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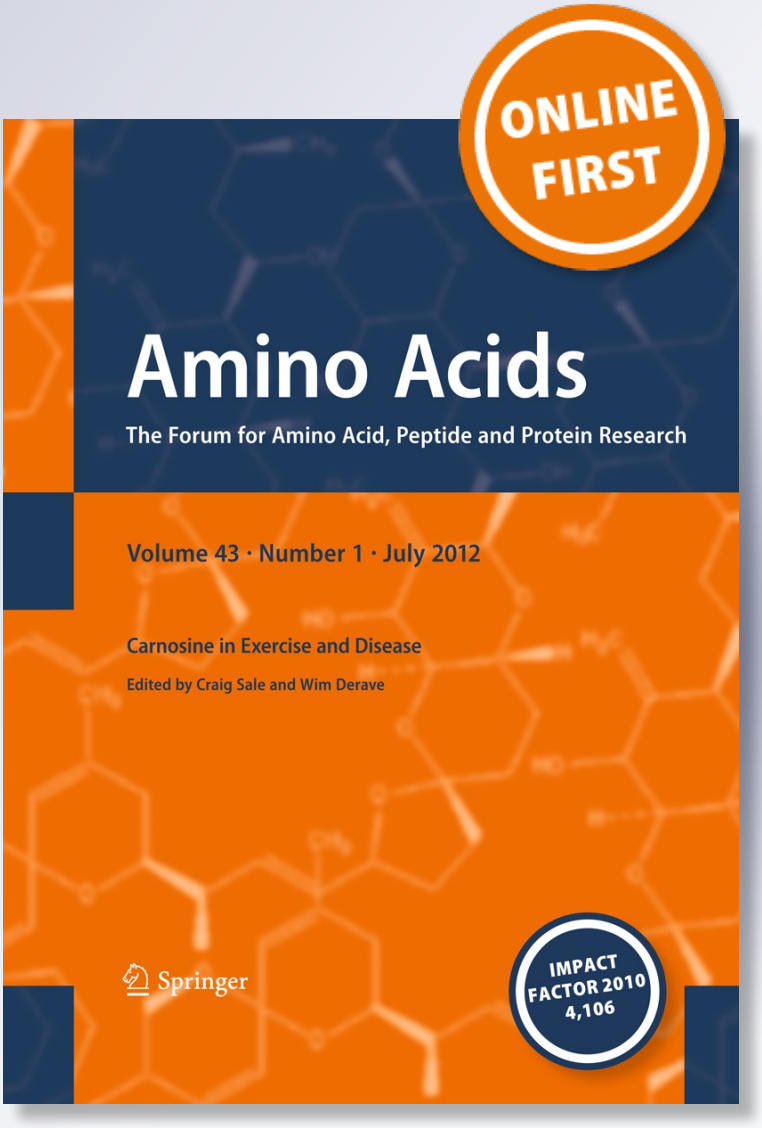

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ORIGINAL ARTICLE

The effect of acute taurine ingestion on 3-km running performance in trained middle-distance runners

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Abstract Limited research examining the effect of taurine (TA) ingestion on human exercise performance exists. The aim of this study was to investigate the effect of acute ingestion of 1,000 mg of TA on maximal 3-km time trial (3KTT) performance in trained middle-distance runners (MDR). Eight male MDR (mean ± SD: age 19.9 ± 1.2 years, body mass 69.4 ± 6.6 kg, height 180.5 ± 7.5 cm, 800 m personal best time 121.0 ± 5.3 s) completed TA and placebo (PL) trials 1 week apart in a double-blind, randomised, crossover designed study. Participants consumed TA or PL in capsule form on arrival at the laboratory followed by a 2-h ingestion period. At the end of the ingestion period, participants commenced a maximal simulated 3KTT on a treadmill. Capillary blood lactate was measured pre- and post-3KTT. Expired gas, heart rate (HR), ratings of perceived exertion (RPE), and split times were measured at 500-m intervals during the 3KTT. Ingestion of TA significantly improved 3KTT performance (TA 646.6 ± 52.8 s and PL 658.5 ± 58.2 s) ($p = 0.013$) equating to a 1.7 % improvement (range 0.34–4.24 %). Relative oxygen uptake, HR, RPE and blood lactate did not differ between conditions ($p = 0.803$, 0.364, 0.760 and 0.302, respectively). Magnitude-based inference results assessing the likeliness of a beneficial influence of TA were 99.3 %. However, the mechanism responsible for this improved performance is unclear. TA's potential influence on exercise metabolism may involve interaction with the muscle membrane, the coordination or the force production capability of involved muscles. Further research employing more invasive techniques may elucidate TA's role in improving maximal endurance performance.

