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## **Elevated Arousal following Acute Ammonia Inhalation is not Associated with Increased Neuromuscular Performance**

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**Brief running head:** Ammonia Inhalation, Arousal and Neuromuscular Performance

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## 1 **Abstract**

2 Many athletes seek to enhance their performance using legal ergogenic aids, including  
3 ammonia inhalants (AIs). AIs trigger the inhalation reflex and increase blood pressure,  
4 respiration and heart rate; but, despite their widespread use, there is little evidence for the  
5 benefits of AI on exercise performance. We aimed to determine the psychological and  
6 neuromuscular impact of acute ammonia inhalation. Fourteen non-resistance trained males  
7 completed three trials: control, experimental (AI), and sham. The order of the sham and  
8 experimental trials was randomized. Participants completed handgrip and knee extension  
9 maximal voluntary contractions (MVC), and countermovement jump (CMJ). Heart rate and  
10 alertness were recorded at rest and immediately following control, experimental or sham  
11 treatment, followed by functional performance measurements. Reaction time,  
12 electromechanical delay, rate of force development and peak force were calculated from  
13 MVCs, and peak power from CMJ. On completion of trials, perceived performance was  
14 recorded. Statistical significance was accepted at  $P<0.05$ . Heart rate ( $P<0.001$ ), alertness  
15 ( $P=0.009$ ) and perceived performance ( $P=0.036$ ) were elevated by AIs. Markers of functional  
16 performance were unaltered by AIs. Alertness was moderately correlated with perceived  
17 performance in control ( $r=0.61$ ) and sham conditions ( $r=0.54$ ), and very-highly correlated in  
18 the experimental condition ( $r=0.90$ ). AI elevates alertness and perceived physical  
19 performance, but not peak strength, power, or neuromuscular drive. AIs may be a useful  
20 psychological stimulant to increase focus and mental preparation, however it is unlikely that  
21 this will improve functional performance in an untrained population. Our data suggest  
22 however, that ammonia inhalants may improve the perception of an individual's performance.

23 **Keywords:** Smelling Salts, Ergogenic Aid, Stimulant, Alertness, Performance

## 24 **Introduction**

25 Muscle force and power are key determinants of physical health and sporting performance (1,  
26 2). While chronic adaptations in such functional components are influenced by factors  
27 including muscle mass, morphology, and neural activation (3); psychological arousal may also  
28 have an acute role in influencing functional performance (4). As such, maximising both  
29 physical and psychological capacity will enhance performance (5). While mass and  
30 morphology can only effectively be enhanced through continual exercise training, neural  
31 activation and arousal can be altered instantaneously (6). Because of the potential  
32 instantaneous performance benefits associated with enhanced arousal state (4) many athletes  
33 use ergogenic aids in pursuit of superior performance during competition (7). For example,  
34 various ergogenic aids have been shown to increase central nervous system (CNS) activation,  
35 improving performance outcomes (7). While some such aids are banned within sport because  
36 of potential health risks (8), there remain many legal aids, but most of these lack rigorous  
37 evidence to support their application (9, 10).

38

39 Legal supplementation is commonplace throughout competitive sport. In a survey of American  
40 athletes in the collegiate system, 89% reported using nutritional supplements (11), with ~50%  
41 of powerlifters reportedly making use of non-nutritional ergogenic aids during competition,  
42 including ammonia inhalants (AIs) (12). AIs are a common example of stimulant-based  
43 ergogenic aid used within competitive sport; yet, despite their popularity, there has been little  
44 research into their effect on sporting performance. Greater anaerobic power has been observed  
45 with AI use in a fatigued state (13), but they have been shown not to impact lower limb or full  
46 body static strength (14, 15), dynamic strength (16, 17), or number of repetitions to fatigue  
47 (16). However, no previous study has assessed the influence of AIs on isolated upper body

48 strength only. Meanwhile, rate of force development (RFD) may (14) or may not (15) be  
49 influenced by AI use. While the above-mentioned findings all relate to experienced resistance-  
50 or anaerobically-trained individuals, it has been proposed that untrained individuals may  
51 benefit from psychological arousal to a greater extent than those who are trained (4). Arousal  
52 has been widely assessed by measuring alertness (18, 19); however, to date no study has  
53 assessed alertness specifically following AI use.

54

55 Despite the scarcity of evidence for their efficacy, AI use remains widely popular among those  
56 competing in sports such as powerlifting, weightlifting, track and field, boxing, American  
57 football, hockey and mixed martial arts (20). To help understand their popularity, we can  
58 explore the physiological responses induced by AI use. It is believed that ammonia inhalation  
59 triggers the trigeminal nerve via chemoreceptors within the nasal, oral and pulmonary mucosa  
60 (21). The respiratory and vasomotor centres within the medulla oblongata respond to this  
61 irritation, promoting inhalation reflex and increased blood pressure leading to elevated  
62 respiration and heart rate (HR) (22). Perry et al. (2016) evidenced this response, demonstrating  
63 increased middle cerebral artery blood flow velocity and HR immediately following AI use  
64 (15). Furthermore, improved cerebral delivery of oxygenated blood and CNS excitation, result  
65 in increased consciousness and enhanced sympathetic activity. In terms of an advantageous  
66 effect for sporting performance, these responses could potentially elicit cognitive enhancement  
67 and increase central drive (13). Equivocal findings of an effect of AIs on RFD (14, 15) compel  
68 further investigation; if there is, as suggested, an increase in central drive associated with AI  
69 use, elevated RFD would be expected, accompanied by a shortening of electromechanical delay  
70 (EMD), and therefore, overall reaction time (RT). These enhancements could be expected to  
71 promote an increase in peak power production, although to date the only study to report an AI-

72 induced increase in peak power, investigated performance in already-fatigued athletes (13).  
73 Therefore, it remains unclear whether AIs can acutely enhance neuromuscular processes  
74 sufficiently to impact functional performance.

