Ammonia inhalation for enhancing physical performance and exercise tolerance in physically active individuals and athletes: a systematic review

Inhalación de amoníaco para mejorar el rendimiento físico y la tolerancia al ejercicio en individuos físicamente activos y atletas: una revisión sistemática

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Abstract

Introduction: Ammonia inhalation (AI) has gained popularity among differing athletic populations and physically active individuals. However, studies have investigated the effect of AI on various aspects of physical performance and exercise tolerance and reported contradictory findings.
Objective: Therefore, the aims of the study were to examine the effects of AI on physical performance and exercise tolerance in athletes from different competition levels and physically active individuals.
Methodology: PubMed, Mendeley and Cochrane Library databases were searched for original articles in English from inception to June 2024 according to PRISMA statement. In total 750 records were found, of which eight met the inclusion criteria.
Results: These studies included 120 men and 22 women. Among the analysed physical parameters, the most commonly employed were strength and cardiorespiratory measures, level of perceived exertion, neuromuscular output and sport-specific test performance.
Discussion: Four out of the eight studies reported positive effects of AI, while no statistically significant changes in these parameters were found in three studies.
Conclusions: However, in one study examining postural stability in golfers, the use of AI led to a decrease in performance component. Only one study investigated professional athletes.

Keywords

Ammonia inhalation; ammonium; performance; sport-specific skills; strength.

Resumen

La inhalación de amoníaco (IA) ha ganado popularidad entre diferentes poblaciones atléticas e individuos físicamente activos.
Sin embargo, los estudios han investigado el efecto de la IA sobre diversos aspectos del rendimiento físico y la tolerancia al ejercicio y han informado de resultados contradictorios.
Se realizaron búsquedas de artículos originales en inglés en las bases de datos PubMed, Mendeley y Cochrane Library desde el inicio hasta junio de 2024 según la declaración PRISMA.
En total se encontraron 750 registros, de los cuales ocho cumplieron los criterios de inclusión.
Estos estudios incluyeron 120 hombres y 22 mujeres. Entre los parámetros físicos analizados, los más empleados fueron las medidas de fuerza y cardiorrespiratorias, el nivel de esfuerzo percibido, el rendimiento neuromuscular y el rendimiento en pruebas específicas del deporte.
Cuatro de los ocho estudios informaron de efectos positivos de la IA, mientras que en tres estudios no se encontraron cambios estadísticamente significativos en estos parámetros.
Sin embargo, en un estudio en el que se examinó la estabilidad postural en golfistas, el uso de IA provocó una disminución del componente de rendimiento. Sólo un estudio investigó a atletas profesionales.
La inhalación de amoníaco es un método práctico seguro y tiene el potencial de mejorar algunos aspectos del rendimiento físico y la tolerancia al ejercicio.
También sigue habiendo una falta actual de investigación sobre este tema y los estudios futuros deberían examinar a un mayor número de participantes, incluyendo atletas de élite de una mayor variedad de deportes.

Palabras clave

Inhalación de amoníaco; fuerza; habilidades específicas del deporte; rendimiento; amonio.

Introduction

Performance enhancement is a key focus in both professional and amateur sports (Kellmann et al., 2018; Mujika, 2017; Mujika et al., 2018). Currently, there are few substances and methods with proven effectiveness that are permitted in sport (Adams et al., 2016; Delleli et al., 2023; Fuentes-Barría et al., 2023; Peeling et al., 2018; Pugh & Pugh, 2021). Furthermore, athletes at all levels of competition may be subject to numerous doping tests across a calendar. Consequently, there is growing interest in identifying and investigating new performance-enhancing agents and methods that comply with anti-doping regulations (Alvarez-Rayón et al., 2022; Kerksick et al., 2018). Inhalation of 'smelling salts', an aromatic ammonium compound, has been highlighted as a method to potentially enhance physical performance. Early research suggested that ammonia inhalation (AI) was frequently utilized by athletes of different sports during training and competition, primarily prior to short duration exercises performed at maximum intensity (Velasquez, 2011).