Keywords Oxygen uptake · Ergogenic aids · Time trial · Endurance running

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Introduction

The sulphonic amino acid taurine (TA) is found in its free form in large concentrations in both skeletal and cardiac muscle and brain tissue (Huxtable 1992). The high content of TA within these major organs has stimulated much research examining its role in modulating several physiological actions including osmoregulation, calcium content regulation, oxidative stress and substrate oxidation, all of which are known to have particular relevance to exercise performance (for an extensive review, refer to Huxtable 1992). To date, very little research has been conducted on the effect of acute or prolonged TA ingestion on endurance performance in humans (Rutherford et al. 2010). Existing research has produced inconclusive evidence on the use of TA prior to exercise. Running (Lee et al. 2003) and cycling (Zhang et al. 2004) time to exhaustion has been shown to significantly improve following TA supplementation. However, acute TA administration demonstrated no benefit to cycling performance (Rutherford et al. 2010).

The precise mechanisms underpinning how TA may affect human endurance performance are still largely

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unclear (Galloway et al. 2008). It has previously been shown that endurance-trained individuals have higher TA muscle content compared to their untrained counterparts (Blomstrand and Saltin 1999; Graham et al. 1995), thus indicating a potential role of TA in human exercise performance. However, differences in the uptake of TA into the muscle following ingestion have been demonstrated between human (Galloway et al. 2008) and rodent (Yatabe et al. 2003) models, with no uptake occurring in human models. This precludes previous suggestions that human endurance performance is enhanced via increased force production resulting from improved calcium regulation in the sarcoplasmic reticulum (Zhang et al. 2004). Such a finding has only been demonstrated in an in vitro animal model (Bakker and Berg 2002). The effect of TA ingestion on the human neuromuscular system during exercise is yet to be investigated. It has also been suggested TA exerts metabolic effects via interaction with the muscle membrane; similarly, this has not been confirmed or linked with improvements in exercise performance (Rutherford et al. 2010). A further concept is that acute TA ingestion may enhance exercise performance by attenuating losses from the muscle during exercise given the decreased levels reported following endurance exercise in humans (Cuisinier et al. 2001, 2002; Graham et al. 1995; Ward et al. 1999). Furthermore, it is unclear whether TA alone can improve endurance performance as many studies have used TA co-ingested with other products (Alford et al. 2001; Geiss et al. 1994; Forbes et al. 2007), highlighting the requirement for more studies in humans.

Rutherford et al. (2010) have previously demonstrated TA ingestion to increase fat oxidation during prolonged submaximal cycling exercise in trained individuals, citing a likely effect of TA on the muscle membrane. However, this enhancement in fat oxidation did not translate to enhanced exercise performance in a subsequent time trial. Moreover, the use of prolonged submaximal exercise before a time trial performance has limited ecological validity and may have potentially reduced the sensitivity of the time trial to detect differences between conditions (Lepers et al. 2002). Furthermore, it is unclear whether TA may influence a physiological effect when solely maximal endurance performance is assessed, as none of the existing research in this area has employed such a design. Therefore, the aim of this study was to investigate the effect of acute TA ingestion on maximal exercise performance, oxygen uptake and rating of perceived exertion (RPE) during a simulated 3-km time trial (3KTT) on a treadmill.

Methods

Eight well-trained competitive male middle-distance runners (mean ± standard deviation: age 19.9 ± 1.2 years, body mass 69.4 ± 6.6 kg, height 180.5 ± 7.5 cm, sum of seven site skinfolds 45.2 ± 5.9 mm, 800 m personal best time 121.0 ± 5.3 s) participated in the present study following the submission of their informed consent. Participant training at the time of recruitment consisted of a minimum of 45 miles of running per week including a minimum of two organised training sessions per week with their respective athletics clubs. Prior to participant recruitment, ethical approval was obtained from the local ethics committee. All testing was conducted during a non-competitive phase of the participant's training.