75

76 The aim of this study was to determine the effect of AI use on peak power production, and on  
77 RT and RFD during maximal isometric strength assessment, among non-resistance trained  
78 individuals. Additionally, we assessed the effect of AI use on HR and cognitive alertness and  
79 examined the relationship between these parameters and functional performance. As arousal  
80 may acutely benefit performance and has a greater impact on untrained than trained individuals,  
81 we believe that studying an exclusively untrained cohort may provide the best opportunity to  
82 explain the popularity of AI use via its effect on arousal and enhanced psychological readiness  
83 to perform. Furthermore, enhanced arousal and subsequent psychological readiness to perform  
84 may translate to an overall perception of improved performance compared to when not using  
85 the stimulant and thus, may potentially help to further explain the popularity of AI use. We  
86 therefore hypothesised that alertness would increase in line with HR following AI use, and that  
87 this would be associated with decreased RT and increased RFD, which would result in elevated  
88 peak power, but not peak strength. It was also hypothesised that participants would perceive a  
89 sense of improved overall performance after AI use.

90

## 91 **Methods**

### 92 **Participants**

93 Fourteen non-resistance trained male participants with no history of neuromuscular or  
94 musculoskeletal disorders were recruited (age 20 (SD 1) years, height 179.9 (SD 5.4) cm, body

95 mass 76.2 (SD 12.7) kg, weekly physical activity 3.5 (SD 1) days). Participants were required  
96 to read a study information sheet and complete a pre-participation questionnaire to determine  
97 eligibility. Eligible volunteers provided written informed consent after being supplied with  
98 information about any benefits and potential risks involved with their participation. The study  
99 was approved by the local Research Ethics Committee (SSREC No. 701/705), and all  
100 procedures performed were in accordance with the ethical standards of the 1964 Helsinki  
101 declaration and its later amendments. Participants were eligible if they were over the age of  
102 18, had not previously used AIs, and had no known respiratory or cardiovascular illnesses.

103

## 104 Design

105 Following full familiarisation of the testing procedures, participants completed 3 trials  
106 separated by 7-days, each at the same time of day. The three trials consisted of control (CN),  
107 experimental (AI) and sham conditions, where the order of the latter two was chosen by  
108 participant block randomisation. Trial 1 (CN) also acted as a participant familiarisation and  
109 followed an identical protocol to trials 2 and 3, except that no inhalant was provided (Figure  
110 1). During trials 2 and 3 participants inhaled either AI within the experimental condition or  
111 water within the sham condition prior to all measurements of functional performance. A sham  
112 condition of water was chosen over a scented alternative (as has been adopted elsewhere (16))  
113 as evidence shows that other strong smelling substances can promote muscle activity (23).  
114 After the control trial, participants were informed that they would inhale the AI during one  
115 trial, and water (sham) during the other, and that these trials would be randomised in order.  
116 The order of the AI and sham trials was not revealed to participants prior to inhalation.  
117 Functional performance was determined via knee extension (KE) and handgrip (HG) maximal  
118 voluntary isometric contraction (MVC) using dominant limbs, and bilateral countermovement



119 jump (CMJ); each incorporating 3 repetitions. Each participant identified their dominant upper  
120 and lower limbs by indicating their handedness, and the leg they would use to kick a ball (24),  
121 respectively. Participants rested for 20-minutes between tasks, and 5-minutes between  
122 repetitions. Finally, participants self-rated their perceived performance across the 3 tasks (KE  
123 and HG MVCs, and CMJ). The order of measurements was consistent across all visits (Figure  
124 1).

125

126 [Figure 1]

127

## 128 Procedures

129 Participants refrained from strenuous physical activity, alcohol, and caffeine for  $\geq 24$ h  
130 preceding laboratory visits, and maintained similar diet for 48h, incorporating 1h fast  
131 immediately prior to each trial. Upon arrival to the laboratory, participant height and mass  
132 were recorded before resting in a semi-reclined, supine position for 20-minutes. Next, resting  
133 HR was recorded (FT1 Polar monitor, FT7 sensor. Warwick, UK); three 5s stable readings  
134 were noted, and the mean value was recorded for analysis; intraclass correlation coefficient  
135 (ICC) of resting HR between trials 1, 2 and 3 was 0.85 with no significant differences in resting  
136 HR between trials. Participants then indicated their alertness on a 200mm visual analogue  
137 scale (VAS), which ranged from 'not alert' at the extreme left to 'highest possible alertness' at  
138 the extreme right, which is believed to be similar to an alertness VAS which have been used  
139 previously (25, 26). The two ends of the VAS were anchored by perpendicular lines, but there  
140 were no increments between the end markers. This method was chosen as VAS has been shown  
141 to be a reliable and valid assessment of alertness (25, 26). The ICC of pre-inhalation alertness

142 between trials 1-3 was 0.94, and there were no significant pre-inhalation differences in alertness  
143 between trials ( $P>0.05$ ). During trials 2 and 3, participants inhaled from an unmarked flask  
144 containing either 35.99g of AI (Nose Tork, Crystals of Ammonium Carbonate, Oklahoma, US)  
145 or water and cotton wool before all MVC and CMJ repetitions. Both flasks were matched  
146 exactly in volume and appearance, although the scent and physical reaction of participants after  
147 inhalation could not be controlled for between the experimental and sham trials. Participants  
148 were instructed to inhale sharply, while the flask was positioned ~150mm below the columella.  
149 HR and alertness were recorded as before, immediately following inhalation prior to one of the  
150 three repetitions, allocated at random. During CN (trial 1), participants followed the same  
151 procedure, but no flask was positioned below the columella.