Ammonium salt is available for personal use in most countries as ammonium carbonate and ammonium hydroxide solutions. The distribution of these substances is not restricted by law in any country and are permitted for athletes by the World Anti-Doping Agency. The primary active ingredient in the substance is ammonia (NH3), a colourless gas with a strong odour. When inhaled, ammonia irritates receptors in the nasal cavity and upper respiratory tract, which may affect breathing patterns, trigger the inspiratory reflex, increase respiratory rate and potentially increase alertness (McCrory, 2006; J. D. Pritchard, 2007; Widdicombe & Lee, 2001). Furthermore, the main physiological reactions during AI are cerebral vasodilation and an increase in heart rate with no alteration in blood pressure (Bender & Popkin, 2024).

The exact mechanisms by which ammonia affects bodily functions are not yet understood. It is thought that the main effects of exposure to ammonium vapour are due to activation of the autonomic nervous system. In addition, animal studies have demonstrated that exposure to ammonia via the upper respiratory tract is accompanied by trigeminal nerve activation with a subsequent increase in adrenergic influence on peripheral tissues, which may also potentially affect blood supply to working muscles, cardiac output and respiratory rate (Malecek & Tufano, 2021; Marshall, 1982; Panneton, 1991). Given these mechanisms, it is plausible that AI may exert ergogenic effects through increased sympathetic activity, improved respiratory dynamics and increased cerebral perfusion, potentially contributing to improved exercise tolerance and physical performance.

It is certain that AI has been widely used in sports where athletes are required to perform maximum intensity actions. For instance, Pritchard et al. reported that 49% of International Powerlifting Federation athletes regularly used AI as an aid to enhance performance. AI was most commonly utilized prior to lifts that incorporated 2-3 attempts (45%), and 18% of athletes also reported using AI before eight or more attempts. Interestingly, powerlifters most frequently (90% of athletes) used AI before the deadlift exercise, although much less frequently before the back squat and bench press (56% and 46%, respectively) (H. J. Pritchard et al., 2014).

However, the available evidence regarding the effectiveness of AI in enhancing performance in well-trained athletes is contradictory (Bender & Popkin, 2024; Malecek & Tufano, 2021). For instance, Bartolomei et al. found that a single bout of AI was able to increase the rate of force development during isometric mid-thigh pull in well-trained men. In contrast, a study by Vigil et al. reported no positive effects of AI on the deadlift one-repetition maximum among university-level powerlifters of both sexes (Bartolomei et al., 2018; Vigil et al., 2018).

The available evidence for possible ergogenic effects of AI is well presented in a recent clinical review by Bender et al. published in 2023. The authors concluded that the existing evidence suggests that there is a possible ergogenic effect of AI, although only during repetitive bouts of high-intensity exercise. In contrast, there is no performance benefit to AI in a short burst of maximal effort despite elevated arousal and an associated perception of performance enhancement (Bender & Popkin, 2024).

Thus, controversies regarding the use of AI are still present, along with the pre-existing popularity among athletes of differing levels, warrant research examining the effects of AI in relation to physical performance measures and load tolerance athletes and physically active individuals. Therefore, the aim of this systematic review was to examine the effects of AI on physical performance and exercise tolerance in athletes from different competition levels and physically active individuals.

Method

PubMed, Mendeley and Cochrane Library databases were searched for original articles from inception to June 2024 according to PRISMA statement (Ardern et al., 2022). The following search query was used: ('ammonia inhalation' OR ammonia) AND (performance OR physical OR loads OR workload OR recovery OR endurance OR stamina OR 'maximal aerobic power' OR strength OR speed OR coordination OR 'ergogenic aids' OR 'recovery state' OR 'psychological recovery' OR well-being OR 'mental state' OR 'mood state') The texts of all articles that met the inclusion criteria were examined. To minimise the risk of omitting relevant studies from the review, the reference lists of these articles were analysed, along with the references of any reviews related to the effects of AI on various aspects of human health.

