], [37].
- **Co-Supplementation:** BA has been successfully combined with sodium bicarbonate (SB) to enhance high-intensity intermittent performance, suggesting a complementary effect between intracellular and extracellular buffering [11], [38], [43]. When combined with creatine (Cr), BA enhances performance in scenarios requiring repeated maximal efforts and fatigue resistance, although Cr remains the primary driver for maximal strength gains (1RM) [2], [31].

Summary

In conclusion, β-alanine supplementation is a scientifically supported strategy for athletes seeking to improve performance in high-intensity activities lasting between one and ten minutes, where fatigue is primarily driven by muscle acidosis. Its efficacy is maximized not just by the duration of supplementation, but also by using fragmented daily doses (4–6.4 g) to optimize carnosine uptake and reduce side effects. The consistent findings regarding increased work capacity, enhanced training volume tolerance, and reduced perceived exertion underscore BA's value as a dietary aid across various high-intensity sports, including cycling, running, and combat sports. Future research should focus on optimizing acute dosing protocols and further clarifying the physiological benefits of BA in highly trained populations, as well as its mechanistic role in specific strength and cognitive outcomes.

Disclosure

Author's contribution
Conceptualization: Maciej Kozicki and Karolina Bartkiewicz and Karolina Domosud
Methodology: Maciej Kozicki and Karolina Bartkiewicz and Karolina Domosud
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Formal analysis: Gabriela Makulec and Damian Zienkiewicz and Lizaveta Novik
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Writing – review and editing: Anna Libera and Julia Kostro
Supervision: Anna Libera, Julia Kostro and Maciej Kozicki

All authors have read and agreed with the published version of the manuscript.

Funding Statement
The study did not receive special funding.

Institutional Review Board Statement
Not applicable.

Informed Consent Statement
Not applicable.

Data Availability Statement
Not applicable.

Conflict of Interest Statement
The authors declare no conflicts of interest.
Acknowledgements
Not applicable.

Declaration of the use of generative AI and AI-assisted technologies in the writing process.
In preparing this work, the authors used ChatGPT for the purpose of assisting with grammar and readability. After using this tool the authors have reviewed and edited the content as needed and accept full responsibility for the substantive content of the publication.

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