Experimental design

Participants reported to the laboratory on two occasions to complete self-paced maximal 3KTTs, in a randomised, double-blind, crossover design. A 3KTT was selected as this is the upper distance limit of the middle-distance running discipline. The 3KTT has commonly been used in recent research literature investigating different interventions with endurance-trained running populations (Julian et al. 2004; Robertson et al. 2010; Rodriguez et al. 2007). The 3KTT has previously been reported to have a coefficient of variation of 1.2 % (Julian et al. 2004). Each 3KTT was separated by 1 week in order to allow a sufficient washout period following TA administration (Galloway et al. 2008). Test sessions were completed at the same time of day to account for the effects of circadian variation on human exercise performance (Atkinson and Reilly 1996). Participants maintained their scheduled training in the week leading up to each test session. Participants refrained from any form of physical exercise, caffeine or pharmacological treatment for the 48-h preceding the trials. Dietary intake 48-h before the initial test session was recorded. Participants were asked to replicate this pattern of consumption for the remaining experimental session.

On arrival at the laboratory, participants consumed either a placebo (PL) or a 1,000-mg commercially available TA capsule (TA) which was certified to United States Pharmacopeia/National Formulary standards (Holland and Barrett, UK). The TA dose was equivalent to the amount that is commonly ingested in a standard serving of Red Bull^{TM} (Alford et al. 2001) and was equivalent to 2.5 times the maximum daily quantity of TA intake reported in normal human dietary analysis (Laidlaw et al. 1990; Rana and Sanders 1986; Shao and Hathcock 2008). The PL was a blank empty capsule. The capsule consumed within each trial was emptied from an opaque container into the participant's hand whilst both the researcher and participant looked away. The participant then placed the capsule in their mouth without looking at the contents of their hand, which ensured that the trial was double blinded. Randomisation of the capsules into the opaque container for each trial was conducted by a

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member of the research team other than the researcher who was conducting the trial. A 2-h ingestion period has previously been shown to be required to achieve peak plasma TA levels (Galloway et al. 2008). Therefore, pre-3KTT capsules were ingested whole with 250 ml of water 2-h before the start of testing, to achieve peak plasma TA at the start of the time trial. Participants completed a 10-min standardised pace warm-up (2-min at 10 km h^{-1}, 3-min at 12 km h^{-1} and 5-min at 14 km h^{-1}. The standardised warm-up was completed in the final 15 min of the 2-h ingestion period. The 3KTT was completed on a Woodway Pro-Series treadmill (Woodway, Weil am Rhein, Germany) at a 0.0 % gradient. The treadmill was maintained and calibrated in accordance with manufacturer guidelines. Participants were only provided with feedback on the distance covered during each 3KTT and were not informed of the overall performance time or heart rate (HR) data until after the completion of the second test session. All participants had extensive prior experience of high-speed treadmill running and competitive 3KTTs and therefore effective personal pacing strategies. During the 3KTT, participants adjusted pace via buttons located on the side of the treadmill. Participants were familiarised with how to adjust speed during the warm-up for each session and were permitted to adjust speed how and whenever they saw fit during the time trial. Respiratory gases (Medgraphics, CPX-D, St. Paul, MN, USA), HR (Polar A1 HR monitor, Polar Electro OY, Kempele, Finland) and RPE (Borg 1998) were measured at 500-m intervals. In addition, 500-m split times during the 3KTT and overall time to complete the time trial were recorded. Fingertip capillary blood lactate samples (Lactate Pro Analyser, Arkray Inc, Kyoto, Japan) were taken at the end of the 2-h ingestion period before the 3KTT commenced and immediately after its completion.