PICOS framework was used to formulate the inclusion criteria:

«P» (population): physically active individuals or athletes at any competitive level;

«I» (intervention): inhalation of ammonia before or during exercise;

«C» (comparison): participants who inhaled ammonia during the experiment and those who did not or inhaled placebo;

«O» (outcome): Performance measures and exercise tolerance parameters;

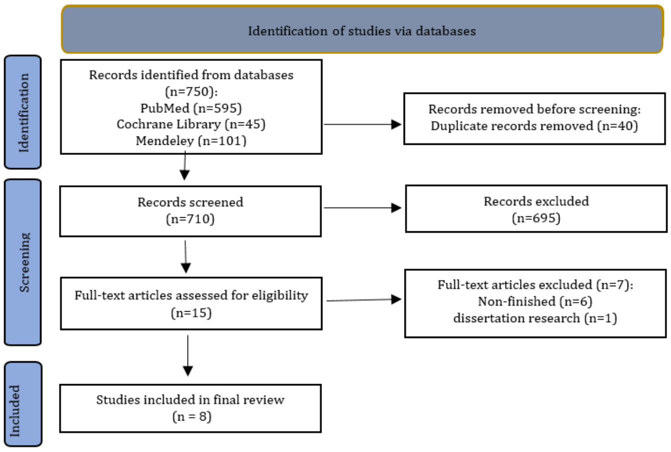
«S» (study design): original randomised controlled trials involving human subjects with parallel groups or crossover design (Methley et al., 2014).

The initial literature search yielded in an initial sample of studies examining various effects of AI. The studies were analysed in detail for design, participant characteristics, methods of measuring physical performance, AI protocol, duration of the trials and other relevant factors. The studies were categorized according to the type of sporting activity and outcomes. These studies were analysed in detail by three independent researchers, V.T.M., M.G.I. and K.E.S. In cases of disagreement on data interpretation, a senior expert, B.E.N., was consulted. The search results were downloaded and filtered in the Mendeley Reference Manager v2.64.0 (Mendeley Ltd. UK) systematic review software. A manual search helped identify other suitable articles in eligible full-text articles to be incorporated in the systematic review. A consensus was formed on the final studies included. All identified studies were assessed for risk of bias employing the revised Cochrane Risk of Bias Tool for Randomised Trials (RoB 2) (Higgins et al., 2011). The RoB2 was covering the following evaluation domains: bias arising from the randomisation process, bias due to deviations from intended interventions, bias due to missing outcome data, bias in measurement of the outcome and bias in selection of the reported result. Two independent reviewers V.T.M. and K.E.S assessed the risk of bias, and in cases of disagreement, a third reviewer B.E.N. was consulted to reach a consensus. This approach ensures the reliability and reproducibility of our findings. However, the heterogeneity of the protocols limits the generalisability of the findings. Following analysis, the results of the studies were compared, general trends were identified and conclusions were drawn regarding the effects of AI on physical performance and exercise tolerance in athletes and healthy individuals.

Results

The search strategy identified 750 records, of which 40 were duplicates and thus excluded. After analyzing the titles and abstracts of the remaining 710 articles, a further 695 were excluded due to the inclusion criteria and topic of this systematic review. Of the remaining 15 articles, 7 were removed following careful screening: 6 studies were abstracts only and one was a thesis study. Thus, this review included eight publications published in peer-reviewed journals in English, including 142 participants (120 men and 22 women), examining the effects of AI on performance measures and exercise tolerance parameters among physically active individuals, military personnel and athletes from strength-based sports and golf (Figure 1).

Figure 1. Study identification and selection PRISMA flow diagram.



Of the eight studies included in the analysis, only one study included professional golfers. It was also the only study to evaluate the effects of AI on a sport-specific skill, such as the 3-m putting test with postural stability assessment. All studies used a single inhalation before test attempt and the duration of inhalation was self-controlled by the participants. None of the studies utilized participant questionnaires to detect possible adverse effects of AI. There were no reported adverse participant reactions. However, the lack of systematic assessment of potential adverse effects, such as the use of participant questionnaires, represents a critical gap in the existing literature and limits our understanding of possible negative consequences of AI use (Table 1). The studies included in the review focused on sport/physical aspects such as strength (1RM, vertical jump, isometric contractions), neuromuscular performance (rate of force development, EMG), performance in sport-specific tests (golf, military shooting accuracy, visual reaction time), exercise tolerance (fatigue index, perceived exertion level, RPE), cardiorespiratory indices (heart rate, cerebral blood flow, BP and PetCO2), and subjective alertness and perceived performance. A detailed analysis of the effects of AI on these outcome measures is presented in Table 1.

Table 1.