152

153 For assessment of MVC, participants were coupled to an isokinetic dynamometer (Biodex  
154 System 3, Medical Systems, Shirley, New York, USA). In accordance with the manufacturers'  
155 instructions, seat positions were adjusted to suit each participant's anthropometric  
156 characteristics, and straps (across the chest and pelvis) were used to secure the participant in  
157 the required position. The final positioning of each participant was recorded on the initial visit  
158 and replicated throughout the experimental period to ensure constancy between trials. Two  
159 pairs of Ag/AgCl self-adhesive electrodes (PNS Dual Element Electrode, Vermed, Vermont,  
160 USA) were affixed to pre-prepared skin, 1 pair over vastus lateralis and 1 pair over  
161 brachioradialis, in accordance with SENIAM guidelines. Ground electrodes were affixed over  
162 patella and olecranon, respectively. Surface electromyogram (sEMG) was captured during all  
163 MVCs, at a sampling rate of 2kHz, via Acknowledge<sup>®</sup> 3.9.1.6 software integrated with Biopac  
164 MP100 hardware (Biopac Systems Inc., Goleta, California, USA). For KE MVC a Velcro cuff  
165 was secured proximal to the medial malleolus. Gravitational corrections were performed, in

166 accordance with existing recommendations, in order to account for the effect of limb weight.  
167 The lateral femoral epicondyle of the dominant leg was visually aligned with the dynamometer  
168 axis of rotation, and a knee joint angle of  $60^\circ$  was set ( $0^\circ$  = full extension) (27). Participants  
169 performed a standardised submaximal warm-up, consisting 2 sets of 3 x 5s isometric KE  
170 contractions at 50% and 75% of perceived maximum, respectively. During all contractions  
171 participants were instructed to cross their arms in front of their chest. For HG MVC the  
172 shoulder of the dominant arm was flexed to  $90^\circ$  ( $0^\circ$  = neutral), and secured to a support, with  
173 an elbow joint angle of  $90^\circ$  (28). A similar warm-up protocol was performed, using a HG  
174 dynamometer (MLT003/D, AD Instruments Inc. Colorado Springs, Colorado, USA), and the  
175 contralateral arm remained in a neutral position.

176

177 Following the respective warm-ups, MVC was assessed via 3 x 5s maximal contractions.  
178 During trials 2 and 3 participants inhaled either AI or water prior to each contraction. The time  
179 between inhalation and contraction varied by small durations between each test due to the  
180 randomised audio prompt which was used to measure RT. However, time between inhalation  
181 and contraction did not exceed 30 seconds. Dynamometer outputs were sampled  
182 synchronously with sEMG via Acknowledge<sup>®</sup> 3.9.1.6 (Biopac Systems Inc., Goleta,  
183 California, USA). Participants were instructed not to hold back any effort for subsequent  
184 contractions; the same investigator provided standardized verbal commands and  
185 encouragement, to assist the participants in achieving maximal effort for every contraction.  
186 Participants reacted to an audio prompt and were instructed to exert as much force as possible,  
187 as quickly as possible, in response to the prompt, allowing RT and RFD to be calculated (29).  
188 The contraction containing the highest peak was designated MVC. The ICC for HG and lower  
189 limb MVCs between trials was 0.96 and 0.94, respectively. From these contractions, RT

190 (latency between audio stimulus and onset of force production) and EMD (latency between  
191 onset of sEMG and onset of force production) were calculated. ICCs for RT and EMD were  
192 calculated as 0.81 and 0.13 for HG, and 0.88 and 0.14 for the lower limb, respectively.  
193 Additionally, RFD was analysed over 0-20, 0-50, 0-100 and 0-200ms from the onset of force  
194 production. In all cases, onsets were considered as  $\geq 2SD$  from baseline. ICCs between trials  
195 for HG and lower limb, respectively, are as follows: 0-20ms (0.63 and 0.58), 0-50ms (0.74 and  
196 0.81), 0-100ms (0.75 and 0.88), and 0-200ms (0.77 and 0.94). Analysis was performed using  
197 MATLAB version 7.11.0.584 (R2010b) software (The MathWorks, Inc. Natick,  
198 Massachusetts, USA) and force and sEMG onsets were visually confirmed *post hoc* (29).

199

200 Peak power was assessed via CMJ (JUMP-MD, Vertical Jump Meter T.K.K.5406) according  
201 to the formula:  $W = (78.6 * d) + (60.3 * m) - (15.3 * h) - 1308$  (where:  $W$  = peak power,  
202  $d$  = displacement,  $m$  = body mass,  $h$  = height) (30). First, participants warmed-up by  
203 completing 3 CMJs at 50% of perceived maximum effort. Three maximal effort CMJs were  
204 then performed, with 5 minutes rest between attempts; during trials 2 and 3 participants inhaled  
205 either AI or water prior to each attempt. The greatest displacement achieved across the 3  
206 attempts was used to calculate peak power. The ICC of all trials was calculated as 0.97.  
207 Following assessment of all functional measures, participants self-rated their perceived  
208 performance level using a 200mm VAS which ranged from 'worst performance' at the extreme  
209 left to 'best possible performance' at the extreme right (31). The two ends of the VAS were  
210 anchored by perpendicular lines, but there were no increments between the end markers.  
211 Perception of performance ICC between the three trials was calculated as 0.85.