Statistical analysis

All values presented are mean ± standard deviation. Normality of data was confirmed following assessment of Q–Q plots. Paired *t* tests were employed to analyse overall 3KTT performance and overall 3KTT speed between conditions. A 2 × 6 (condition x 500-m interval during the 3KTT) general linear model repeated measures analysis of variance (ANOVA) with Bonferroni adjustment post hoc comparisons was used to analyse 500-m split times, HR, oxygen uptake, RPE and blood lactate data. A statistical significance level of $p < 0.05$ was selected to define statistically significant differences. Paired *t* tests and ANOVAs were completed using Minitab 15 statistical software (Minitab Ltd., Coventry, UK). In accordance with recommendations for reporting statistics in physiology-related journals (Batterham and Hopkins 2006; McGlory and Morton 2010), confidence intervals (95 % CI) and magnitude-based inference values were calculated. For the primary outcome variable of exercise performance, differences in competitive world (IAAF 2012) and English National (ESAA 2012) male 3,000-m finals were calculated from the years 2010, 2008 and 2006. Meaningful worthwhile change was defined as the mean difference in performance time between individual positions for the first four finishers in these world and national competitions (e.g. difference between 1st and 2nd, 2nd and 3rd and 3rd and 4th). Elite and national level performance differences between top four placed finishers were 0.30 ± 0.11 and 0.44 ± 0.23 %, respectively. To provide further assessment of the effect of acute TA ingestion on overall 3KTT performance, the meaningful inference of the intervention was determined using the method of Hopkins (2002). To perform this analysis, the *p* value produced from the paired *t* test on overall 3KTT performance was inserted into magnitude-based inference software (Hopkins 2007).

Results

Differences in overall 3KTT performance between conditions (TA 646.6 ± 52.8 s and PL 658.5 ± 58.2 s) reached statistical significance ($p = 0.013$) (Fig. 1a). Seven of the eight participants performed better in the TA trial, equating to a 1.7 % improved performance over the PL trial (range

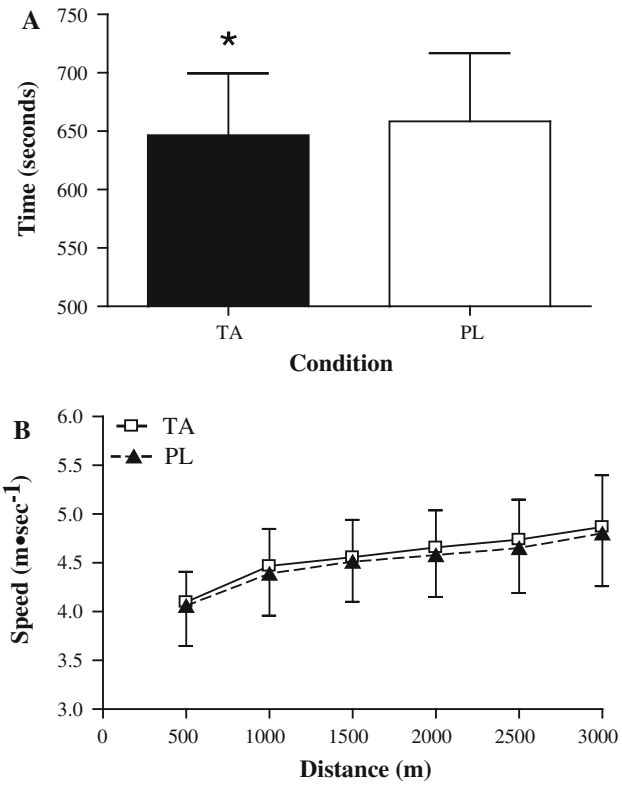

Fig. 1 Overall 3KTT performance time (a) and speed at 500-m splits during the 3KTT (b) in the TA and PL conditions in the TA and PL conditions. *Asterisk* denotes significant difference between conditions

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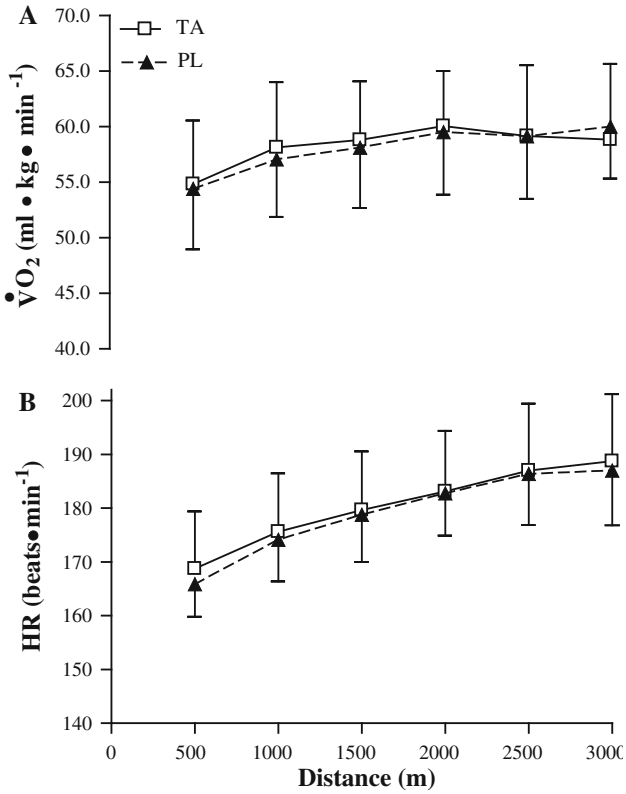