Title, author and publication year	Design	Population	Intervention	Ammonia inhalation protocol	Testing	Control	Outcomes	Results
Ahn H. et al., 2019	Crossover study	10 males, registered professional golfers age=31.50±3.2 years	lavender, citrus, and ammonia olfactory inhalation	The olfactory inhalant treatment was sprayed (in the same amounts) on the front of each participant's mask during the test	3-meter putting task	Mask without scents	3-meter putting performance (percentage of success), postural stability during the test, mean HR	Percentage of success =; postural stability ↓; mean HR=
Richmond S. et al., 2014	Crossover study	25 males, resistance training experience: 7.3±2.6 years, back squat 1.5 times their body weight and bench press 1.0 times their body weight Age = 21.5±2.2 years Height = 181.1±4.6 cm Weight – 93.4±14.2 kg	Ammonia solution	Inhalation three seconds before the test is performed. Distance to nose not specified	Back squat (85% от 1RM), bench press (85% от 1RM)	Vick's® VapoRub® and the results of initial session	NR in back squat; NR in bench press	NR (back squat) =; NR (bench press) =

Bartolomei S. et al., 2018	Crossover study	28 males, resistance training experience – 6.6±3.5 years Age = 26.7±3.7 years Height = 179.5±5.7 cm Weight = 80.59±9.0 kg	Ammonia in capsule	Inhalation 10-sec prior to each attempt for 3 seconds. A distance of 10 cm was maintained between the tube and the participant's upper airways	CMJ, IMTP	Vick's® VapoRub® or no inhalant	MM CMJ MF, pRFD during IMTP	PP CMJ=; MF during IMTP=; pRFD during IMTP↑
Campbell A. et al., 2022	Crossover study	14 males, non-resistance trained Age = 20±1 years Height = 179.9±5.4 cm Weight = 76.2±12.7 kg	Flask with ammonium carbonate	Participants were instructed to inhale sharply before each repetition, while the flask was positioned ~150 cm below the columella	3 repetition of knee extension and handgrip MVC, 3 repetitions of CMJ	Water (sham)	EMD, pRFD, MF during MVC; PP in CMJ; Alertness in rest, before and after inhalation Perceived performance; HR resting, before and after inhalation	After inhalation: HR↑; Alertness↑; Perceived performance↑; pRFD during MVC =; EMD during MVC=; MF during MVC=; PP in CMJ=;
Vigil J. et al., 2018	Crossover study	20 participants, recreational weightlifting athletes 10 males: Age = 21±1,0 years Weight = 75.2±6.8 kg 10 females: Age = 22±5 years Weight = 66.6±8.1 kg	Ammonia capsules	Ammonia capsules were placed in identical opaque plastic bottles Immediately before administration, the bottle was shaken which broke the ammonia capsule by contact with the coin. The contents of the bottle were then inhaled through a small hole in the bottle cap.	Deadlift	Water	Deadlift 1RM	1RM=
Maleček J. et al., 2023	Crossover study	18 healthy male military cadets, total years of service – 4.0±0.9 years Age = 24.1±3.0 years Height = 181.5±6.3 cm Weight = 79.3±8.3 kg	Ammonia capsules	When the ammonia fumes were released, researcher immediately held the capsule under the participant's nose to inhale until a voluntary withdrawal reflex was observed. Distance to nose not specified	Reaction time testing, handgun shooting accuracy protocol, a rifle disassembly and reassembly protocol, and countermovement jump testing during periods of total sleep deprivation: 0h, 12h, 24h, 36h; after 8h of recovery sleep	No inhalation	SRT; number of errors; shooting accuracy; HR during shooting; CMJ height; RPE; disassembly and reassembly time;	SRT↑; Number of errors=; Shooting accuracy=; HR↑; CMJ height↑; RPE↓; disassembly and reassembly time=
Perry B. et al., 2016	Crossover study	15 healthy males, strength training three or more times per week for 1 year prior to the experiment Age = 25.0±5.0 years Height = 183.0±17.0 cm Weight = 99.0±16.0 kg	Ammonia capsules	The capsule was crushed and immediately held under the participant's nose until a voluntary withdrawal reflex was observed. Distance to nose not specified	IMTP, MVIC of the quadriceps	No inhalation	MCAv; MAP; $PetCO_2$; HR; MF, pRFD during IMTP; EMG obtained during MVC and IMTP.	MCAv↑; HR↑; MAP=; $PetCO_2$=; MF=; EMG=; pRFD=;
Rogers R. et al., 2023	Crossover study	12 physically active females (≥150 min/week of moderate-intensity aerobic physical Activity)	Ammonia ampule	Participants were instructed to exhale fully and inhale deeply for 3 s with the corresponding treatment approximately 10 cm away from	Wingate anaerobic test 3 sets of 15 seconds. Each test was separated by 2 min of active recovery.	Water	MP, PP, FI during Wingate test HR, RPE, alertness, feeling "psyched up"	MP↑; PP↑; FI=; HR=; RPE=; Alertness↑; feeling "psyched up"↑;