212

## 213 Statistical Analyses

214 Data were assessed for normal distribution and equal variances using Shapiro-Wilk and  
215 Levene's Test for Homogeneity of Variances, respectively. The percentage change ( $\Delta\%$ ) in  
216 pre- to post-inhalation HR and alertness was firstly calculated for all three conditions. These  
217 data were subsequently used to calculate the percentage change from the CN during the AI and  
218 Sham conditions. MVCs, CMJ power, EMD, RT and perceived overall performance were also  
219 calculated as the percentage change from the CN. Heart rate, alertness, MVCs, CMJ, EMD,  
220 RT and perceived overall performance were then analysed using a paired sample Student's *t*-  
221 test to identify significant differences between AI and sham conditions. Wilcoxon W rank test  
222 was used when normality assumptions were violated. Cohen's D (d) effect size was  
223 subsequently calculated for t-tests, where values of 0.2, 0.5 and 0.8 represented a small, medium and  
224 large effect, respectively. Additionally, RFD (0-20, 0-50, 0-100 and 0-200ms) from each  
225 condition were analysed using two-way repeated measures ANOVA. Where significant and  
226 non-significant effects were observed, partial  $\eta^2$  effect sizes ( $\eta^2_p$ ) were calculated by  
227  $\eta^2_p = SS_{conditions} / (SS_{conditions} + SS_{error})$ . Association between pairs of variables was assessed using  
228 Pearson's correlation coefficient. Correlation coefficients were interpreted as  $< 0.30 =$   
229 *negligible*,  $0.30 - 0.49 =$  *low*,  $0.50 - 0.69 =$  *moderate*,  $0.70 - 0.89 =$  *high*,  $0.90 - 1.00 =$  *very*  
230 *high* (32). Statistical significance was accepted at  $P < 0.05$ . All statistical analysis was  
231 performed using Jamovi (Version 0.9), and figures were created using Microsoft Excel  
232 (Version 16.31) and Jamovi.

233

234

235

## 236 Results

237 When measured relative to the CN condition, the percentage difference in heart rate ( $t_{(13)}=4.76$ ,  
238  $d=1.27$ ,  $P<0.001$ ) and alertness ( $t_{(13)}=3.1$ ,  $d=0.837$ ,  $P=0.009$ ) were elevated by 11.5% [95%  
239 CI: 6.3, 16.7] and 20.1% [6.1, 34.2] respectively following AI use compared to the sham  
240 condition (Figure 2). The change in perception of performance from the CN condition was  
241 also higher after AI use by 8.6% [0.66, 16.6] when compared to the sham condition ( $t_{(13)}=2.34$ ,  
242  $d=0.63$ ,  $P=0.036$ ; Figure 2C).

243

244

[Figure 2]

245

246 KE MVC ( $W_{(13)}=72$ ,  $d=0.31$ ,  $P=0.24$ ), HG MVC ( $t_{(13)}=-0.264$ ,  $d=-0.07$ ,  $P=0.80$ ), and peak  
247 power ( $t_{(13)}=0.625$ ,  $d=0.17$ ,  $P=0.54$ ) were all unaffected by AI use. The percentage change in  
248 RT and EMD from the CN also did not differ between conditions during KE MVC ( $t_{(13)}=1.72$ ,  
249  $d=0.46$ ,  $P=0.11$ ;  $t_{(13)}=0.13$ ,  $d=0.03$ ,  $P=0.9$ , respectively), or during HG MVC ( $W_{(13)}=46$ ,  
250  $d=0.08$ ,  $P=0.72$ ;  $t_{(13)}=1.34$ ,  $d=0.36$ ,  $P=0.2$ , respectively) (Table 1). RFD during KE MVC  
251 ( $F_{(2,13)}=3.1$ ,  $\eta^2_p=0.04$ ,  $P=0.064$ ) and HG MVC ( $F_{(2,13)}=3.27$ ,  $\eta^2_p=0.2$ ,  $P=0.54$ ) did not differ  
252 between the three conditions. However, a significant main time effect for RFD development  
253 between 20 – 200ms was observed during the KE and HG MVC ( $F_{(2,13)}=9.7$ ,  $\eta^2_p=0.08$ ,  
254  $P<0.001$ ;  $F_{(2,13)}=50.2$ ,  $\eta^2_p=0.79$ ,  $P<0.001$ , respectively), and the results of post-hoc analysis  
255 are displayed in Table 1).

256

257

[Table 1]

258

259 There were positive correlations between alertness and perceived performance post-AI  
260 ( $r_{(12)}=0.90$ ,  $P<0.001$ ), post-sham ( $r_{(12)}=0.54$ ,  $P=0.046$ ), and post-CN ( $r_{(12)}=0.61$ ,  $P=0.02$ )  
261 (Figure 3). There was no relationship between HR and alertness post-AI ( $r_{(12)}=-0.33$ ,  $P=0.25$ ),  
262 post-sham ( $r_{(12)}=-0.20$ ,  $P=0.50$ ), or post-CN ( $r_{(12)}=0.07$ ,  $P=0.81$ ); nor between HR and  
263 perceived performance post-AI ( $r_{(12)}=-0.25$ ,  $P=0.38$ ), post-sham ( $r_{(12)}=-0.15$ ,  $P=0.62$ ), or post-  
264 CN ( $r_{(12)}=0.06$ ,  $P=0.84$ ).