Fig. 2 Relative oxygen uptake (a) and heart rate (b) at 500-m splits during the 3KTT in the TA and PL conditions

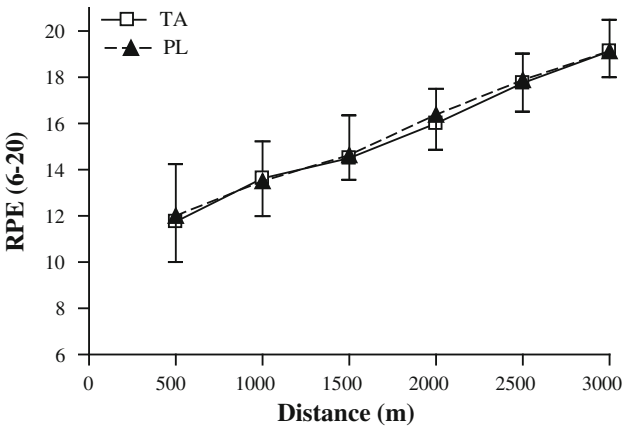

Fig. 3 RPE at 500-m splits during the 3KTT in the TA and PL conditions

0.34–4.24 %). The reported improvement in performance was 0.5 % above the coefficient of variation for the 3KTT and also greater than the defined minimal worthwhile change for related national and elite populations. The 95 % CI for mean differences in overall performance time between TA and PL were −3.4 to −20.4 s. Differences between conditions for 500-m splits throughout the 3KTT (Fig. 1b) did not reach statistical significance, but demonstrated a tendency towards an effect ($p = 0.081$, $f = 4.140$). Relative oxygen uptake (Fig. 2a), HR (Fig. 2b) and RPE (Fig. 3) did not differ between conditions ($p = 0.803$, $f = 0.070$; $p = 0.364$, $f = 0.940$ and $p = 0.760$, $f = 0.100$, respectively). Blood lactate concentrations (Post 3KTT, TA 10.48 ± 3.25, PL 9.39 ± 2.81 mmol^{-1}) did not differ statistically between conditions ($p = 0.302$, $f = 0.214$). Magnitude-based inference results assessing the probability that acute TA ingestion was beneficial/trivial/harmful to overall 3KTT performance were 99.3, 0.1, 0.6 %, respectively.

Discussion

Overall 3KTT performance

The current study provides novel data for the literature regarding the effect of acute TA ingestion on human exercise performance. No other study investigating the effect of TA ingestion alone on running performance has used a self-paced time trial to assess performance or investigated the effect of TA on endurance-trained participants (Lee et al. 2003; Zhang et al. 2004; Geiss et al. 1994; Alford et al. 2001). Overall, 3KTT performance was 11.9 s quicker in the TA condition, with seven of eight participants demonstrating improvement in exercise performance. Similar research investigating time trial performance with TA administration in trained cyclists did not demonstrate a significant difference between conditions (Rutherford et al. 2010). The differences in overall time trial results between the current study and Rutherford et al.'s (2010) are likely due to methodological differences. Factors such as TA ingestion timing and exercise protocol may have contributed to whether or not TA enhanced endurance performance and to what extent. Rutherford et al. (2010) utilised a 1-h ingestion period followed by a further 1.5-h submaximal intensity ride before their cycling time trial. A 1-h ingestion period has been shown to be insufficient for maximising plasma TA concentration, with 2-h previously defined as optimal for achieving acute peak plasma TA concentrations (Galloway et al. 2008). It is physiologically plausible to suggest that a 2.5-h period between ingestion and the start of the cycling time trial as well as conducting a submaximal intensity cycle in the intervening time may have dampened any influence the ingested TA may have had on time trial performance. Previously, it has been demonstrated that both force production and neuromuscular activation are decreased following 1-h of submaximal cycling compared to pre-exercise measures resulting from decreased central drive (Lepers et al. 2002). Additionally, plasma TA levels have been shown to decrease drastically at rest after peak levels have been reached (Galloway et al. 2008). The drop in plasma TA levels is between one-third and one-half of peak, 1-h after peak levels have occurred,