	Age = 21.4±0.8 years Height = 154.9±5.1 cm Weight = 60.4 ± 9.1kg	nose

Abbreviations: 1RM – one-repetition maximum; CMJ – counter movement jump; EMD – electromechanical delay; EMG – Electromyography; FI – fatigue index, HR – Heart rate; IMTP – isometric mid-thigh pull; MAP – Mean arterial pressure; MCAv – Middle cerebral artery blood flow velocity; MF – maximal force; MP – mean power, MVC– maximal voluntary contractions; NR – number of repetitions; PetCO2 – Partial pressure of end tidal CO2; PP – peak power ; nRFD – rate of force development; RPE– rating of perceived exertion; SRT – simple reaction time

The risk of bias analyzes using the RoB2 tool demonstrated that all studies included in this review had a low risk of bias (Table 2).

Table 2. Risk of bias assessment (RoB 2 tool).

Author and publication year	D1	D2	D3	D4	D5	Overall risk-of-bias
Ahn et al., 2022	+	?	+	+	+	+
Richmond et al., 2014	+	+	+	+	+	+
Bartolomei et al., 2018	+	+	+	+	+	+
Campbell et al., 2022	+	+	+	+	+	+
Vigil et al., 2018	+	+	+	+	+	+
Maleček et al., 2023	+	+	+	+	+	+
Perry et al., 2016	+	+	+	+	+	+
Rogers et al., 2023	+	+	+	+	+	+

Domains: D1: Randomisation process; D2: Deviations from intended interventions; D3: Missing outcome data; D4: Measurement of the outcome; D5: Selection of the reported results; "+" indicates a low risk of bias; "?" indicates that there are some concerns; "–" indicates a high risk of bias.

Discussion

The aim of this systematic review was to summarise the results of all available randomised controlled trials evaluating the effects of AI on performance and exercise tolerance in a variety of athletes and physically active individuals. The review includes eight original studies published in peer-reviewed journals between 2014 and 2023, demonstrating the scant although emerging interest in this topic over the past decade.

From the three examined studies, the participants were strength athletes with an average training experience ranging from two to seven years, thus potentially not an accurate reflection of AI application in athletic populations (Bartolomei et al., 2018; Richmond et al., 2014; Vigil et al., 2018). Three studies included healthy physically active volunteers of both sexes (Campbell et al., 2022; Perry et al., 2016; Rogers et al., 2023) and two studies included military and professional golfers (Ahn & Ko, 2022; Maleček et al., 2023). The most common experimental intervention used in these studies were commercially available ammonium compounds in a solid form (Bartolomei et al., 2018; Campbell et al., 2022; Maleček et al., 2023; Perry et al., 2016; Vigil et al., 2018), while only three studies utilised an ammonium solution (Ahn & Ko, 2022; Richmond et al., 2014; Rogers et al., 2023). Two of the eight studies were placebo-controlled (Bartolomei et al., 2018; Richmond et al., 2014), in which Vick's® VapoRub® gel, which has an odour similar to ammonia, was employed as a placebo. The remaining studies applied an odourless water inhalation (Campbell et al., 2022; Rogers et al., 2023; Vigil et al., 2018) or no inhalation (Ahn & Ko, 2022; Maleček et al., 2023; Perry et al., 2016) as controls. However, the use of Vick's® VapoRub® as a placebo may have several limitations. Firstly, although this gel has a pronounced odour, the study authors did not assess blinding, thus no conclusion regarding the effectiveness in masking the true treatment was provided. Secondly, this gel also contains menthol in its composition, which may have an ergogenic effect and thus act as an intervening factor in the interpretation of the results (Rites et al., 2024). Thirdly, in some countries Vick's® inhalation products contain L-methamphetamine, which is a prohibited substance under WADA regulations, therefore limiting its application in professional athletes (Dufka et al., 2009).