265

266

[Figure 3]

267

## 268 Discussion

269 The aim of this study was to examine the effects of ammonia inhalant use on functional  
270 performance and psychological alertness, in non-resistance trained males. Despite being  
271 commonly used as a performance-enhancing stimulant, we observed no improvement in any  
272 aspect of functional performance following AI use. Interestingly however, use of the stimulant  
273 did elicit an increase in individual perception of overall performance, which was very highly  
274 associated with elevated rating of alertness.

275

276 Despite a lack of research existing to support their beneficial effects, AIs are commonly used  
277 in resistance-based exercise as they are believed to temporarily increase consciousness and  
278 arousal of an individual during training and competition (20). The current study is the first to

279 assess arousal, via an alertness scale, alongside markers of functional performance, following  
280 AI use; specifically, we observed an increase in alertness ratings after stimulant inhalation. It  
281 is possible that alertness was elevated as a result of a sympathetic nervous response, as AIs  
282 have previously been reported to increase breathing rate and HR following inhalation (15, 20,  
283 21). However, despite an acute elevation in HR (Figure 2A), there was no correlation between  
284 HR and alertness, which suggests that sympathetic nervous response was not exclusively  
285 responsible for increases in alertness with AI use. Elsewhere, Perry et al. (15) evidenced an  
286 acute increase in blood flow to the brain, as measured by middle cerebral artery blood velocity,  
287 immediately after AI use. Consequently, our finding that alertness was elevated following AI  
288 use may be attributable to greater delivery of oxygenated blood to the brain (33). It is known  
289 that a reduction in cerebral blood flow impairs cognitive function (34), which may well be  
290 linked to performance decrements associated with inadequate levels of arousal during training  
291 and competition (35). With this in mind, AI-induced enhancement of alertness may help to  
292 explain the popularity of this particular stimulant within performance sport. However, such  
293 interpretations are beyond the scope of this study.

294

295 The current study was also the first to investigate the effects of AIs on perception of overall  
296 performance, with participants self-rating that a superior performance was achieved during the  
297 AI trial (Figure 2C). Interestingly, moderate-very high positive correlations were observed  
298 between perceived performance and alertness ratings within all three conditions, with the  
299 highest correlation observed in the AI trial (Figure 3). It is possible that elevated alertness  
300 induced by AI use could have improved participant's perception of their performance by  
301 enhancing focus and ensuring optimal psychological state was achieved. Furthermore, AIs are  
302 believed to increase not only the focus, but also the effort exerted by athletes (20).  
303 Subsequently, an individual's reflection of their performance with increased alertness, reduced



304 distraction, and potentially higher levels of effort may have translated into higher self-rating of  
305 perceived performance. An improved psychological readiness to perform and consequently,  
306 enhanced perception of performance may provide further evidence as to why AI use is  
307 prevalent during competition (11, 12). Furthermore, limited data exist regarding the use of AI  
308 within different sporting performances. Therefore, when uninformed on physical performance,  
309 individuals may argue that AI use are important as from a perceived performance perspective,  
310 they believe to perform better after using the stimulant.

311

312 Although psychological factors were immediately improved by AI use, there were no  
313 improvements in any of the functional performance variables measured when compared to the  
314 CN or sham conditions. These findings support previous studies which have attempted to  
315 investigate the effects of AIs on functional performance such as maximal strength and power  
316 output. Resistance trained individuals (> 2 y training experience) have previously  
317 demonstrated no improvement in isometric or dynamic contractions of submaximal or maximal  
318 intensity, following AI inhalation (14–17). These previous studies assessed strength using  
319 closed-chain exercises involving multiple muscle groups; in such cases participant familiarity  
320 with the exercise test is critical, even among well-trained individuals (36). The current study  
321 recruited healthy, recreationally active participants who were unfamiliar with resistance  
322 training techniques, as these individuals could be expected to receive a greater beneficial effect  
323 from increasing arousal (4). By adopting open-chain exercises, we were able to isolate single  
324 muscle groups to assess maximum isometric contraction with minimal participant learning  
325 effects (37) and greater sensitivity. Additionally, internal joint angles of 60° (KE) and 90°  
326 (HG) were selected to optimise isometric force (27, 28). Nonetheless, MVC, expressed relative  
327 to CN, did not differ between AI and sham conditions (KE: [-1.36, 7.04], HG: [-6.22, 4.87]).