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following a single acute dose of TA. How this rapid decline in peak plasma TA may influence exercise performance remains uncertain. The current study involved an immediate maximal time trial performance following the designated TA ingestion period, whereas Rutherford et al. (2010) assessed differences in substrate oxidation between conditions in the intervening 2.5-h between ingestion and the start of the cycling time trial. Such a design may have limited ecological validity for endurance performance assessment.

Similarly to the current study, research assessing endurance capacity rather than simulated time trials (as in the current study) has also reported a positive effect of TA administration (Lee et al. 2003; Zhang et al. 2004). Zhang et al. (2004) utilised an incremental intensity cycle test, whereas Lee et al. (2003) employed a time to exhaustion run at 75 % of $\dot{V}O_{2\ max}$. The magnitude of the improvement in the TA condition in these studies was considerably greater than that in the current study perhaps due to the longer exercise duration. Additionally, the TA administration protocols used in these studies differed considerably from those of the current study. Supplementation of TA consisted of 6 or 4 g per day for 7 (Zhang et al. 2004) or 14 days (Lee et al. 2003), respectively. These studies do not indicate how close to the start of the endurance assessment the final TA ingestion of the supplementation period occurred. Recent studies have indicated human TA supplementation over a similar time period does not increase muscle TA content and acute ingestion must be carefully timed to achieve peak levels (Galloway et al. 2008). Therefore, it is difficult to interpret if TA supplementation may have benefited exercise capacity in these two studies or whether other dietary factors may have influenced any response.

Research examining TA ingestion within energy drinks has shown to improve exercise performance. Exercise time to fatigue during incremental intensity cycling following a submaximal intensity ride (Geiss et al. 1994), submaximal endurance exercise time defined by HR (Alford et al. 2001) and the number of submaximal intensity bench press repetitions performed before volitional fatigue (Forbes et al. 2007) have all been reported to significantly benefit from the ingestion of energy drinks containing TA. These findings add to the growing prevalence of energy drinks being utilised in the sport and exercise science domain as a means of improving exercise performance. However, these data must be interpreted with extreme caution. Extrapolating findings from such studies in an attempt to examine the influence of TA on endurance performance is problematic due to the additive ingredients contained within such energy drinks. Furthermore, such studies have used ingestion periods of 0.5–1 h (Alford et al. 2001; Forbes et al. 2007; Geiss et al. 1994) that would be too short to obtain peak TA plasma levels, assuming TA uptake is not augmented or diminished when consumed with the other ingredients within such drinks.

Physiological variables and RPE

The physiological and subjective measures performed within the current study provide support for existing TA ingestion research. However, the current study investigated these variables in a simulated endurance performance assessment more similar to real-world competitive endurance events than previous TA ingestion studies. The finding from this study that HR was not significantly different between the TA and PL conditions was consistent with previous research (Galloway et al. 2008; Rutherford et al. 2010; Zhang et al. 2004). However, TA has previously been shown to have positive clinical applications for cardiac tissue through the modulation of intracellular Ca^{2+} (Azuma et al. 1992; Satoh and Sperelakis 1998). Acute TA ingestion has also been demonstrated to decrease the HR of endurance-trained athletes after 45-min of submaximal intensity cycling compared to an equivalent drink without TA during exercise (Geiss et al. 1994). In this study TA was co-ingested with caffeine and glucuronolactone, as a result it cannot be concluded whether it was TA alone or a combination of the ingredients that decreased HR after 45-min of cycling (Geiss et al. 1994). Based on these findings, the duration of the endurance assessment within the current study may have been too short to demonstrate TA's influence on HR or if co-ingestion with caffeine and glucuronolactone may have been required to elicit such an effect (Geiss et al. 1994). Therefore, the ingestion of 1,000 mg of TA alone does not appear to exert any effect on sympathetic nervous system function in trained endurance athletes during maximal intensity exercise as previously detailed during prolonged submaximal activities (Geiss et al. 1994).