Furthermore, it is worth noting the lack of a standardised inhalation protocol, such as distance from face and duration, in the currently examined studies. In four studies the distance from the ammonium source to the nose ranged from 5 to 15 cm (Bartolomei et al., 2018; Campbell et al., 2022; Rogers et al., 2023; Vigil et al., 2018), in three studies this distance was not specified (Maleček et al., 2023; Perry et al., 2016; Richmond et al., 2014), and in one study a mask sprayed with ammonium solution was placed directly on the participant's face (Ahn & Ko, 2022). Additionally, the inhalation duration in two of the studies was 3 seconds (Bartolomei et al., 2018; Rogers et al., 2023), while in four studies it was described as “until voluntary withdrawal reflex” (Maleček et al., 2023; Perry et al., 2016) or “one maximum inhale” (Campbell et al., 2022; Vigil et al., 2018). However, in a recent study, participants wore a mask soaked in ammonium solution throughout testing, with an inhalation range of 5 minutes and 28 seconds to 8 minutes and 22 seconds (Ahn & Ko, 2022). In all studies, except Ahn et al., inhalation was performed prior to the start of each attempt or the start of each test. Perry et al. investigated the effect of IA on performance immediately, as well as 15, 30, 45 and 60 seconds after inhalation (Perry et al., 2016). Therefore, future studies should address the gap in the existing literature and examine the potentially varying physical performance responses to different application protocols.

When considering the washout time (the time interval between the control test day and the AI test) required from AI, the literature stated ranges from two to seven days in five of the studies (Bartolomei et al., 2018; Campbell et al., 2022; Richmond et al., 2014; Rogers et al., 2023; Vigil et al., 2018), and 5, 2 and 30 minutes in Perry et al., Maleček et al. and Ahn et al. respectively (Ahn & Ko, 2022; Maleček et al., 2023; Perry et al., 2016). Although, Perry et al. noted that the duration of changes in cardiorespiratory system indicators persisted for only two minutes (Perry et al., 2016). However, due to the lack of high-quality methodological data regarding the duration of changes in other organs and bodily systems following AI, it is not possible to draw definitive conclusions regarding a sufficient ‘washout period’.

Strength performance was also an outcome measure in most of the studies (Bartolomei et al., 2018; Campbell et al., 2022; Maleček et al., 2023; Perry et al., 2016; Richmond et al., 2014; Rogers et al., 2023; Vigil et al., 2018). Studies have also examined the effects of AI on cardiorespiratory parameters (Ahn & Ko, 2022; Campbell et al., 2022; Maleček et al., 2023; Perry et al., 2016), neuromuscular performance (Bartolomei et al., 2018; Campbell et al., 2022; Perry et al., 2016) and sport-specific testing (Ahn & Ko, 2022; Maleček et al., 2023). Post-intervention rating of perceived exertion (RPE) was only assessed in two studies (Maleček et al., 2023; Rogers et al., 2023). Campbell et al and Rogers et al, however, also examined the effects of AI on subjective feelings of arousal, alertness and self-rated performance measured using a visually analogue scale (Campbell et al., 2022; Rogers et al., 2023).

Only two out of seven studies analysing strength performance showed a positive effect of AI, with an increase in counter-movement jump (CMJ) height following AI usage in sleep deprived soldiers and an increase in mean and maximal power during the Wingate test in physically active females (Maleček et al., 2023; Rogers et al., 2023). In the remaining studies, no significant strength performance effects of AI were found measured by maximal force during muscle contraction (Bartolomei et al., 2018; Campbell et al., 2022; Perry et al., 2016), number of repetitions performed using 85% of 1RM (Richmond et al., 2014), CMJ height and power (Bartolomei et al., 2018; Campbell et al., 2022; Maleček et al., 2023) and 1RM assessment (Vigil et al., 2018). Three studies used rate of force development (Bartolomei et al., 2018; Campbell et al., 2022; Maleček et al., 2023), surface electromyography activity (Perry et al., 2016) and electromechanical latency (Campbell et al., 2022) to assess neuromuscular performance. At the same time, the positive effect of AI was demonstrated only in one of the studies in relation to the rate of force development (Bartolomei et al., 2018). Thus, the use of AI to enhance strength or neuromuscular performance measures currently has limited evidence.