328

329 Similar to previous research, we recorded no improvement in absolute maximal force  
330 production with AIs. However, aspects of force generation, such as RFD and EMD have  
331 previously been shown to improve following AI use (14), as well as with other stimulants, such  
332 as caffeine, both in the presence (38) and absence (39) of enhanced performance. Interestingly,  
333 Bartolomei et al. (2018) reported an association between RFD and CMJ performance, despite  
334 no effect of AI use on CMJ peak power (14). However, in contrast to the previous study we  
335 observed no effect of AIs on RFD, and further, no effect on EMD or RT. Similar RFD results  
336 have been reported previously elsewhere, as Perry et al. (2016) also reported no difference  
337 following AI use compared to a control (15). The inconsistency in RFD outcomes with AI use  
338 could stem from the type of exercise used to assess RFD – while both Perry et al. (2016) and  
339 Bartolomei et al. (2018) utilised maximal isometric mid-thigh pull, participants in the latter  
340 study sustained 6 s contractions (compared to 2 s contractions in the former) (14, 15). While  
341 our present study adopted 5 s contractions, these involved fewer muscle groups, and were  
342 separated by 5 min rest periods (compared to 3 min (14)). As such, and similar to during the  
343 study by Perry et al. (2016), participants in the present study may have been less subject to  
344 fatigue than were those involved in the study by Bartolomei et al. (2018). As previous findings  
345 have shown AIs to improve peak and mean power in fatigued individuals (13), so too it is  
346 possible that improvements in RFD may also be observable only in individuals exhibiting  
347 greater levels of fatigue. It is well established that RFD is impaired by fatigue, indeed such  
348 impairment is more pronounced than is impairment in strength (40). Fatigue-induced decline  
349 in RFD presents a greater potential for a stimulant-derived increase, therefore future research  
350 should explore the relative impact of AI use on aspects of force production, including RFD, in  
351 the presence of fatigue-induced decrements.

352

353 Contrary to our hypothesis, we observed no effect of AI use on peak power. Previously, peak  
354 and mean anaerobic power have been seen to increase post-AI use (13). In that study  
355 participants completed a 30 s Wingate anaerobic cycling test - given the large muscle mass  
356 used in such a test, and the benefits of increased blood flow to working muscles in the latter  
357 half of the test (41), elevated mean power could be explained by an AI-induced sympathetic  
358 response. However, peak power would not be enhanced by such an increase in oxidative  
359 metabolism. Unlike the present study, where participants were well rested prior to performing  
360 CMJ, participants in the aforementioned study by Secrest et al. (2015) were required to reach  
361 fatigue before the effects of AI use on anaerobic power was assessed (13). Similar to RFD; AI  
362 use may only produce substantive effects on power performance when peak power has  
363 previously been depleted by individuals reaching a state of fatigue, such as may be experienced  
364 in the latter stages of sporting competition. Indeed, based on the results of their survey of  
365 powerlifters, Pritchard et al. (2014) reported that use of AIs is most common near the end of  
366 competition (12). Although existing evidence permits us to speculate that AI use may be able  
367 to offset some of the decrement in RFD and peak power that is experienced alongside fatigue,  
368 our findings demonstrate that in a well-rested state, there is no performance benefit to AI use,  
369 despite elevated arousal and an associated perception of performance enhancement.

370

371 There are limitations which must be considered when interpreting our findings. Despite AIs  
372 being held at a distance of 150 mm (in accordance with manufacture suggestions), it is possible  
373 that participants did not inhale a consistent volume throughout the trial, however this closely  
374 reflects real world practice. To the best of our knowledge, no research provides data regarding  
375 the volume of substance inhaled from set distances. Whilst one similar study held AI 10cm  
376 below the nose (14), other studies in this area did not identify a distance. As inhalation volumes  
377 for each participant and test cannot be controlled for, we incorporated a distance of 15cm and

378 asked participants to sharply inhale when instructed to aid with intra- and inter-visit  
379 consistency. In addition, rapid rating of alertness was required to ensure that the observations  
380 represented participant alertness immediately after AI use, precluding the use of an extensive  
381 questionnaire, as such alertness was reported using VAS. VASs have been shown to be an  
382 effective method of collecting data efficiently, however, the limited time available to record  
383 alertness prevented us from collecting a rating from participants prior to every repetition (i.e.,  
384 following every inhalation). A pragmatic decision was taken to record alertness during one  
385 repetition (from three) of each assessment, randomly selected. Furthermore, whilst we  
386 attempted to reduce potential learning effects by familiarising participants during the control  
387 visit and randomising the order of the experimental and sham conditions, it is possible that  
388 randomising the order of the strength and power performances during each visit may have  
389 reduced this risk further. Lastly, it must be acknowledged that EMD displayed poor reliability  
390 within this study. Therefore, the EMD results within this study should be interpreted with  
391 caution.

392

393 In conclusion, we have demonstrated for the first time that ammonia inhalant use elevates levels  
394 of alertness and perception of overall performance in active, non-resistance trained males.  
395 However, peak force and rate of force development, reaction time, and peak power all remain  
396 unaffected by ammonia inhalant use. Ammonia inhalants remain a popular sporting  
397 supplement, although perceived benefits may outweigh any true ergogenic effect; further  
398 research is required to explore the potential of acute ammonia inhalation to counter the  
399 performance-damaging effects of fatigue.

400

401

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404

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407

408 **Disclosure Statement**

409 The authors report no conflict of interest.

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523 **Tables**

524

525 **Table 1. Mean (SD) rate of force development over 0-20, 0-50, 0-100 and 0-200 ms from onset of**  
 526 **force production, electromechanical delay (EMD), and reaction time (RT), within the control**  
 527 **condition (no inhalant) and post-inhalation within the experimental (ammonia) and sham**  
 528 **conditions (water).**

529

		Control	Ammonia	Sham
HG RFD (N·s <sup>-1</sup> )	0-20 ms	232.79 (260.23)	386.86 (434.09)	396.97 (395.75)
	0-50 ms	475.23 (445.69) *	683.29 (545.07) *	806.15 (638.21) *
	0-100 ms	958.43 (596.87) **†	1195.76 (639.31) **†	1445.52 (893.24) **†
	0-200 ms	1315.20 (464.45) **†	1442.78 (612.09) **†	1398.89 (481.44) **†
	EMD (ms)	55.14 (36.56)	58.54 (17.27)	49.57 (21.70)
HG	RT (ms)	339.86 (134.83)	297.36 (116.36)	280.86 (60.41)
KE RFD (N·s <sup>-1</sup> ) 1)	0-20 ms	294.10 (333.12)	537.14 (647.69)	312.91 (277.81)
	0-50 ms	570.85 (510.52) *	730.35 (612.35) *	579.35(453.77) *