The findings of the current study are congruent with previous research as TA ingestion was not shown to influence oxygen uptake (Rutherford et al. 2010; Galloway et al. 2008), blood lactate concentrations (Galloway et al. 2008; Lee et al. 2003) or RPE (Lee et al. 2003; Rutherford et al. 2010). In contrast, maximal oxygen uptake has been demonstrated to improve following TA supplementation in sedentary individuals in an incremental cycle test to exhaustion (Zhang et al. 2004). However, the fact that oxygen uptake did not differ between conditions despite 3KTT being completed in significantly less time in the TA condition could be interpreted as a favourable effect of TA ingestion on central factors or muscular coordination independent of metabolic influence. Previously, it has been

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suggested that the effect of TA on exercise metabolism during simulated time trial performance would appear to act through interaction with the muscle membrane (Rutherford et al. 2010). This is particularly relevant given that acute TA ingestion only increases plasma content and not muscle content (Galloway et al. 2008). Conversely, it could be postulated that prior TA ingestion may attenuate TA losses from the muscle during maximal endurance exercise. However, it cannot be confirmed that a 1,000-mg dose of TA as used in the present investigation is sufficient to induce a concentration gradient to prevent losses from the muscle and only that it represents a substantially larger content than reported maximal daily intakes in normal diets. Such studies are yet to be conducted, although it has been demonstrated that TA content in the muscle decreases following endurance exercise (Cuisinier et al. 2001, 2002; Graham et al. 1995; Ward et al. 1999), therefore further investigation seems warranted.

The primary focus of the present study was to ascertain if TA ingestion improved maximal endurance performance when not preceded by prolonged submaximal intensity activity. Whilst we identified no significant difference in a variety of physiological measures, we speculate that the improvement in 3KTT may be due to improved neural function. The role of TA in neuronal function has previously been identified, with TA exerting both inhibitory and excitatory influence within the brain (El Idrissi and Trenkner 2004). In vivo animal model research also suggests the potential for extracellular TA to modulate calcium ion content, stabilise membranes and enhance the generation of neurotransmitters (Richards et al. 1995). Although no research currently exists investigating the effect of TA ingestion on the human nervous system during exercise, TA ingestion has shown the potential to positively influence neural function in populations suffering dysfunction (Konig et al. 1977). Therefore, the use of alternative measures such as electromyography with synchronised kinematic and force production data during running may be warranted. This would allow for assessment of whether TA influences neuromuscular function or muscular force production in an in vivo human model, as has previously been detailed in an in vitro animal model (Bakker and Berg 2002). If alterations in muscle force production were responsible for improved performance with TA ingestion in the current study, the measures employed were not sensitive enough to detect them. Indeed, given only the small but worthwhile improvement in performance and the variability in both oxygen uptake and HR, differences in these measures between conditions may have been too minimal to detect. Furthermore, enhanced time trial performance due to improved muscular coordination may suggest enhanced running efficiency which would not have increased HR or oxygen uptake. Studies observing enhanced endurance capacity following TA supplementation have not demonstrated alterations in perceived exertion (Lee et al. 2003) or have not measured RPE values (Zhang et al. 2004). Therefore, minimal research exists clarifying any potential effect TA may have on perceptions of effort.

Conclusion

In conclusion, this study provides novel data for the literature, as it was demonstrated that the ingestion of a 1,000-mg dose of TA 2-h prior to a 3KTT significantly enhanced endurance running performance. Furthermore, magnitude-based inference results denoting practical significance state that TA is likely to be beneficial and unlikely to be harmful to the 3KTT performance of trained middle-distance runners. The performance improvement in the TA condition also exceeded the minimum worthwhile change in performance for both UK national and elite level performance in competitive 3-km races. However, the current study indicates that the ingestion of 1,000 mg of TA does not affect HR, oxygen uptake, blood lactate concentrations or RPE of trained endurance athletes during maximal middle-distance running. Therefore, the mechanism responsible for the beneficial effect of TA ingestion on 3KTT performance in the current study remains to be elucidated. Future research should employ more invasive procedures in an attempt to identify a potential mechanism.

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Conflict of interest None.

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