Three of the five studies demonstrated a statistically significant increase in heart rate following AI (Campbell et al., 2022; Maleček et al., 2023; Perry et al., 2016), whereas Ahn et al. and Rogers et al. found no effect (Ahn & Ko, 2022; Rogers et al., 2023). Perry et al. also reported a significant increase in middle cerebral artery blood flow velocity without alterations in blood pressure and partial pressure of end tidal carbon dioxide (Perry et al., 2016). However, these physiological changes are unlikely to benefit athletic performance. In the context of AI usage in power sports, it may be associated with hypotension and an increased risk of syncope (Perry et al., 2016).

In only two studies the effects of AI on performance in sport-specific tests was investigated (Ahn & Ko, 2022; Maleček et al., 2023). The tests included shooting accuracy, rifle disassembly and reassembly and visual reaction speed (Maleček et al., 2023), and a 3 meter putting task (Ahn & Ko, 2022). Ahn et al. found that AI had no significant effect on the successful putting percentage in professional golfers, while the use of AI significantly impaired postural stability in the address setup, which may negatively affect overall golf performance (Ahn & Ko, 2022). Nevertheless, these authors reported the results of previous research in which AI had a positive effect on postural stability scores. However, this study was published in Korean and thus not included in this review (Ahn & Ko, 2022; Seoul National University et al., 2018).

The study by Maleček et al. demonstrated a positive effect of AI on visual reaction speed in military personnel with no change in the number of errors. However, no significant effect of AI was found on shooting accuracy and weapon assembly speed. Additionally, the authors also reported a decrease in RPE and an increase in CMJ height (Maleček et al., 2023). In contrast, Rogers et al. found no significant effect of AI on RPE (Rogers et al., 2023). Despite numerous anecdotal reports of increased arousal following AI administration, only two studies have examined the effects of AI on subjective measures of alertness and arousal (Campbell et al., 2022; Rogers et al., 2023). While, Campbell et al. found that alertness became significantly higher following AI, and perceived performance increased after exercise with pre-inhalation of AI, (Campbell et al., 2022) Rogers et al. also demonstrated a significant increase in participants' feelings of alertness and arousal following AI (Rogers et al., 2023).

Further, it is worth noting the safety of AI usage. Ammonia is indeed a toxic substance, although adverse effects have been observed when large concentrations of ammonia accumulates in the body, which does not occur during short-term AI use (Capistrán et al., 2000; Dasarathy et al., 2017). None of the studies included in this review reported adverse changes in the well-being of athletes following both single and repeated AI. The absence of structured tools to monitor adverse outcomes, including questionnaires, highlights a significant limitation in the researches regarding the risks associated with AI applications. Although, previous studies have reported a risk of adverse events in people with bronchoobstructive conditions or hypersensitivity, with a number of studies reporting no adverse effects of AI on the symptomatology of chronic respiratory disease (Pacharra et al., 2017; Petrova et al., 2008). Furthermore, AI may mask concussion symptoms, thereby complicating the interpretation of the initial physician examination (McCrory, 2006).

This review identified some key information considering AI application; however, it is noteworthy to highlight a limitation. The lack of data from other major scientific databases such as Scopus, SportDiscuss, PEDro, which are often used in systematic reviews was the main limitation and must be considered in similar future studies. To minimise the risk of not including suitable articles for review, the reference list of articles meeting the inclusion criteria was analysed. It should also be noted that the small number of studies and the heterogeneity of the protocols used limit the generalisability of the results obtained and make it difficult to formulate practical recommendations for the widespread use of this method in practice.

Conclusions

Ammonia inhalation is a safe, practical method and has the potential to improve some aspects of physical performance and exercise tolerance. However, the current review did not find an ergogenic potential for AI in sports where technical skills requiring intense concentration are critical for success. Although there is preliminary evidence that AI may be effective in the short term for some aspects of physical performance, the available scientific evidence is not yet sufficient to recommend its widespread use. There is currently a lack of research on this topic, and the studies that have been conducted have a number of limitations, mainly related to the small number of participants and their low level of fitness. Future studies should include a larger number of participants, including professional athletes from different sports, and sport-specific tests. There is also a need for more standardised protocols for the use of AI with detailed descriptions.

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