	0-100 ms	676.03 (461.36) **	813.37 (487.33) **	652.94 (414.91) **
	0-200 ms	556.96 (298.20) †	452.77 (200.95) †	604.34 (281.76) †
KE	EMD (ms)	84.89 (30.88)	88.75 (46.45)	87.64 (27.22)
	RT (ms)	380.79 (129.58)	402.54 (150.68)	357.18 (84.99)

530

*HG = handgrip; KE = knee extension.*

531

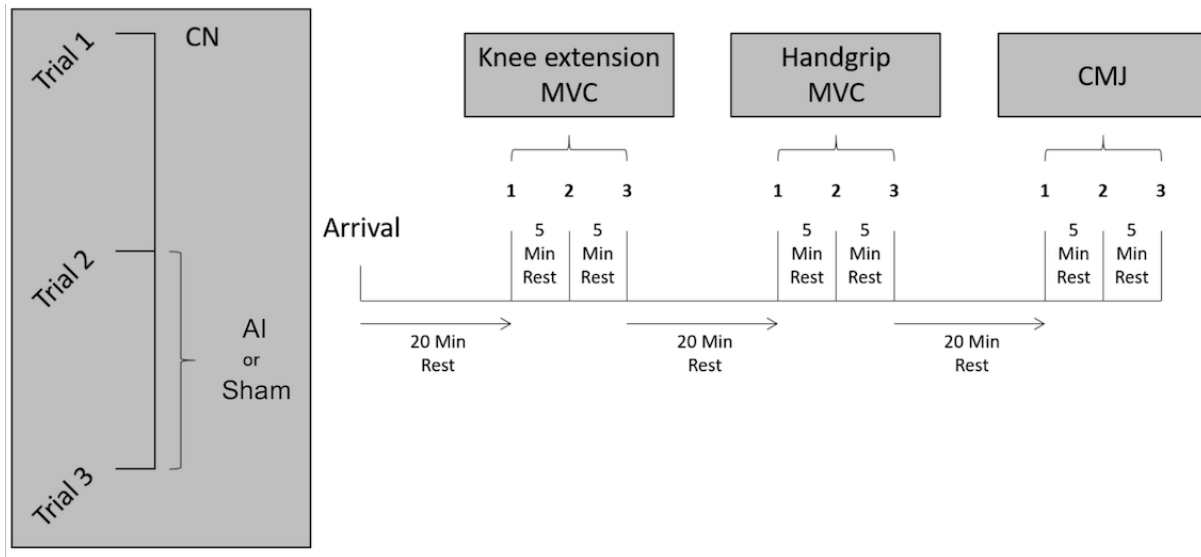
532 Significant main effect for time during rate of force development is represented by the following  
 533 symbols: \* = P < 0.05 from 20ms; \*\* = P < 0.001 from 20ms; † = P < 0.001 from 50ms; †† = P < 0.05  
 534 from 100ms.

535

536

537 **Figures**

538



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541

542 Figure 1. Timeline of measures during the 3 laboratory visits.

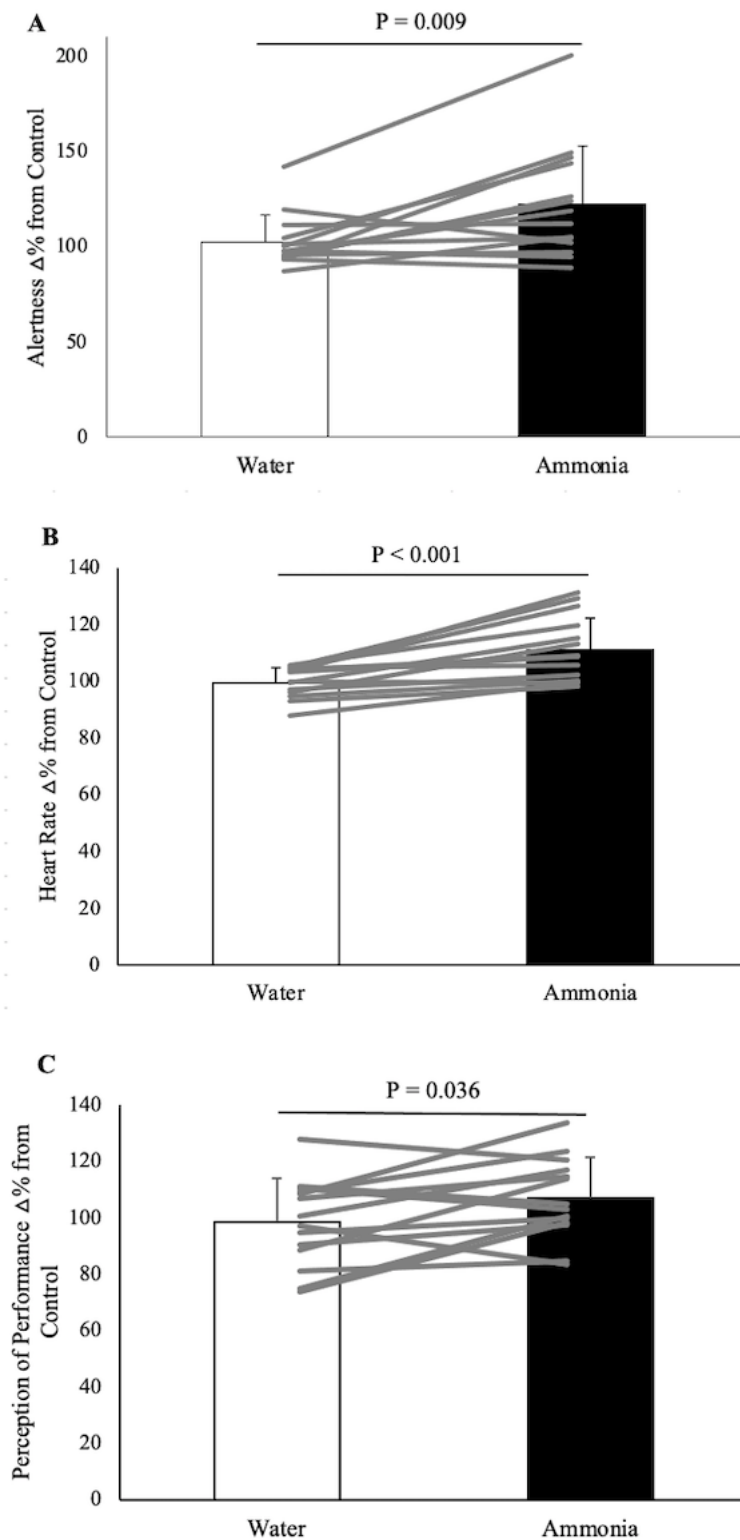
543 *CN = control, AI = ammonia inhalant.*544 *MVC = maximal isometric voluntary contraction, CMJ = countermovement jump.*545 *Participants inhaled AI or water prior to each contraction and CMJ during trials 2 and 3. Heart rate*  
546 *and alertness were measured immediately post-inhalation prior to repetition 1, 2 or 3 (assigned*  
547 *at random) of knee extension MVC, handgrip MVC and CMJ.*

548

549

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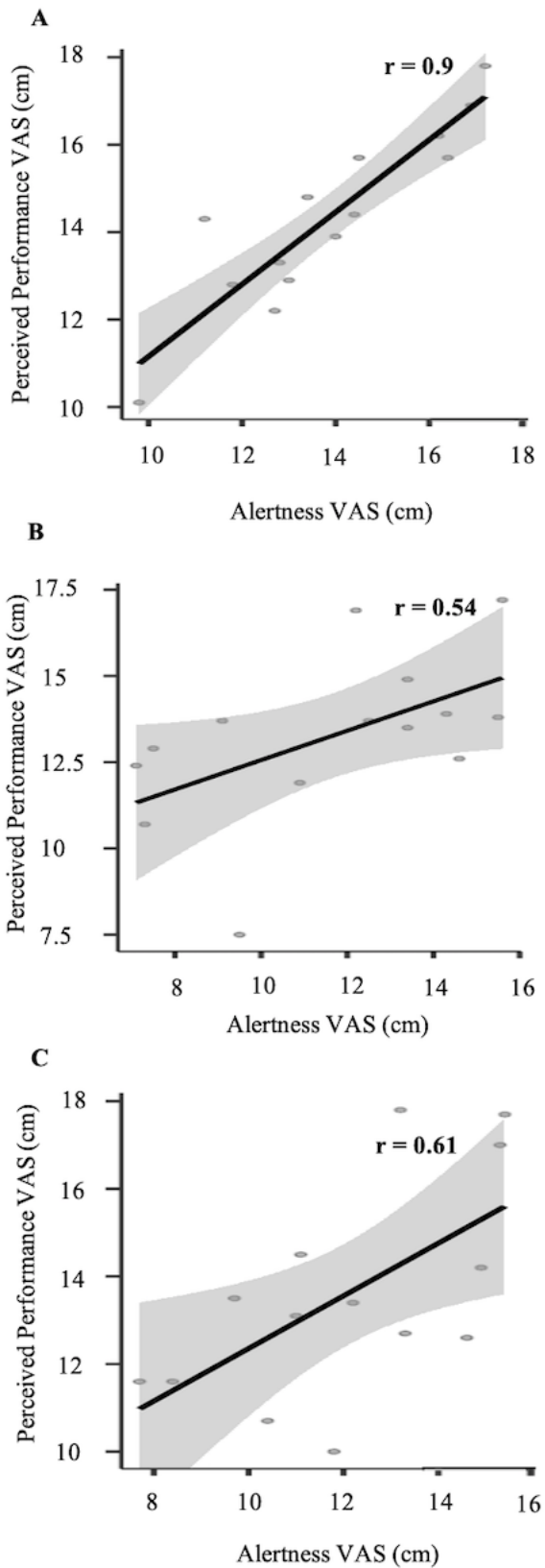


552

553 Figure 2. Mean (SD) of heart rate (A), alertness (B), and perceived performance (C) presented  
 554 as the percentage difference from the control during the experimental (ammonia) and sham  
 555 (water) conditions.

556 VAS = *visual analogue scale*.

557



558

559

560 Figure 3. Relationship between alertness and perceived performance including 95%  
561 confidence intervals: (A) post-inhalation of ammonia (AI), (B) post-inhalation of water, (C)  
562 during control condition (no inhalant).

563 *VAS = visual analogue scale.*

564

565